Report on the second EURISOL User Group Topical Meeting [1]

Neutron deficient exotic nuclei and the Physics of the *proton rich side* of the nuclear chart.

Colegio Mayor Rector Peset, Valencia, Spain, 21-23 February 2011.

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[1]Coordinated by Berta Rubio, IFIC, Valencia, Spain and Angela Bonaccorso, INFN, Sez. di Pisa, Italy.

EURISOL SECOND TOPICAL MEETING
“Neutron-deficient nuclei and the physics of the proton-rich side of the nuclear chart”

Foreword

This booklet contains the highlights of the second EURISOL Topical Meeting which was held in Valencia from 21st to 23rd February 2011. It followed the EURISOL Topical Meeting in Catania on “The formation and structure of r-process nuclei, between N=50 and 82 (including ^{78}Ni and ^{132}Sn areas)”. It was organised by the EURISOL Users Group and supported by the European Commission (ENSAR project), CPAN (Centro Nacional de Física de Partículas, Astropartículas y Nuclear, Spain) and IFIC (Instituto de Física Corpuscular, Spain).
During the two and a half days of the meeting an interesting and dense programme was accommodated. Seventy participants, including almost all members of the previous and present EURISOL User Group Executive Committee contributed either to the presentations or to the lively discussions. The programme and the presentations are available at the workshop web site http://ific.uv.es/~eug-valencia.
There are two marked differences with the Physics discussed at previous meeting. One originates in the expected production of neutron-deficient nuclei at EURISOL. They will be produced through spallation (or other specific) reactions on solid targets. The estimated intensity increase in comparison with current facilities is around 50 (it goes in essence with the increase in primary beam intensity). This factor, although substantial is not overwhelming. It is not comparable with the improvement on the neutron-rich side where it is expected to increase by three orders-of-magnitude. It is also not very different from the expected improvement at other planned facilities such as FAIR. This means that an extra effort is needed in beam specifications as well as in instrumentation if new physics is to be discovered. The other important difference comes from the fact that we have a more detailed knowledge of what happens at the proton drip line than at the neutron drip line, the position of which is unknown even for medium and heavy nuclei. This makes the physics discussion more specific. It also allows for a more focussed plan.

In the following we summarise the problems addressed during the workshop.

One-, two- and three-proton radioactivities

These topics were addressed by E. Maglione, I. Mukha, P. Woods and M.J.G. Borge.

We have come a long way since the first discovery of one-proton radioactivity in the 1970s. What appeared at that time as an exotic decay mode is today a well understood phenomenon with many known examples ranging from Z=53-83. Its simplicity can be exploited to make studies of the effects of nuclear shape and shell structure on quantum tunnelling. On the other hand the proton energy gives a direct measure of the proton separation energy. Most of the cases have been discovered using fusion evaporation reactions. P. Woods proposes to continue to pursue this approach but using secondary reactions with radioactive proton-rich beams such as 56Ni and 72,74Kr. He also proposes to make use of the decay-tagging technique to exploit the decay-specific mode of these nuclei to study their excited states using powerful Ge-gamma arrays.
The discovery of one-proton radioactivity below Z=50 is also a challenge. Some indications of its existence have been observed in recent fragmentation experiments at GSI (see T. Faestermann’s contribution to this meeting). They can also be reached using fusion-evaporation reactions provided intense enough beams are available.

A summary of our knowledge of two-proton radioactivity was presented by I. Mukha, As in the case of one-proton radioactivity this is important for the nuclear structure information it provides, and also for the quantification of 2p-capture processes bridging bottlenecks at the rp-process waiting points. A stringent limit arises here due to the short half-life of some of these systems. Only if their half-lives are of the order of a ms or longer they can be implanted and studied. Another recently developed method consists in implanting the radioactive nuclei in gaseous detectors based on time projection chambers. This method has been used so far in fragmentation reactions at high energy, and it could perhaps be adapted to very low energies but it would need a dedicated effort.

The detection of beta-delayed charged particle emission is a very powerful tool to study proton-rich nuclei far from the stability. The reason is two-fold: on the one hand the measured particles provide important spectroscopic information about the two levels involved, namely the initial and the final level, and on the other hand, the efficiency to detect charged particles is often much higher than the gamma-efficiency. As a result, the charged-particle spectrum is often the only piece of spectroscopic information we have on very exotic nuclei. Moreover, it can be used to estimate their masses. M.J. Borge gave an overview of the cases that have been studied so far; this included the approximately 200 beta-delayed proton-decay and the 9 beta-delayed two proton decay cases. More exotic decays were also mentioned. Thinking of the physics at EURISOL, one of the main emphases is to study the fp shell nuclei with the same level of accuracy as that already achieved today for the sd shell. The observation of more cases, in addition to 31Ar, of two proton emission from levels other than the IAS would also be important.

Finally, theoretical aspects were addressed by Maglione and Ferreira in their contributions. Considerable progress has been made in the last decade in describing the main features of proton emitting nuclei. Experimental half-lives are well reproduced for odd and odd-odd parent nuclei near closed shells as well as in deformed nuclei solving the full quantum mechanical problem with all interactions and deformations, without approximations and including Coriolis coupling and pairing.

Looking towards EURISOL one would be interested in having experimental data on nuclei heavier than Bi and more detailed information, as in the emblematic case 141Ho, for which we know: half-lives of the ground and isomeric states, the fine structure of both states, and the energies of the rotational bands built on the two states. This very complete information, at present only available for one single nucleus, is extremely important in order to fine tune the theory.

N≈Z Nuclei

Contributions by J.J. Valiente Dobón, A. Macchiavelli, P. van Isacker, Y. Fujita and T. Faestermann.

The properties and structure of nuclei with equal or very similar numbers of protons and neutrons have been an intense field of research in the last two decades, both experimentally and theoretically. The structure of these nuclei provides essential information *inter alia* on isospin symmetry of the nuclear force or proton-neutron correlations. J.J. Valiente Dubón summarised the impressive improvement in our knowledge of excited states in mirror nuclei. This is a consequence of the advent of large Compton suppressed gamma-ray arrays and the associated ancillary detectors which allow to access very exotic N≈Z nuclei at high spins. The limit today lies at mass 67 where Mirror Energy Differences (MED) between ^{67}Se and ^{67}As have been well reproduced theoretically. Similarly, the very recent discovery of excited states in the N = Z

nucleus ^{92}Pd and the claiming of the presence of an isoscalar T = 0 pairing correlation at low-spins sets the present experimental limits to this kind of physics. This very special topic is discussed further below.
Future in-beam studies of exotic neutron-deficient nuclei will mainly require the use of reactions (for instance fusion evaporation reactions) induced by intense radioactive heavy-ion beams such as those provided in the future by EURISOL. In this respect, one should not forget the need of high performance, highly selectivity detectors such as the new generation of gamma-ray array detectors like AGATA and the neutron-detector array NEDA. This will allow us to pin down the nuclei of interest which in most of the cases represent only a tiny part of the total cross section, especially when going towards the possibly heaviest bound N = Z nucleus in nature, ^{112}Ba (N=Z=56).
Competition between isovector (T=1) and isoscalar (T=0) Cooper pairs in N=Z nuclei was discussed by Macchiavelli from the experimental point of view and van Isacker from the point of view of the theory. Macchiavelli proposes to use pn transfer reactions and compare the cross section to 0+ and 1+ spin-parity final states to measure the strength of T=1+ over the T=0 paring forces. Experiments have been carried out on stable N=Z nuclei, some of them in inverse kinematics, and for the case of the radioactive nucleus ^{44}Ti, also in inverse kinematics. There is a programme at Argonne and GANIL to carry out this kind of experiment which will be an excellent preparation for experiments with EURISOL beams of more exotic N=Z nuclei. One can envision approaching nuclei near ^{88}Ru, a region where the most collective effects are expected. Van Isacker on the other hand argued that the interacting boson model of Arima and Iachello provides a natural framework to discuss neutron-proton pair correlations. It can be applied to pn transfer reactions as well as to the description of low lying excited states in N=Z nuclei, for both even-even and odd-odd cases. As mentioned above ^{92} Pd (in particular its excitation energy spectrum) is today the heaviest case studied experimentally. To map the rest of the N=Z cases up to 100Sn or even above demands very intense beams and could be at the forefront of new physics at EURISOL.

Another possible comparison of mirror nuclei can be made by means of beta decay and charge exchange reactions. If the latter is performed under certain conditions, namely at approximately 100 MeV/u and at 0^{o}, it is governed by the same operator (\sigma\tau) as the beta decay. Based on this idea a number of experiments have been carried out in recent years on N≈Z Nuclei. This has been possible thanks to a considerable experimental progress on both sides, with the impressive improvement in resolution in Charge Exchange (CE) reactions, and to the higher sensitivity achieved in beta decay studies, both in production and in the use of sophisticated composite high efficient Ge detectors. One of the many interesting problems which remains still obscure is the long standing problem of the quenching of the GT strength in nuclei. Fujita explained how this problem can be addressed in a “clean way” using beta decay if enough intensity (EURISOL) for the production of radioactive nuclei is provided. He uses the knowledge gathered in CE reactions to propose specific examples on where the Giant Gamow Teller resonance should be accessible in beta decay. During the lively discussion at the workshop, it was concluded that the regime of 100 MeV per nucleon should be provided at EURISOL as well as a dedicated space where a high resolution spectrometer “a la Grand Raiden” could be installed.
^{100}Sn is one very special case among N=Z nuclei. It is also the one where progress in production can be followed in time. About ten nuclei were produced almost simultaneously at GSI and GANIL in 1994, and 259 were recently produced in the very much heralded experiment at GSI in 2008. Although still too few T. Faestermann could demonstrate how much new physics one was

able to deduce from the modest statistics. It is not difficult to imagine that a factor of 50 in beam intensity would certainly allow real spectroscopic studies of this and neighbouring nuclei.

Special N=Z nuclei subtopic: Superallowed Fermi decays, precise $T_{1/2}$, branching ratios and Q values

Contributions by J. Giovinazzo, T. Eronen, M. Kowalska

The nuclear beta decays between isobaric analogue states of spin-parity 0+ and isospin T=1 (and other superallowed beta decays) provide valuable information for testing the Standard Model of particle physics. These so-called superallowed beta decays are of pure Fermi type so that the decay matrix element is very simple. The most precise V_{ud} matrix element of the Cabibbo-Kobayshi-Maskawa (CKM) quark-mixing matrix is obtained from the superallowed beta decays. The observables to be determined are the $T_{1/2}$, the beta branching ratio to the final states in the daughter nucleus and the Q-value.

High precision T1/2 and branching ratios measurements for superallowed 0+ to 0+ transitions starting with N=Z odd-odd nuclei were explained by J. Giovinazzo. Special emphasis was laid on the strict control of systematic errors. In order to progress further, one should either study heavier T_Z=0 cases, or to improve the precision of the branching ratio measurements for T_Z=-1 nuclei. One current limitation is again the very limited production rates for these isotopes, something that could be clearly improved with EURISOL. One should notice the importance of purification traps in order to avoid daughter (or parent) contaminations. This should by all means be part of a decay set-up portfolio at EURISOL. The other important ingredient, namely the mass difference between the parent and the daughter nuclei was discussed by Tommi Eronen (efforts at Jyväskylä) and Magda Kowalka (efforts at ISOLDE). In both cases the trap is used not only as a purification device but as a precision mass spectrometer. Eronen explained recent progress at Jyväskylä with the JYFLTRAP Penning trap installation coupled to IGISOL where Q values of 14 different superallowed beta emitters have been determined with a precision of Q/M of 10^{-9}. A similar set-up, namely, a purification trap and a high precision mass spectrometer would be extremely useful at EURISOL where high-precision Q-value, half-life and branching ratio measurements could be performed. They would perhaps not contribute substantially to the CVC tests since the strongest influence there clearly originates from lighter, already precisely measured, nuclei. In turn, these heavy nuclei would provide valuable data for evaluating isospin symmetry breaking corrections.

Nuclear Astrophysics

F. Montes, F. De Oliveira Santos, A. A. Chen.

The rp-process is the main source of energy and determines the X-ray light curve in the X-ray bursts of thermonuclear explosions in the Galaxy. The path is dominated by proton captures and -decays. Quantitative comparison between X-ray burst calculations and typical X-ray burst observations have shown excellent agreement but have also shown that the nuclear physics of the rp-process is not sufficiently well known to test the calculations at the level of precision provided by observations. The main reason is of course that the key (p,gamma) reactions happen on unstable nuclei while indirect methods do not reach the desired level of accuracy.

...Montes explained that at MSU, there is a plan to perform these reactions at the energies relevant for astrophysics for nuclei directly involved in the rp-process. Present efforts are aimed at developing "ad hoc" instrumentation such as the Separator for Capture Reactions (SECAR). Similarly, Oliveira explained how at GANIL a study of using a Wien Filter as a spectrometer for (p, gamma) reactions is under study. He also reminded us of the importance of the radioactive beam purity and the possibility of using laser ionisation sources. A point that was further developed by Cocolios and van Duppen (see later).

There are cases however, not very far away from the stability, which are already possible. More specifically, at TRIUMF the ISAC facility has been specially designed to perform this kind of reaction. Chen gave us a good example in the recent ^{26}Al(p,gamma)^{27}Si reaction measurement. This case is especially important since it influences the production of ^{27}Al and the associated 1.8 MeV gamma ray which has been used to map our Galaxy since the 1980s. In his conclusions he pointed towards the importance of performing similar experiments with ^{25}Al or ^{26m}Al at EURISOL.

In summary, direct measurement of reaction cross sections at low energy for astrophysics is an excellent physics case for EURISOL. A detailed study of several reactions should be performed in order to determine the required experimental conditions and the limits of the measurements. At the same time, EURISOL could profit a lot from present efforts such as those carried out at MSU, TRIUMF or GANIL in developing adequate instrumentation among which a suitable recoil separator seems to be a must.

Other Reaction Experiments: Coulex and transfer
J. Cederkall and D. Jenkins

The chain of Sn isotopes starting with ^{100}Sn and ending beyond ^{132}Sn is very interesting from the nuclear structure point of view. Inverse kinematic reactions using these beams were analysed by J. Cederkall with special emphasis on Coulomb excitation and transfer reactions to locate single particle states. An experimental challenge that needs to be addressed in the future for these inverse kinematics reactions is a proper observation of the outgoing charged particles. For instance, in an inverse (d,p) reaction at 10 MeV/u in the 100 mass region, the outgoing proton can have an energy up to ~ 70 MeV. Consequently, the angular range covered is important. The application of a separator in conjunction with charged particle and gamma-ray detection would also be advantageous.
Jenkins also explained the use of Coulomb excitation to pin down information on nuclear deformation in light Pb isotopes. He also presented the experiments which will be possible with HIE-ISOLDE. Much thinking has to be devoted to the set up required to exploit these future possibilities, where more sophisticated reactions such as pn transfer, could be performed. There are many open questions here such as the best detector system for particle identification. No doubt EURISOL could profit from progress in this area.

Other Reaction Theory
C. Bertulani and H. Arellano

Nuclear reaction theory is very important and pursued by only a small number of colleagues. This

is in itself a problem which was thoroughly discussed during the meeting. We had two of them at the meeting (H. Arellano and C. Bertulani).
Direct measurements relevant for nuclear physics and nuclear astrophysics involving unstable nuclei are difficult and have led to the development and use of indirect methods using reactions at radioactive beam facilities. The list of indirect techniques that are used today includes the measurement of elastic scattering, Coulomb dissociation, nuclear breakup, transfer reactions, knock-out reactions, fragmentation reactions, and other indirect techniques. But even with the advent of rare isotope facilities worldwide, many pieces of valuable information will require a dedicated facility such as EURISOL. Bertulani discussed some of the open problems when using indirect techniques with reactions involving proton-rich nuclei.

Arellano provided microscopic descriptions of the optical potential necessary in the calculation of nucleon scattering from nuclei including an explicit dependence on the matter distribution of their neutron and proton constituents. This is particularly relevant considering the possibility of EURISOL beams colliding with hydrogen targets which would be just the inverse kinematics equivalent of a free nucleon-target scattering. He arrived at the interesting conclusion that for medium energy proton scattering (70 MeV) observables are more sensitive to the details of the neutron than to the proton density.

Atomic Physics for Nuclear Physics
R—D. Herzberg, P. van Duppen, T. Cocolios, M. Kowalska

This section is concerned with the use of atomic physics to extract nuclear physics information. It starts with the use of electron conversion to characterise nuclear transitions, and it follows with the use of laser-induced ionisation either to selectively ionise and separate the nucleus (or even the isomer) of interest, or to deduce fundamental ground state properties such as spin, quadrupole moment or magnetic moment. The characterisation of the ground state is essential if we want to understand the excited states of the nucleus built upon it. It will be very difficult to settle, for instance, the spin-parities of excited states if we do not know the spin of the ground state.
We start by discussing measurements of gamma and electron intensities. They allow one to calculate the internal conversion coefficients of nuclear transitions and consequently to determine their electric or magnetic character as well as their multi-polarity. This very powerful tool has been a bit neglected in recent times in in-beam experiments partially due to the emphasis of these measurements in detecting as much as possible of the gamma decay branch with highly sophisticated 4pi Ge arrays, and partially due to the intrinsic difficulty of measuring electrons emitted promptly with the reaction. In-beam electron spectroscopy suffers from a large background produced either by delta electrons or other charged particles produced in the reaction. Herzberg presented a beautiful example of the spectrometer SEGA in Jyväskylä which combines a germanium detector array with a highly segmented silicon detector and an electron transport system and allows simultaneous in-beam γ-ray and internal conversion electron measurements. Moreover, the recoil separator RITU allows one to perform decay tagging and hence to clean up the many reaction channels produced in the reaction. This is a very good example of the kind of set-up one would dream of for fusion evaporation reactions with EURISOL using radioactive beams. One should note that electron conversion measurements are especially important if one wants to study very heavy elements.
The possibilities of laser spectroscopy and laser resonance ionisation at EURISOL were analysed

by van Duppen, Cocolios and Kowalska. Laser spectroscopy studies deliver charge radii, nuclear magnetic moments, quadrupole moments and spins in a model independent way, provided the atomic physics is well understood. A strong programme for these studies at EURISOL, including the study of neutron-deficient isotopes, should be foreseen. As the production of isotopes from refractory type elements will be hampered at EURISOL when using the high-temperature target-ion source systems, it is essential that other efforts such as the on-going project at SPIRAL-2 of coupling a laser ion source with the focal plane of the Super Separator Spectrometer are pursued. At EURISOL, the stable beams of the type available at SPIRAL-2 could be replaced by RIBS.

In these three contributions one can see nice examples of measurements of ground state properties in very low mass nuclei, with special emphasis on symmetries, on medium nuclei, Cu and Ag isotopes, and on Po isotopes.

The other important application of lasers is the Resonance Ionization Laser Ion Sources (RILIS) which will inevitably have to be part of the EURISOL facility. The ionizing cavity used is the simplest and most rugged ion-source system available for producing RIBs. RILIS are essential to deliver pure (or purified) radioactive ion beams and have the potential to produce isomerically pure beams.

An even more sophisticated scheme currently under investigation at ISOLDE is collinear resonance ionisation spectroscopy (CRIS). This technique should be able to study beams with intensities as low as 1 ion per second with a resolution close to that of the standard collinear laser spectroscopy. It will produce highly purified beams and can be considered as a possible tool for providing clean beams at EURISOL.

Ground State Shapes from beta decay

A. Algora and A. Petrovici

Nuclear shapes and particularly nuclear deformation play a key role in our understanding of the nuclear structure. There are several ways and methods to deduce nuclear shapes. For example we can obtain information on the deformation by means

of measurements of nuclear electric quadrupole moments (see Kovalska and Cocolios), which provide direct measurements of the departure from sphericity. We can also determine the nuclear radii by scattering experiments and deduce the corresponding nuclear shape. We can probe the shape by Muonic atoms which again can provide information on the departure from sphericity. The interpretation of nuclear spectroscopic data is also a source of shape information. From level lifetimes, B(E2)-s or Coulex (Jenkins and Cederkall), etc., deformation can be deduced. E0 transitions are also a “traditional” source of information (Jenkins and Herzberg), mainly related to shape changes and shape mixing. More difficult is to obtain information on the sign of the deformation. One possibility is Coulex angular distributions, but this needs a substantial intensity in the radioactive beam.

In Algora´s contribution an alternative method is presented which consists in comparing the beta-strength distribution as a function of energy with theoretical calculations assuming different shapes for the parent state. The success of this procedure depends on the precision of the experimental determination of the strength distribution. For these measurements the beta-delayed gamma-Total-Absorption Spectroscopy (TAS) technique is the only possibility to avoid systematic errors. At the same time one should look in regions where different strength distributions are expected for the possible shapes of the decaying ground state (prolate, spherical, oblate). The calculations described by Petrovici, beyond mean field with the Excited Vampir Model, can describe beta decay strength distributions among several other observables. She has worked intensively in the mass 70 region and N near Z nuclei where she has now a good description of the effective interactions. The method described above has been shown to work correctly in this mass region and it is now being tested in the light lead region. A TAS setup at EURISOL would allow one to study more exotic cases in these two mass regions and perhaps in others such as those of the heavier N near Z nuclei.

Exotic excitations in proton rich nuclei and clusterisation
D. Vretenar, M. Freer, G. Verdi

In contrast with neutron-rich nuclei, bound nuclei with an excess of protons can be found only below Z=50, and even here the excess of protons is never very large. The question arises whether exotic excitations such as pygmy resonances, clearly observed in neutron-rich nuclei, can still appear in nuclei that are proton-rich. Vretenar showed that proton pygmy dipole resonances can indeed develop in light and medium mass proton-rich nuclei. Moreover, in contrast with neutron-rich nuclei, the separation between the electric Pygmy Dipole Resonance (PDR) and the Giant Dipole Resonance increases as the nucleus becomes more proton-rich. This very interesting prediction facilitates the observation of the PDR as the nuclei become more exotic. A very interesting aspect from the experimental point of view. Moreover, the Ar case presented is very attractive for the EURISOL facility.

Clusterisation of light nuclei into alpha particles in N=Z nuclei is a well known phenomenon which is revealed in the binding energies of nuclei “composed by alpha bonds”. Its effect is however not very strong and it is clear that fermionic effects dominate over cluster effects even at the g.s level. However a very interesting observation is the appearance of clusterisation at the neutron drip-line. Freer argued that the same effect, perhaps attenuated, should exist at the proton drip-line and this unexplored aspect could again be part of the EURISOL scientific programme. It could be studied by fragmenting proton-rich nuclei previously accelerated to 30 MeV/u, or using alpha transfer reactions, at lower energy and measuring the associated spectroscopic factors. The proposition of Verdi to construct a detector array intended to measure correlations between particles and fragments in coincidence and with a large coverage in solid angle could be the right tool for these experiments.

Conclusion

As we can see, there were many extremely interesting physics problems related to proton-rich and neutron-deficient nuclei, especially at the N=Z line, which demand further experimental investment. All of them demand higher intensities of radioactive beams than presently available. However EURISOL will need to compete with other planned facilities also delivering higher intensities. A very clear advantage at EURISOL would be to provide the means to build ad-hoc instrumentation, some of them in a “permanent” mode.

- An area for stopped beams (decay studies, mass measurements and other ground state properties, including traps and laser ionisation…). A hall similar to the present ISOLDE hall or the planned DESIR hall.

- A low energy area for reactions of astrophysical interest. Similar to ISAC in TRIUMF, but one should also look at the dedicated effort at MSU.
- Coulex and transfer at low energy. One could take REX-ISOLDE as an example adding a recoil spectrometer.
- In-beam, gamma, electron spectroscopy and decay tagging station. The set-up at Jyväskylä is a good example but with the state-of-the-art in Gamma arrays and including the possibility to measure neutrons (for channel selection purposes).
- Intermediate energy regime. Ideally with a high resolution spectrometer such as the one at RCNP in Osaka.

Set-ups with dedicated instrumentation, and high quality beams at these energies will make EURISOL a unique place to attack most of the physics problems discussed in this workshop.

Neutron deficient exotic nuclei and the Physics of the "proton rich side" of the nuclear chart

Monday 21 February 2011 - Wednesday 23 February 2011

Colegio Rector Peset

Programme

Monday 21 February 2011

Monday February 21st, 2011. 9:00 - 10:30 (09:00-10:30)

- Conveners: Bonaccorso, Angela

time	title	presenter
09:00	Welcome	
09:20	Eurisol update	BLUMENFELD, Yorick
09:50	Beta-delayed proton-emission, exotic decays in light nuclei	G. BORGE, Maria José

Monday February 21st, 2011. 11:00 - 13:00 (11:00-13:00)

- Conveners: Blank, Bertram

time	title	presenter
11:00	Studies of Two Proton radioactivity	MUKHA, Ivan
11:40	Structure of proton emitting nuclei	MAGLIONE, E.
12:20	New Vistas in Experimental Searches for Proton Radioactivity	WOODS, Philip J.

Monday February 21st, 2011. 15:00 - 17:00 (15:00-17:00)

- Conveners: Maj, Adam

time	title	presenter
15:00	Spectroscopy studies of N≈Z nuclei	VALIENTE DOBON, J.J.
15:40	Gamow-Teller Resonances in the beta decay and Charge-Exchange Reactions	FUJITA, Yoshitaka
16:20	Superallowed Fermi decays: precise T1/2 and branching ratios measurements	GIOVINAZZO, Jérôme

Monday February 21st, 2011. 17:30 - 19:00 (17:30-19:00)

- Conveners: Blumenfeld, Yorick

time	title	presenter
17:30	High Precision Q-EC Value Measurements of Superallowed beta decays	ERONEN, Tommi
18:10	In-gas cell laser spectroscopy of neutron-deficient silver isotopes	VAN DUPPEN, Piet
18:35	Early onset of deformation in the neutron-deficient polonium isotopes identified by in-source resonant ionization laser spectroscopy	COCOLIOS, T.E.

Tuesday 22 February 2011

Tuesday February 22nd, 2011. 9:00 - 10:20 (09:00-10:20)

- Conveners: Gelletly, William

time	title	presenter
09:00	Rp-process	MONTES, Fernando
09:40	Explosive hydrogen burning studied with RIB	OLIVEIRA, Francois

Tuesday February 22nd, 2011. 11:00 - 13:00 (11:00-13:00)

- Conveners: Fynbo, Hans

time	title	presenter
11:00	Aluminum-26 nucleosynthesis with proton-rich exotic beams	CHEN, Alan
11:40	Studies of neutron-deficient nuclei with breakup reactions	BERTULANI, Carlos
12:20	Exotic modes of excitations in neutron-deficient nuclei	VRETENAR, Dario

Tuesday February 22nd, 2011. 15:00 - 17:00 (15:00-17:00)

- Conveners: Ackermann, Dieter

time	title	presenter
15:00	Spectroscopy of N~Z Nuclei: 100Sn and Neighbours	FAESTERMANN, Thomas
15:40	Studies in the 100Sn region with radioactive Beams	CEDERKALL, Joakim
16:20	Spectroscopic methods for the heaviest nuclei	HERZBERG, Rolf-Dietmar

Tuesday February 22nd, 2011. 17:30 - 19:10 (17:30-19:10)

- Conveners: Jokinen, Ari

time	title	presenter
17:30	Fundamental research using the high intensity proton beams of MYRRHA	POPESCU, Lucia
17:55	Selective sensitivity of proton scattering to densities on the nuclear surface	ARELLANO, Hugo
18:20	The FARCOS Project - A Femtoscope ARray for COrrelations and Spectroscopy	VERDE, Giuseppe
18:45	Symmetries in proton-rich nuclei seen through ground-state properties	KOWALSKA, Magdalena

Wednesday 23 February 2011

Wednesday February 23rd, 2011. 9:00 - 11:00 (09:00-11:00)

- Conveners: Ferreira, Lídia S.

time	title	presenter
09:00	Shape coexistence in heavy nuclei	JENKINS, D.
09:40	Shape effects and beta decay: what can we learn from TAS measurements	ALGORA, Alejandro
10:20	np pairing in N=Z nuclei studied through 2N transfer reactions	MACCHIAVELLI, Augusto

Wednesday February 23rd, 2011. 11:40 - 14:00 (11:40-14:00)

- Conveners: Lewitowicz, Marek

time	title	presenter
11:40	Aligned neutron-proton pairs in N=Z nuclei	VAN ISACKER, Piet
12:20	Beyond mean-field description of exotic structure and decay of proton-rich nuclei in A ~ 70 region	PETROVICI, Alexandra
13:00	Alpha clusters	FREER, Martin
13:40	Concluding remarks	BONACCORSO, Angela

Beta-delayed Charged Particle Emission and Exotic Decays

M.J.G. Borge
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PRESENT STATUS AND HIGHLIGHTS

The beta-decay of exotic nuclei touches upon many different and highly relevant issues. The study of nuclear decay modes reveals a great number of nuclear structure phenomena and permits to investigate the behaviour of atomic nuclei with a large imbalance of the number of neutrons and protons with respect to stable nuclei.

The high efficiency for the charged particle detection makes the study of the beta delayed particles a unique tool to understand the nuclear structure of very rare species through very exotic decay modes. Beta-delayed α emission dates back to the early days of nuclear physics, but β-delayed proton emission and proton radioactivity were still not discovered in the late 1950's. The β-delayed proton emission was first identified in ^{25}Si in 1963 thanks to the use for first time of Si surface barrier detectors. Today close to 200 cases have been identified.

Most of the beta-delayed decay modes will be enhanced at the driplines, since nucleon and multi-nucleon separation energies will be low. Furthermore we know that for very loosely bound systems the continuum play an important role. This effect also manifests itself in beta decay. In very light systems very exotic decay modes and multi decay modes happen.

The study of the charged-particle spectrum has often been the only spectroscopic tool to study very exotic nuclei and to rather accurately define their masses, see, for instance [1] where the βp decay scheme, $T_{1/2}$ and determination of masses from the position of the IAS were obtained. for nuclei in the $20 \leq A \leq 50$ region.

The βd, βt, $\beta\alpha$ decay modes are open even in light very neutron rich nuclei. The βt, has been observed in ^{8}He and ^{11}Li indicating in the former the presence of neutron skin. The Q-value for βd can be written as $Q_{\beta d}$ (MeV) = 3-S_{2n} indicating that this decay mode should be present in halo nuclei. This decay mode has been observed in ^{6}He and ^{11}Li. In both cases the βd decay mode is confirmed to be happening directly to the continuum.

The $\beta\alpha$ process is favoured in light nuclei with Tz = -1 such us ^{8}B, ^{12}N or ^{20}Na. In cases where both $\beta\alpha$ and βp are allowed βp dominates due to barrier penetrabilities. Branches of $\beta\alpha$ > 1% are only observed in nuclei with A < 20 and exceptionally in ^{110}I. The βpα or $\beta\alpha$p decay mode is open for ^{9}C, ^{13}0, ^{17}Ne and ^{23}Si, but it has only been identified in ^{9}C and ^{17}Ne. The absence of this decay mode in a case such as ^{13}0 is surprising as the proton daughter clearly exhibits a α-cluster structure that will favours the following α-decay.

The βp process is open for most elements for the isotopes close to the proton drip line. The IAS falls into the Q_β-window for nuclei with Z > N. The IAS decays by very narrow isospin-forbidden transitions to the ground and excited states of the proton daughter. When the IAS is in the middle of the Q_β-window the decay of the IAS dominates the βp spectrum and a large part of the Gamow Teller (GT) strength, including the GT Giant resonance becomes accessible. So the measured GT strength distribution can be compared with the sum rule. Comparison of the observed GT strength distribution with the theoretical prediction allows the *extraction of the quenching of the axial-vector strength*. In addition, the detailed information obtained from the excited states of the emitter becomes a stringent test of the shell model calculations in the region. Mirror asymmetry has also been tested for many cases in the p and sd-shell. The Fermi matrix element will be restricted to the transition to the IAS with a very weak contribution to other states due to isospin mixing. These contributions can be determined experimentally becoming a demanding test of nuclear-structure theory. For more details see recent reviews [2,3].

The β-ν correlation studies in β decay is an important probe of the nature of the weak interaction, i.e. it was used to deduced the Vector and Axial-Vector character of the interaction in the 60's by measuring the energy distribution of the recoiling nucleus. This is very hard as the daughter recoiling energy is around only few hundreds eV. If the daughter state is unbound, βp occurs. The enhancement in recoiling energy is the ratio between the momentum of the emitted particle and the recoiling nucleus. By measuring the β-decay recoil energy shift of a proton peak or the shape of the proton peak spectroscopic quantities such as spin, intrinsic widths of highly-excited levels and the F/GT ratio can be determined [4,5] if the instrumental energy resolution is good enough. Search for physics beyond the standard model was done by the study of the proton line shape from the IAS of ^{32}Ar to the ^{31}S ground state. These measurements provided very clear limits on the search of scalar components: $M_S \geq 4.1\ M_W$ [6].

For systems with $20 \leq Z \leq 28$, multiple decay modes can co-exist including 2p-radioactivity. For higher Z the β-delayed particle has a narrower window probing states of high density. The level density largely exceeds what can be resolved with today's detector technology. In experiments with good resolution the fine structure of the delayed proton spectrum can be measured. From the observed fluctuations the density

TABLE 1. Identified β2p precursors. For more details see [1,2,8] and references therein.

Nucleus	**Tz**	**$T_{1/2}$ (ms)**	**Q_{EC} (MeV)**	**S_p (keV)**	**S_{2p} (keV)**	**B_p (%)**	**B_{2p}(%)**
^{22}Al	-2	91.1(5)	18.58(9)	5501.8(19)	7933.1(13)	61.9(54)	1.10(11)
^{23}Si	-5/2	42.3(4)	18.55(69	120(20)	5624(19)	71(5)	3.6(5)
^{26}P	-2	43.7(6)	18.26(9)	5517(3)	7789(3)	37(2)	2.16(25)
^{27}S	-5/2	15.1(15)	17.64(9)	861(27)	6379(26)	4.2(6)	1.1(4)
^{31}Ar	-5/2	14.1(7)	18.49(10)	290(50)	4690(50)	64,6(9)	12.4(5)
^{35}Ca	-5/2	25.7(2)	15.77(7)	81(20)	4743(20)	96.3(15)	4.2(3)
^{39}Ti	-5/2	28.5(9)	15.96(9)	-602(24)	3946(24)	87.5(65)	12.5(65)
^{43}Cr	-5/2	21.1(4)	14.16	190(230)	3960(230)	86.7(39)	5.6(7)
^{45}Fe	-7/2	2.6(2)	18.92	-1060(300)	1670(380)	18.9 (25)	7.8(23)
^{50}Ni	-3	17.2(13)	13.41(12)	208(44)	2863(45)	86.7(39)	14(5)

of states for a certain spin value can be determined [7]. This information is relevant in astrophysics for the modelling of the rp-process.

In the case of β2p or other β-delayed multi-particle emission process the breakup mechanism is not fully determined by energy and momentum conservation. Either the break-up proceeds via these resonances sequentially or the beta-daughter breaks up directly into the continuum. The β2p emission has been observed in 9 nuclei, in all but ^{31}Ar only β2p decay from IAS was observed and the decay energy, the β2p branching ratio from the IAS, and the half-life could be determined, see table 1. The precursor studied in most detail was ^{31}Ar, in this case 2p-decay from other excited states in the daughter was also observed [9]. In the cases investigated, the individual proton spectrum from 2p-pairs showed the typical energy dependence of a sequential decay. The β3p decay mode search thoroughly in the case of ^{31}Ar [5] it has been recently identified and "seen" for the 2p-emitter ^{45}Fe[10].

The only process where particles heavier than alphas are emitted after β-decay is β-delayed fission discovered in Dubna in 1966 for ^{232,234}Am. The probability for this process depends both of the beta strength at high excitation energy and on the fission barriers, so this decay mode can provide unique information on fission barrier for unusual Z/N ratios. The recent study of ^{180}Tl at ISOLDE showed a surprising asymmetry in the mass distribution of the fragments [11]. This astonishing result should be followed up by the study of other cases in the Pb-region to understand the asymmetric emission.

OUTLOOK TOWARDS EURISOL

In this contribution we have revised the past to prospect the future. For further insight into the previous work I refer to two recent review papers in the field [2,3]. Identified and predicted precursors for the β-xp and βα modes are displayed in Fig. 1 as full and empty squares, respectively. The progress has occured in two directions. When the production was enough, the combination of the selective character of the beta decay and the high detection efficiency have been used to answer fundamental questions of nuclear structure even with nuclei only produced at the rate of 1 at/s. Identification of new precursors was recently done in the pf shell to map the region in a quest to search for 2p-radiactivity precursors.

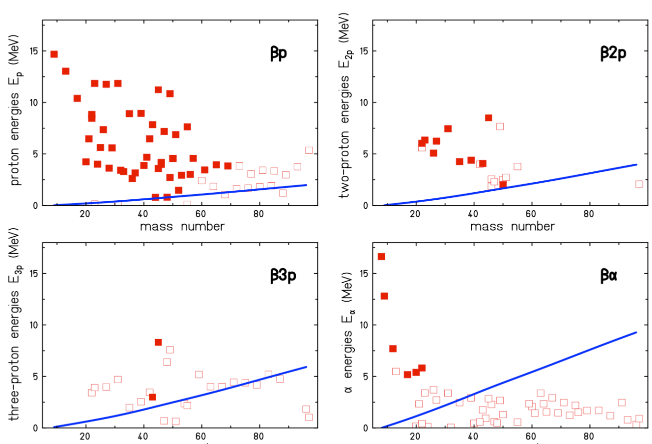

FIGURE 1. Plots of the βp, β2p, β3p and βα energies from the IAS for all nuclei where these decay channels are open. Full squares represent known cases and empty squares possible ones. The continuous line gives the limit below which barrier penetration for each decay mode takes for a l=0 emission more than 1 fs. *Courtesy of B. Blank.*

For the near future and beyond, to pave the way to EURISOL, particle emission studies done with high precision are an **unbeatable** probe of nuclear structure at the microscopic level and a powerful tool to explore fine effects. In particular it is of great interest to characterize states near particle threshold, to determine the particle and gamma widths of states of astrophysical relevance, both for the Helium burning process or in novae or X-ray bursts. For this purpose highly performing gas-Si telescope array with large angular coverage and efficient gamma-ray cluster array are needed.

A detailed study of the βp precursors in the fp-shell will give a good determination of the excited states in the daughter and become a demanding test in a wide energy range of the shell model calculation for the pf-shell. Of great relevance is to test the mirror asymmetry in a region where the isospin should not be such a good quantum number due to the increasing influence of the Coulomb field. In the cases where the theoretical GT-distribution follows the experimental one and the Q_β-window is large enough we can compare both distribution and extract the quenching factor for the fp-shell. This quenching factor is very important for the calculations of r-process.

The systematic study with high resolution and large angular coverage of charged particles and gamma detection systems will allow for the mapping of the change of structure in the βp spectrum from peaks to continua. The proton emitting states have a narrow width but the level density exceeds what it can be currently resolved with our detectors. A statistical analysis has been applied only to four nuclei of Tz = ½ in order to extract information to level densities [7]. The analysis of the data indicates that the fluctuations depend uniquely on the density parameters. The study of heavier cases will permit to deduce level density parameters of great importance for astrophysics.

The β2p decay process should be explored in detail in other candidates. Table 1 summarizes the parameters for the known β2p precursors. A detailed inspection of the table 1 points to ^{27}S and ^{35}Ca as the best candidates for a further study of β2p in the near future. High intensity as the one expected in EURISOL will allow for the discovery and characterization of weak branches with strong p-p correlation emission from excited states. Of particular charm and special challenge for theoreticians will be the study of ^{45}Fe and other 2p-radioactivity emitters where one can compare direct two proton emission with the β-delayed one.

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Studies of Two Proton Radioactivity

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In the last decade, impressive progress has been made in the production and study of exotic short-lived nuclei by reactions with radioactive ion beams produced at large-scale accelerators. Nevertheless, nuclear structure beyond the proton drip line, where nuclei are unbound and exist only as resonances in the continuum, is still a rather unexplored topic despite the experimental advance. The recently discovered two-proton (2p) radioactivity, the spontaneous break-up of an atomic nucleus by the 2p emission, exhibits unexpectedly long half-lives of all reported 2p precursors, ^{45}Fe, ^{54}Zn,^{48}Ni, ^{19}Mg, ^{94m}Ag [1–6]. The main features of the studied nuclei and the corresponding experiments are listed in Table 1.

TABLE 1. Two-proton emitters studied experimentally.

Isotope	***E*** **keV**	**Γ or** $T_{1/2}$	**Fragment correlation**	**Experimental method, reference**
^{6}Be	1371(5)	92(6) keV	*No*	Missing mass, [13]
			$E_{p\text{-}p}$	Kinematically complete, [14]
			three-body	Invariant-mass, [15]
^{12}O	1820(120)	400(250) keV	no	Missing mass, [16]
	1790(40)	580(200) keV	no	Missing mass, [17]
	1800(400)	600(500) keV	three-body	Kinematically complete, [18]
^{16}Ne	1350(80)	200(100) keV	no	Missing mass, [16]
	1400(20)	110(40) keV	no	Missing mass, [19]
	1350(80)	<200 keV	three-body	Tracking decay-in-flight, [20]
^{19}Mg	750(50)	4.0(1.5) ps	three-body	Tracking decay-in-flight, [5]
^{45}Fe	1100(100)	$3.2(^{+2.6}_{-1.0})$ ms	no	Implantation-decay, [1]
	1140(50)	$5.7(^{+2.7}_{-1.4})$ ms	no	Implantation-decay, [2]
	1154(16)	$2.8(^{+1.0}_{-0.7})$ ms	three-body	Kinematically complete, [21]
	–	3.7(0.4) ms	three-body	Kinematically complete, [22]
^{48}Ni	1350(20)	$8.4(^{+12.8}_{-7.0})$ ms	no	Implantation-decay, [3]
^{54}Zn	1480(20)	$3.2(^{+1.8}_{-2.8})$ ms	no	Implantation-decay, [4]
^{94m}Ag(21+)	1900(100)	390(40) ms	$E_{p\text{-}p}$	ISOL implantation-decay, [6]

The time scales of nuclear decay by proton emission, accessible by experiment, spans from 10^{-2} s (for the longer lifetimes, weak decays prevail) to 10^{-21} s (for the shorter lifetimes, continuum dynamics are important). Such a broad range can be accessed only by different experimental techniques. In the case of nuclear 1p and 2p decays with lifetimes larger than a few microseconds, one can implant the radioactive atoms and subsequently detect their decay. The first 2p radioactivity experiments were performed with such technique [1-4]. For much shorter half lives, the conventional in-flight-decay method aims at detecting all fragments of a proton precursor in missing-mass or invariant-mass measurements [13-19]. A novel experimental technique for measuring in-flight decays of proton-unbound nuclei with lifetimes in the intermediate time range of 10^{-7}–10^{-12} s was suggested and discussed in Ref. [13-15]. In such a measurement, the trajectories of all decay products are tracked. The decay vertexes as well as the angular correlations of the decay products can be deduced from the measured trajectories, in analogy to the methods of high-energy physics. The observations of previously-unknown isotope ^{19}Mg and its 2p radioactivity [5], p-p correlations from 2p decays of ^{19}Mg and ^{16}Ne [16], and new resonances in ^{15}F populated by 1p decay of excited states in ^{16}Ne [17] were reported. The tracking technique was verified by reproducing the properties of the previously known 1p and 2p unbound states in the isotopes ^{15}F, ^{16}Ne, ^{19}Na , which was described in detail in Ref. [18], the key article for understanding the method. This tracking technique is very powerful in studies of the extremely exotic nuclei. The method is ideally suited for low-intensity beams of exotic nuclei. Thick targets (up to several g/cm^2) and large-emittance radioactive beams can be used without losing precision in the derived resonance energies and widths. Since such measurements require only a rather simple setup and can be applied to proton-unbound isotopes with very small production yields, many more unexplored nuclei may be studied with this method in the future. Novel 2p-detection techniques are also gaseous implantation detectors, based on the principle of the time projection chamber (TPC), and being developed to directly record emitted protons and to establish the correlations between them. The first direct observation of two protons ejected by ^{45}Fe was achieved in [24] when projections of protons' tracks on the anode plane of the TPC were recorded. Later, this detector was used to directly demonstrate 2p in decay of ^{54}Zn [25]. A novel type of a detector, utilizing the optical readout of the TPC signals [22], was applied to the detailed study of ^{45}Fe 2p-decays with reconstruction of tracks of two emitted protons in three dimensions. The full correlation picture for the 2p decay of ^{45}Fe established in this experiment is shown in Fig. 1(g,h).

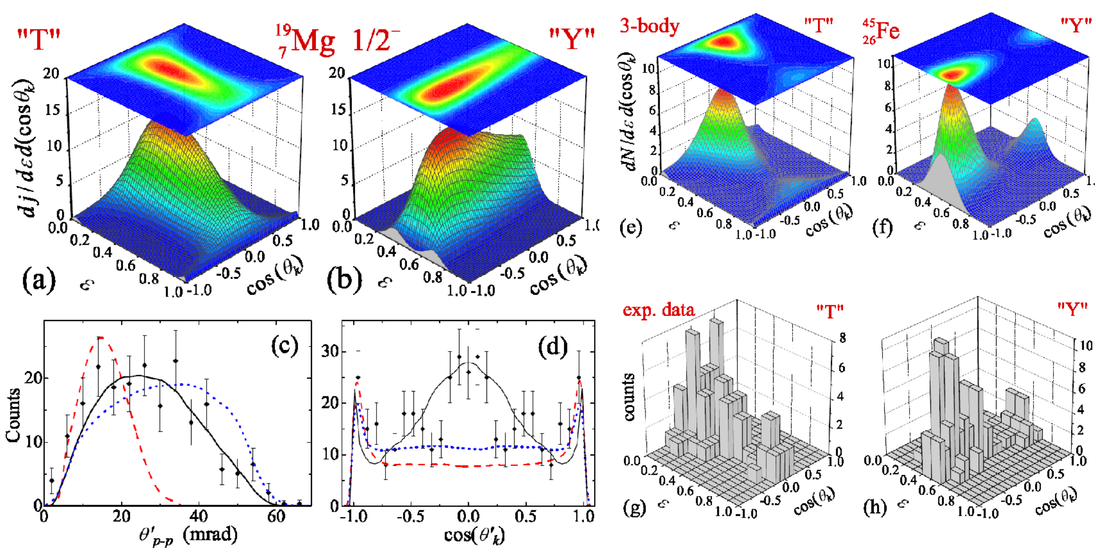

FIGURE 1. Experimental three-body correlations of two-proton radioactivity of ^{19}Mg shown in the panels (c,d) [20], and of ^{45}Fe, see the panels (g,h) [22]. The respective theoretical complete-correlations (a,b) and (c,f) are from the Ref. [23] where all observable are explained in detail. In panels (c,d), the

solid curves are the three-body model predictions, the dashed curves – the diproton model estimates, and the dotted curves – the phase-space calculations.

The theory of 2p decay was recently developed much comparing with the first simple quasi-classical estimates like the diproton model [26,27], or the model of direct three-body decay [28]. The first quantum-mechanical theory of 2p radioactivity (it is based on a 3-body model of 2p precursors by configurations p+p+"core") explains their long half-lives as the result of a decay retardation due to a higher 3-body centrifugal barrier [7–9]. The theory predicts many long-lived 2p precursors beyond the proton drip line. Specific features of 2p radioactivity are three-body correlations of fragments. The 3-body model is the only theory explaining the observed correlation patterns, see the examples on ^{19}Mg and ^{45}Fe in Figure 1. One should also mention developments of the shell model embedded into continuum [29,30] applied to 2p radioactivity which though are not able to provide the correlation observables.

Properties of 2p-unbound nuclei are of interdisciplinary interest, in particuar for nuclear astrophysics. The inverse reaction to 2p decay, radiative 2p capture, may be important in the synthesis of elements in the universe by bridging bottlenecks in the rp process, so-called "waiting points" [10–12]. Measurements of 2p decays are the only way to study radiative 2p capture so far.

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Structure of Proton Emitting Nuclei

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Along the valley of stability, the nucleon separation energy, i.e. the energy needed to extract a proton or a neutron, for medium-heavy nuclei, is of the order of 6-10 MeV. Moving away from the valley of stability, for instance decreasing (increasing) the numbers of neutrons, because of the Pauli principle, neutrons (protons) become more bound while the protons (neutrons) become less bound. These nuclei will decay back in the direction of stability by β+ (β-) decay. Moving further away one reaches the point where the proton (neutron) separation energy is zero. That means that a proton (neutron) has enough energy to leave freely the nucleus. These points are called the proton (neutron) drip-line. For neutron, very little is known about the position of the drip-line for medium-heavy nuclei, since it is not easy to reach so far out from the stability valley using the current techniques like fragmentation or fission. From the theoretical point of view, since current nuclear models give different locations for the neutron drip-line, an experimental determination of it would give a very strong constraint.

Concerning the proton drip-line, although the proton has a positive energy, it experiences a Coulomb and centrifugal barrier that classically would bind it inside the nucleus. The emission of the proton is thus a quantum-mechanical tunnelling effect, like alpha decay, that gives rise to resonances, and the escaping proton is characterized by a discrete value of the energy and a width or its inverse, the half-life.

The half-life depends mainly on the spectroscopic factor and the penetrability. The spectroscopic factor measures the probability that, after the decay, the daughter nucleus is left in the ground state, and carries information on the structure of the two nuclei. Concerning the penetrability, in contrast to the similar phenomenon of alpha decay, the Coulomb barrier is lower, since it is linearly dependent on the charge of the emitted particle, while the centrifugal barrier is higher, since it depends inversely on the mass, implying a stronger sensitivity to the orbital angular momentum. In fact, in medium-heavy nuclei, an increase of one unit of angular momentum causes an increase of approximately one order of magnitude of the half-life.
The Coulomb barrier causes an exponential dependence of the penetrability on the inverse of the energy. This makes proton emission unfavoured with respect to other decay modes, for instance β+ decay, if the energy is too small. For example, around charge 82, the proton should have an energy of at least 1. MeV to be able to escape

before β+ decay occurs. That means that one has to cross the proton drip line by several isotopes, before being able to observe experimentally the decay.

Another limitation to the possible observation is given by the detection procedure. Usually the parent nuclei are created with fusion evaporation reactions, and identified with a mass spectrometer, before being implanted on a proton detector. This takes some time, and only lifetimes longer than approximately 1 microsecond can be measured. That implies that with the techniques used up to now, one cannot measure proton decays with energies higher than approximately 2. MeV.

Experimentally, proton decay from the ground state has been observed in almost all odd-Z nuclei between Tin (Z=50) and Bismuth (Z=83). For lower charge, the Coulomb barrier is too low, and the half-life is too short to be measured. In this case, fragmentation reactions can be used to detect the proton stability. The absence of observation of even-Z proton emitters is because nuclei with an even number of protons have an extra binding given by the residual pairing interaction that makes them more stable with respect to the neighbouring odd-Z nuclei. The quantities that are measured experimentally are the energy of the proton and the half-life. The energy can be compared immediately with the predictions of mass formulas.

The half-life, through the spectroscopic factor and the penetrability, contains information on the nuclear structure of both parent and daughter nucleus. For nuclei in which either neutrons or protons are close to a magic number, the strongest part of the residual interaction is the pairing interaction that energetically favours couples of identical particles with angular momentum zero. This can be treated in the usual BCS formalism and the daughter ground state wave function can be written as a condensate of pairs with angular momentum zero, while the parent wave function is given by the odd proton on a single particle level close to the Fermi surface coupled to the same condensate. In this case the spectroscopic factor is just the probability (u^2) that the single particle level of the outgoing proton is empty in the daughter nucleus. Using angular momentum conservation one notices immediately that the outgoing proton has the angular momentum of the odd-proton, i.e. the angular momentum of the single particle level closest to the Fermi surface. Since the half-life depends strongly on the angular momentum, in this case it is possible to determine the position of the Fermi surface and the properties of the mean field far away from stability. Theoretically, simple WKB calculations of the penetrability, based on a phenomenological single particle Woods-Saxon potential, have been quite successful [1] in reproducing the experimental values.

In the case in which both neutrons and protons are away from magic numbers, one has to take into account also the residual quadrupole interaction between unlike particles. This interaction gives rise to rotational bands, and can be treated by a transformation similar to the Bogoliubov one for the pairing. The symmetry that is broken is the rotational invariance, giving rise to a deformed mean field and to the so-called Nilsson levels. A simple WKB calculation of the penetrability is not possible in this case, since the barrier is two- or three-(if one takes into account the possibility of a non-axial deformation) dimensional. Recently this very difficult problem has been solved either finding resonances in a deformed potential [2], or integrating the coupled-channels Schrödinger equation [3], getting a very good agreement with the experimental data. For these rotational nuclei, the angular momentum of the ground state of the odd decaying nucleus can be quite different from the angular momentum of the spherical single particle levels. The spectroscopic factor does depend not only on the u^2 of the BCS, but also on the amplitude of the component of the Nilsson wave function with angular momentum equal to the one of the ground state. Therefore, in addition to the position of the Fermi surface, it is possible to get detailed information on components of the wave function that can be quite small, and not detectable by other means. The calculations have been mainly done in the so-called adiabatic approximation, i.e. the moment of inertia of the nucleus is supposed to be infinite. Recently it has been shown [4] that the inclusion of the Coriolis interaction, that takes into account the finite moment of inertia, usually does not modify substantially the good agreement with the up to now known experimental data, if the calculation is done using quasi-particles, except in the case of 121Pr, where [5] an evidence of partial rotational alignment has been discovered.

In the case of deformed nuclei, beside decay to the ground state, also decay to the first excited state of the daughter nucleus has been observed. These experimental data give further constraints to the theoretical interpretation, since in this case angular momentum conservation allows the proton to escape with different angular momenta, since the first excited state of the daughter nucleus has angular momentum 2. In this way, different components of the Nilsson wave functions are tested.
Theoretical calculations have been able, also in this case, to reproduce the experimental data [6].

Recently, using the recoil-decay tagging technique, experimentalist have been able [7] to determine the excitation spectrum of some the proton emitting nuclei. This poses a new challenge to the theoreticians. Emblematic is the case of 141Ho, where the experimental information to be reproduced are: half-life of the ground and isomeric state, fine structure of both states, and finally the energy of the rotationals bands build on the two states. A further complication is that the gamma spectrum suggested a non-axial (gamma) deformation. Applying the non-adiabatic quasi-particle model, modified to take into account the gamma deformation, we were able [8] to reproduce all the experimental data, suggesting a new angular momentum for the isomeric state.

Another interesting case is the decay of odd-odd nuclei. The daughter nucleus in this case has an odd number of nucleons, and his angular momentum is determined by the Nilsson level occupied by the odd neutron. Different values of this angular momentum, will allow different values of the angular momentum of the escaping proton. Therefore, the odd neutron, without participating actively in the decay, with his angular momentum can influence the half-life, and behaves as an “influential spectator”. Models [9] based on Nilsson resonances, using the adiabatic approximation, have been able to describe these decays, using the same proton Fermi level and deformation of the neighbouring odd-even nuclei. This gives a further consistency check of the models. A challenge for the theoreticians is the inclusion of the Coriolis interaction in the calculations.

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New Vistas for Studies of Proton Radioactivity

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INTRODUCTION

Proton radioactivity represents a simple quantum tunneling process whereby a constituent proton is emitted from the nucleus. Its simplicity can be exploited to make studies of the effects of nuclear shape and shell structure on quantum tunneling and its energy gives a direct measure of the proton separation energy. It has provided unique insights into the structure of nuclei beyond the proton drip line [1]. All previously identified examples of ground-state one proton radioactivity have been produced using heavy ion fusion evaporation reactions induced by intense stable beams. Odd-Z proton drip-line nuclei exhibiting proton radioactivity ranging from Z = 53-83 have been discovered using this approach, with the one exception of Pm (Z = 61) being yet to be discovered in this region. In the next section alternate approaches are explored for new regions of proton radioactivity.

CURRENT PLANS FOR NEW PROTON DECAY SEARCHES

Ground-state proton radioactivity has yet to be discovered in the region of the proton drip line below Sn. Recent fragmentation experiments in the region of ^{100}Sn have demonstrated the existence of isotopes such as ^{89}Rh, ^{93}Ag and ^{97}In which are potential new candidates for proton radioactivity [2]. These can be produced both by heavy ion fusion evaporation and fragmentation and proton decays measured using standard implantation detection techniques.

In the region of the proton-drip line above Z = 83, there are predictions of shape co-existence [3] that offer a fascinating laboratory to explore for the first time the effect of shape change on quantum tunneling in a single nucleus. So far attempts to access this region have been limited by fission competition however a new approach is being explored using fragmentation of high energy ^{238}U beams on the FRS at GSI [4,5].

A FUTURE ROLE FOR EURISOL?

As discussed above, there are significant new developments ongoing to probe the previously unexplored regions of the proton drip-line using intense stable beams. Can ISOL be competitive with stable beams? The answer currently would be ISOL facilities are not presently competitive due to the lack of intense beams of the key proton-rich isotopes needed to access the proton drip-line. However, in the future with intense RIBs from EUSRISOL, studies could potentially be attempted to move further beyond the proton drip-line in existing regions of proton radioactivity using heavy ion fusion evaporation reactions. Key beams to develop would be even-even proton-rich isotopes (not limited by short half-lives) such as ^{56}Ni and ^{72,4}Kr. For example, using a beam of ^{74}Kr to bombard a ^{58}Ni target, the new proton emission candidate ^{129}Eu could be produced via the 1p2n fusion evaporation channel using beams ~10^8 pps. The neighbouring isotope ^{131}Eu was the first nucleus to exhibit the rare phenomenon of proton decay fine structure and is highly prolate deformed [6], it would be very interesting to see if this phenomenon is observed for ^{129}Eu, although a caveat would be the nucleus my be too unbound/short-lived for observation.

Alongside radioactive decay studies it is also important to study the in-beam gamma-ray spectroscopy of these nuclei to obtain independent information on the structure and shape of proton emitting nuclei – Recoil Decay Tagging (RDT) [7] is a very sensitive technique to do this. In some cases, such as ^{131}Eu, the splitting of the band strength means while individual transitions have been identified, level schemes cannot be reliably produced. Here again increased production yields from intense RIBs could improve the situation with for example ~10^9 pps of ^{76}Kr beams could be used to produce ^{131}Eu nuclei, and study its in-beam gamma-decay level scheme with the RDT technique.

In summary EURISOL can play a significant role in this field of proton radioactivity studies if it can take beam intensities of proton-rich beams such as ^{56}Ni and ^{72,4,6} Kr to a significantly higher level than presently available at current generation RIB facilities.

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Spectroscopy Studies of N≈Z nuclei

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The properties and structure of nuclei with equal number of protons and neutrons have been in the last decades an intense field of research, both experimentally and theoretically. The structure of these nuclei provide essential information, among other things, about the isospin symmetry of the nuclear force as well as on proton-neutron correlations. Spectroscopy of excited states of these neutron-deficient nuclei has been demonstrated to be a powerful tool to understand in detail the nature of the nuclear force. These studies have been possible due to the advent, in the last decades, of large Compton suppressed gamma-ray arrays and the associated ancillary detectors that allowed to access these very exotic N≈Z nuclei at high spins.

The isobaric analogue states in mirror nuclei have shed light on the presence of isospin non-conserving forces in nuclear matter. From the detailed studies of energy differences between those states, an important theoretical understanding of this aspect of the nuclear force in nuclei of the *fp* shell [1] has been achieved, and more recently also in heavier nuclei where the contribution of the the $g_{9/2}$ orbital is relevant [2, 3]. In this latter study of the ^{67}Se ^{67}As nuclei (the heaviest mirror pair known so far), the Mirror Energy Differences (MED) have been nicely reproduced theoretically and it has been demonstrated that the inclusion of the $g_{9/2}$ orbital is essential to reproduce properly the experimental data. Furthermore, the comparison between theory and experiment suggests that in this mass region the isospin non-conserving NN term is negligible. However, since the strength of the radial term in the Coulomb energy contribution has been renormalized for ^{67}Se ^{67}As, the result is not conclusive and more experimental data is required in the upper *fpg* shell to fully understand this issue.
Heavy N = Z nuclei are expected to present enhanced correlations between neutrons and protons since they both occupy orbitals with the same quantum numbers. The T = 0 isoscalar correlations become more relevant than the usual T = 1 isovector pairing, giving rise to an unusual type of nuclear superfluidity [4]. Until very recently the heaviest N = Z nucleus, where in beam spectroscopy was known, was ^{88}Ru. Many experimental and theoretical studies of excited states in the A=80 mass region have been done and they seem to suggest that indeed the isovector T=1 pairing is dominant, although not real decisive conclusions have been drawn in this respect. Very recently the N = Z ^{92}Pd nucleus was studied via the ^{58}Ni(^{36}Ar,2n)^{92}Pd fusion evaporation reaction, where it was populated with a very low cross section.
Using state-of-the-art traditional gamma-ray arrays, charged particle detectors and

neutron detectors, it has been possible to locate the first three excited states up to (6^+) in ^{92}Pd. To explain the level scheme, the presence of an isoscalar T = 0 pairing at low-spins has been claimed as it was since long predicted [5]. However, further studies of the spectroscopy properties of ^{92}Pd, such as electromagnetic transition probabilities are needed to fully understand the possible coherent isoscalar T=0 pairing. Of course, study of even heavier N = Z nuclei will help to elucidate the possible existence of this unusual nuclear superfluidity.

Future studies of exotic neutron-deficient nuclei will mainly require the use of reactions induced by intense radioactive heavy-ion beams such as those provided by near-future facilities (ex. Spiral2 and Fair) and in the future by Eurisol. This will allow an unprecedented study of the heaviest N = Z nuclei located much further from the line of beta stability. In this respect, one should not forget the need of highly performing, highly selective detectors to be able to pin down the nuclei of interest that in most of these cases represent a tiny part of the total cross section, especially when going towards the possible heaviest bound N = Z nucleus in nature, ^{112}Ba (N=Z=56). This nucleus is expected to be the best example of octupole deformation in nuclei, due to the interaction of the opposite parity _L=3, _J=3 $d_{5/2}$ and $h_{11/2}$ orbitals. It will be an object of study that only Eurisol with the most performing detectors can address, using, for example, the fusion evaporation reaction ^{58}Ni(^{56}Ni,2n)^{112}Ba, which will take advantage of the high intensity (10^{11} pps) that Eurisol should provide for the radioactive ^{56}Ni beam. The study of ^{112}Ba will be possible in combination with detectors of new generation like the gamma-ray array AGATA and the neutron-detector array NEDA. The last one will be essential to enhance the two neutron channel from the enormous background of the reaction.

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Gamow-Teller Resonances in the β decay and Charge-Exchange Reactions

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Possible observation of Gamow-Teller resonance (GTR) structure in a β decay study was investigated for the T_z= -3/2 → -1/2 decays having large Q_β values. It became clear that the expected large yields of T_z= -3/2, far-from-stability nuclei in the EURISOL facility was inevitable for the study of GTR structure expected to exist in the E_x = 5-8 MeV region.

β decay and Charge-Exchange Reactions for the Study of Gamow-Teller Transitions

Gamow-Teller (GT) transitions are caused by the most common weak interaction of spin-isospin ($\sigma\tau$) type with ΔL = 0. Since spin and isospin are unique quantum numbers in nuclei, GT transitions represent important nuclear response.

GT transitions are studied by the _ decay and charge-exchange (CE) reactions. The _ decay has a direct access to the absolute GT transition strengths B(GT) from a study of half-lives, Q-values and branching ratios, but it can only access excited states lower than the decay Q-value. In contrast, the CE reactions, such as the (p, n) or (^{3}He,t) reactions at intermediate beam energies and 0°, can selectively excite GT states up to high excitation energies in the final nucleus. It has been found that there is a close proportionality between the cross-sections at 0° and the transition strengths B(GT) in these CE reactions. Therefore, CE reactions are useful tools to study the relative values of B(GT) strengths up to high excitation energies.

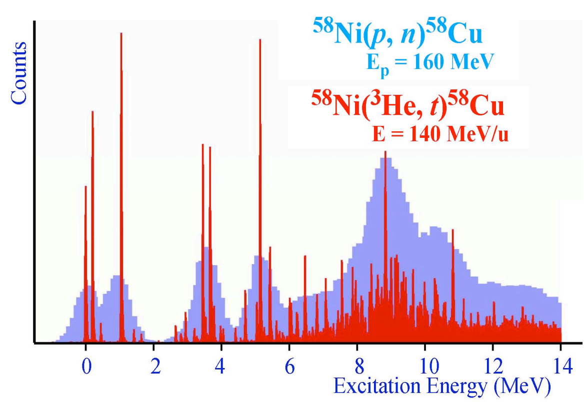

FIGURE 1: Energy spectra of charge-exchange reactions at 0°. The broad spectrum is from ^{58}Ni(p, n)^{58}Cu reaction measurements in the 1980s. In the recent ^{58}Ni(^{3}He, t)^{58}Cu reaction study, fine structure and sharp states have been observed up to an excitation energy of 13 MeV. The proton separation energy (S_p) is 2.87 MeV. An increase in the quasi-elastic scattering (QES) continuum is observed above E_x = 6 MeV.

In recent (^{3}He,t) measurements, one order of magnitude improvement in the energy resolution has been achieved at RCNP, Osaka. This has made it possible to make one-to-one comparison of GT transitions studied in the CE reaction and _ decay. Thus GT strengths in (^{3}He,t) reactions can be normalized by the _-decay values. In the comparison, the isospin quantum number T and associated symmetry structure in the same mass A nuclei (isobars) play a key role. Isospin symmetry can extend our scope even to the structures of unstable nuclei that are far from reach at present unstable-beam factories [1].

Observation of GT Resonance and GT Strength in Charge-Exchange Reactions

It was noticed that the sum of the GT transition strengths observed in the _ decay study was much smaller (quenched) than the value expected by the model-independent GT sum rule (often called the Ikeda sum rule [2]) of $S(\mathrm{GT}) = S(\mathrm{GT}^-) - S(\mathrm{GT}^+) = 3(N-Z)$. In the beginning of the 1980s, it was found by the systematic (p, n) study at IUCF, Indiana that the main part of the GT strength was pushed up to the highly excited energy region of 7-12 MeV and formed a resonance structure called GT resonance (GTR). However, the GT strength in the GTR was still quenched (~50 %) for medium and heavy nuclei in which GTRs are clearly observed [3].

In CE reactions, the quasi-elastic scattering (QES) continuum is always observed beneath the GTR as well as at much higher excitation region, as seen in Fig. 1. In addition ΔL = 1 and 2 strengths, although they are usually small, and the strength excited by the isovector tensor (Tτ) interaction can contribute even to the spectrum measured at 0$^{\mathrm{o}}$. Recently, ΔL = 0 and ΔS = 1 strength in both the structured part and the QES continuum was investigated up to the energy region of ~50 MeV, and a existence of the 90% of the GT strength was suggested [4].

Observation of GT Resonance and GT Strength in β decay Measurements

Although the study of GT strength in the _ decay is restricted by the decay Q-value, unstable nuclei can have the Q-value of 12 MeV or larger, which, in principle allows the study of the central part of the GTR where the GT strength is concentrated. Since the _ decay study does not suffer from the reaction mechanism and the mixture of ΔL = 1 or 2 strengths associated with CE reactions, a pure GT response, i.e., the spin-isospin response of nuclei can be investigated. A precise comparison with the isospin mirror GT transitions studied in CE reactions will give us further knowledge on the long standing quenching problem of the spin-isospin excitations in nuclear physics.

β-decay Measurements at EURISOL

Observations of GTR-like structures in _-decay studies at E_{x}~5-6 MeV have been discussed in [5], but the main part of the GTR strength is expected in the E_{x} =7-12 MeV region. Therefore, it is important to seek a candidate in which we can see the main part of the GTR structure inside the Q-window of the β decay. It is known that the Q-value of the β decay with $T_z = -3/2 \rightarrow -1/2$ nature can be more than 12 MeV. It should be noted that the strength distributions of these GT transitions can be deduced by studying the GT transitions with $T_z = +3/2 \rightarrow +1/2$ nature assuming mirror-symmetry structure in nuclei. We studied the GT transitions for various $T_z = +3/2$ targets using the (^{3}He,t) reaction, and it was found that we can see a compact GTR structure for the target nucleus ^{45}Sc.

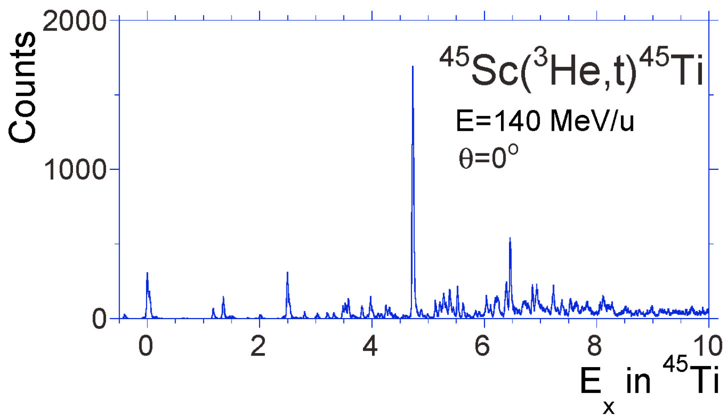

FIGURE 2: An energy spectrum observed in the ^{45}Sc(^{3}He, t)^{45}Ti reaction. We see largely fragmented GT strengths in the E_x = 5-9 MeV region. The contour of these strengths suggests an existence of a compact GTR structure. The strongly excited state at 4.7 MeV is the IAS, mainly representing the Fermi transition strength.

Assuming a good isospin symmetry of nuclear structure and transitions, we can deduce the Fermi strength and the GT strength distribution in the mirror β decay, i.e., in the T_z= -3/2 $\rightarrow$ -1/2, ^{45}Cr β decay having a large Q_β value of 12.9 MeV. As the first step, we have to correct the difference of the interaction strengths in the β decay and the CE reaction for the Fermi and GT transitions. We multiplied a factor of 3.6 to the Fermi strength in the spectrum shown in Fig. 2. In addition, the phase-space factor (f-factor) in the β decay should be multiplied to the spectrum. As a result, an expected ^{45}Cr β-decay spectrum shown in Fig. 3 is obtained. Due to the f-factor, the strength in the GTR region is suppressed in comparison with the GTR strength observed in the ^{45}Sc(^{3}He, t) reaction, but the large yields of the far-from-stability nuclei in the EURISOL facility will open the chance to observe the GTR structure.

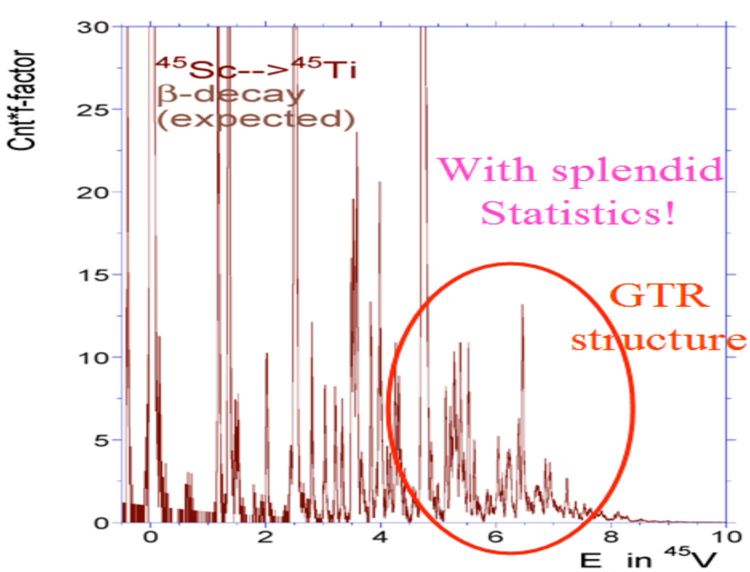

FIGURE 3: The ^{45}Cr $\rightarrow$ ^{45}V β-decay spectrum deduced from the ^{45}Sc(^{3}He, t)^{45}Ti spectrum. It is expected that we see the GTR structure, although the strength will be weak. The proton separation energy (S_p) is 1.62 MeV. An efficient and good resolution β-delayed proton measurement will play an important role.

A study how the GTR structure develops in different isotopes is another interesting subject. In the (^{3}He*, t*) study for the Ca isotopes with Z=20 shell closure having mass numbers A = 42-48, it was found that the GTR structure develops as a function of A, and in the ^{48}Ca(^{3}He*, t*) ^{48}Sc reaction a prominent GTR structure was observed. It is expected that such development of the GTR structure will be observed in the mirror β-decay of nuclei ^{42}Ti, ^{44}Cr, ^{46}Fe and ^{48}Ni with N =20 neutron shell closure. A similar development will be observed in the β-decay studies of nuclei ^{18}Ne, ^{20}Mg and ^{22}Si with N =8 neutron shell closure. The mirror GT transitions that can be studied in CE reactions for A =18-22 oxygen targets having Z =8 proton shell closure will also show the development of the GTR structure. However, since A =20 and 22 oxygen isotopes are unstable, measurements of GT transitions by use of CE reactions require a high intensity and a high energy of more than 100 MeV/nucleon for the beams of these nuclei.

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Superallowed Fermi decays: precise $T_{1/2}$ and branching ratio measurements

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INTRODUCTION

Through the studies of Fermi transitions between $\mathbf{0^+}$ analog states with $\mathbf{T = 1}$ (superallowed transitions), nuclear physics provides a valuable test of the Standard Model of particle physics [1]. These transitions depend only on the vector part of the weak interaction, and according to the conserved vector current (CVC) hypothesis, their strength $\boldsymbol{Ft}$ is a constant. Then this value is used to determine the $\boldsymbol{V_{ud}}$ term in the CKM quark mixing matrix, that should be unitary.

The constant $\boldsymbol{Ft}$ strength determination requires very high precision measurement of the decay energy $\boldsymbol{Q_{EC}}$ (related to masses) and of the partial half-life of the transition (parent nucleus half-life $\boldsymbol{T_{1/2}}$ and branching ratio $\boldsymbol{BR}$), but it also requires some theoretical corrections of the experimental values. Then, beside the search for "new physics" if deviations from the standard model are observed, such studies are a very sensitive test of the theoretical descriptions used to calculate those corrections.

A recent review that summarizes all the physics context and the efforts made in that field is given in ref [1]. The present proceeding will focus on recent experimental results concerning the $\boldsymbol{T_{1/2}}$ and $\boldsymbol{BR}$ measurements that we performed at Jyväskylä university (for $^{26}\boldsymbol{Si}$, $^{30}\boldsymbol{S}$, $^{42}\boldsymbol{Ti}$ and $^{62}\boldsymbol{Ga}$) and ISOLDE at CERN (for $^{38}\boldsymbol{Ca}$).

The different cases presented here will be used to describe the experimental challenges to achieve the required level of precision, which is of the order of few 10^{-4} for half-lives and Fermi transition branching ratios.

EXPERIMENTS DESCRIPTION

In all cases, the measurement consists on the repetition of a measurement cycle during which the isotopes of interest are accumulated on a tape, the decay of the isotopes is measured and the activity is evacuated by moving the tape.

The decay events are identified using a beta-particle detector : either a plastic scintillator as used in Jyväskylä experiments (fig. 1), either a Geiger counter as used at CERN. The decay events are registered on both a fast multi-scaler type acquisition system, either on a list-mode type VME system, that allows to store β-γ coincidences events, using germanium detectors for gammas, in addition to the beta counter. Each event is registered with a time stamp relative to the measurement cycle, to build decay time spectra for each cycle.

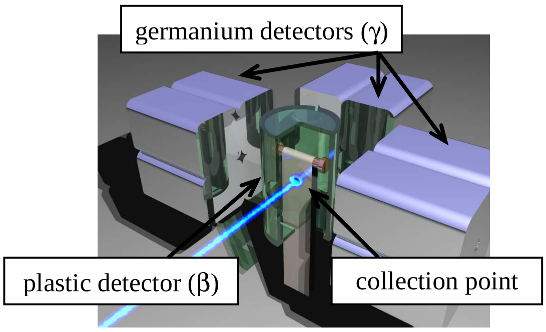

FIGURE 1. Schematic view of the experimental setup used in Jyväskylä experiments: the isotopes are deposited on the tape and the collection point is surrounded by the beta detector. Germanium counters are used to measure the gamma de-excitation for branching ratio determinations.

HALF-LIVES MEASUREMENTS

The half-lives are resulting from the analysis of time spectra from all measured cycles. In order to reach a precision better than 10^{-3}, only from a statistical point of view, at least 10^6 to 10^7 events have to be registered. The basis of the analysis is a fit, cycle by cycle, of the exponential decay curve, including a background signal. Due to this background, the measurement has to be performed on a time window that is at least of the order of 15 to 20 times the half-life to be estimated, to ensure a good precision of the fit.

The first correction needed is then the data acquisition (DAQ) dead-time correction. For the multi-scaler DAQ this dead-time is chosen to typically 2 and 8 μs. For the VME DAQ, it is forced to a fixed value of 100 μs. The correction applied with different dead-times must lead to the same value of the estimated half-life. In this way, we measured the half-life of ^{62}Ga : 116.09 ± 0.17 *ms* [2].

During the accumulation of isotopes on the tape, there may also be accumulation of some mass contaminant and of the daughter nucleus, either as contaminant, either due to the decay during accumulation phase. If the daughter/contaminant half-life is very long compared to the isotope of interest, its contribution can be treated as background, but if it is not the case, it has to be properly separated from the background. To achieve this, a short time in the beginning of each cycle is devoted to a background measurement, before any activity has been collected on the tape. This was necessary in the case of ^{30}S half-life, for which we obtained 1175.9 ± 1.7 *ms* [3].

Nevertheless, if the daughter half-life has the same order of magnitude than the parent half-life, the fitting algorithm is not able to separate both contributions. This is the case for the decay of ^{42}Ti for which the daughter (^{42}Sc) half-life is only about 3 times longer. In such cases, the solution is to accumulate the isotopes in a purification trap. Then a pure sample is extracted at the beginning of the measurement, and the amount of daughter decay is constrained only by the parent decay. In the case of ^{42}Ti, we determined a half-life of 208.14 ± 0.45 *ms* [4], using JYFLTRAP. The same kind of measurement was performed at ISOLDE with ISOLTRAP for ^{38}Ca, and a half-life of 443.8 ± 1.9 *ms* [5] could be deduced.

Using the same technique, we measured the half-life of ^{26}Si: 2228.3 ± 2.7 *ms* [6]. An independent experiment performed at Texas A&M University leaded to another result: 2245.3 ± 0.7 *ms* [7]. The disagreement between the two values is very important with respect to the quoted uncertainties, and the reason for it is not yet clearly known. Nevertheless, a possible cause could be the very small difference of the detection efficiency for beta particles coming from the parent or the daughter decay. This effect must be corrected with the help of simulations.

BRANCHING RATIO MEASUREMENTS

The branching ratio of the $0^+ \rightarrow 0^+$ analog transition is estimated by measuring the non-analog feeding to other states, by mean of β-γ detection. The part of the strength feeding the isobaric analog state is a critical aspect for precision measurement.

If only ~0.1% of the decay is non-analog, then a 25% error on the β-γ intensities will result only in a 0.025% error on the analog feeding. This is the situation for the decay of T_Z=0 nuclei, and we could thus measure the analog BR for ^{62}Ga : 99.893 ± 0.024 % [8]. For the decay of T_Z=1 nuclei, the non-analog branching is much more significant (~25% for ^{26}S and ^{30}S, ~50% for ^{42}Ti). Then, to achieve a precision of 10^{-3} on the BR, the same precision must be achieved on the β-γ intensities. This requires to characterize the γ detection absolute efficiency at the 10^{-3} to 10^{-4} level. An important work on this difficult aspect is done at Texas A&M University and has also started at CENBG.

In addition, due to the relatively low efficiency of germanium detectors, and depending on the β-γ intensities, a higher statistics is required than for half-lives (10^2 to 10^4 times more).

CONCLUSION

The high precision measurement of half-lives and branching ratios for the study of super-allowed Fermi transitions is a typical physics case for ISOL facilities. Our recent results are now partially included in the world averages. In order to go further, either for heavier T_Z=0 cases, either to improve the precision of the branching ratios for T_Z=1 nuclei, a current limitation is the production rate of these isotopes (or detection efficiency). Future facilities like EURISOL should offer a solution to this problem.

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High Precision Q Value Measurements of Superallowed Beta Emitters

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INTRODUCTION

The nuclear beta decays between isobaric analog states of spin-parity 0+ and isospin T=1 provide valuable information for testing the Standard Model of particle physics. These so-called superallowed beta decays are of pure Fermi type rendering the decay matrix element to be very simple [1]. The most precise V_{ud} matrix element of the Cabibbo-Kobayshi-Maskawa (CKM) quark-mixing matrix is obtained from the superallowed beta decays.

There are about 20 nuclei that decay via superallowed beta decay that are possible to produce at present radioactive ion beam facilities. To be able to use these nuclei for extraction of V_{ud} of the CKM matrix, three experimental quantities are needed: the half-life, the branching ratio and the decay energy. From these, an ft value is obtained. Additionally a few theoretical corrections are needed to correct for instance isospin mixing and nuclear structure [2]. Together the theoretical corrections and experimental information provide an Ft value for each superallowed decay. According the conserved vector current hypothesis these values should be the same for all. Currently, data for 13 such emitters are known to comparable precision and contribute to the world average Ft value.

The decay energies (Q-values) determine the f value, which is proportional to Qυ requiring the Q value to be determined about 5 times more precisely than half-life and branching ratio to obtain *ft* value. The decay energy is perhaps the most easiest quantity to measure and presently precision in Ft is most often not limited by the Q value but other factors like the branching ratio or theoretical corrections. In this contribution Q-value measurements with JYFLTRAP Penning trap setup are presented.

EXPERIMENTAL SETUP

The JYFLTRAP Penning trap installation [3] at the University of Jyväskylä, Finland, has been extensively used for superallowed Q-value measurements. Coupled to the IGISOL [4] radioactive ion beam production facility, any element is available and so far Q-values ranging from 10-C to 62-Ga have been determined. Using mass doublet technique in which the Q-value can be directly determined, precision down to

$\Delta Q/M = 10^{-9}$ have been reached. This roughly corresponds to 50-eV level for the studied nuclei. The Q-values are determined with time-of-flight ion-cyclotron resonance (TOF-ICR) technique [5]. The most precisely determined Q-values are measured employing the Ramsey's method of time-separated oscillatory fields [6]. Since the probing time of ions is limited due to short half-lives, these studies significantly benefit from the Ramsey method since it provides same precision in about three times shorter time.

RESULTS

Until June 2010, when IGISOL and JYFLTRAP were shut down for relocation, Q values of 14 different superallowed beta emitters have been determined. These are shown in Figure 1 with values measured with other Penning trap facilities.

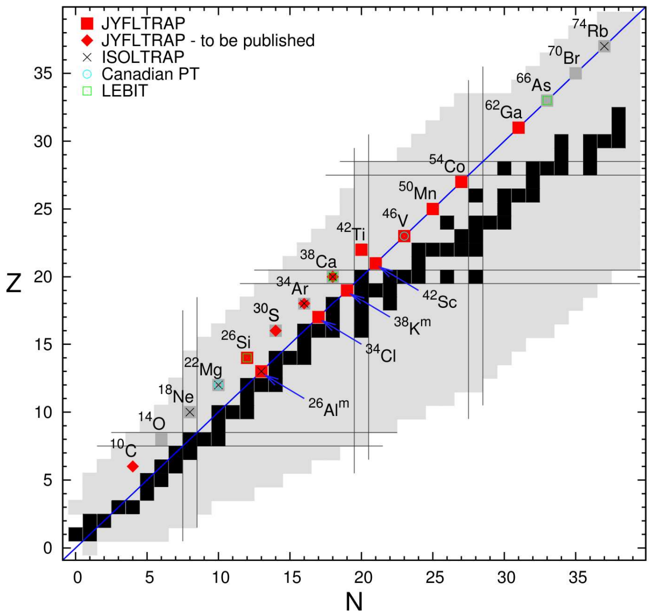

FIGURE 1. Chart of the nuclei where superallowed beta emitters have been indicated. The Q values of nuclei marked with red color have been measured with JYFLTRAP, with cross at ISOLTRAP (ISOLDE, CERN), with circle at Canadian PT (Argonne) and with squares at LEBIT (MSU).

All of the Q values have been measured with mass doublet technique in which the Q value is directly determined by measuring the frequency ratio of superallowed parent and daughter ions. Thus, the daughter ion mass is needed only with moderate (1 keV) precision in order to be able to determine the Q value to 10-eV level. Also mass dependent systematic shifts are negligible.

Ten Q values of superallowed beta emitters that belong to the set of "best 13" contributing to the world average Ft value have been determined with JYFLTRAP. In cases of ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co a significant deviation to old (3He,t) reaction Q value measurements were found [7] and in later compilation [1] results reported in this reference were removed. Q values of other emitters ^{10}C, ^{26m}Al, ^{34}Cl and ^{38m}K were found to be consistent with old reaction based measurement results. The result for Q-value of ^{62}Ga enabled it to be included to the set of best known emitters. Also the Q value of ^{34}Ar was measured.

Additionally several Q values have been determined. These include ^{26}Si, ^{30}S, ^{38}Ca and ^{42}Ti that can contribute to the world average Ft value once the half-lives and branching ratios have been determined precisely.

SCOPE FOR EURISOL

Several superallowed emitters that are not yet experimentally accessible or have very poor production yield with current on-line facilities exists. These are N=Z (T_z=0) nuclei heavier than ^{62}Ga and Tz=-1 nuclei heavier ^{42}Ti. High-precision Q-value, half-live and branching ratio measurements would not perhaps contribute to the CVC tests since strongest influence there clearly originates from lighter, already precisely measured, nuclei. Instead, these heavy nuclei would provide valuable data for evaluating isospin symmetry breaking corrections δ_C.

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In-Gas Cell Laser Spectroscopy of Neutron-Deficient Silver Isotopes

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IN-GAS CELL LASER IONIZATION

Basic Principles

In-gas cell laser spectroscopy has been developed at the Leuven Isotope Separator On-Line (LISOL) set-up. The radioactive isotopes of interest are produced using heavy- and light-ion induced reactions. The primary beam hits the target that is situated in a buffer gas cell filled with 100 to 500 mbar argon. The reaction products that recoil from the target are thermalised in the buffer gas, neutralized in the presence of the weak plasma created by the primary beam passing through the gas cell and transported together with the flowing gas towards a region for laser irradiation. Subsequently the ions are resonantly photoionized using a two-step laser-ionization scheme, extracted from the gas cell, injected into a radiofrequency sextupole ion guide, accelerated to 40 keV, analysed according to their A/Q value, and sent towards a detection station where their radioactive decay is observed [1,2]. By measuring the number of atoms arriving at the detection station as a function of the first step laser frequency, the atomic hyperfine structure of the atomic ground and/or excited state can be measured and charge radii, magnetic dipole and electrical quadrupole moments extracted provided the atomic physics is well understood. A review on laser spectroscopy measurements and other atomic physics techniques used to extract nuclear-physics properties can be found in [3].

Magnetic Moment of Neutron-Deficient Copper and Silver Isotopes

At LISOL, the magnetic moment for a number of neutron deficient copper isotopes, including ^{57}Cu (N=28), were determined using in-gas cell laser spectroscopy and questioned the need for extra N=28 shell breaking beyond what was assumed in the current large-scale shell-model calculations [4].

In more recent experiments a study of the neutron deficient silver isotopes produced via $^{92}Mo(^{14}N,pxn)^{A}Ag$ and $^{64}Zn(^{36}Ar,pxn)^{A}Ag$ reactions was pursued and the magnetic moments of a number of them were obtained for the first time, including the semi-magic N=50 isotope ^{97}Ag. The analysis of the data is still ongoing, but the extracted g-factor indicate dominance of the proton $g_{9/2}$ orbital in the ground state of these neutron-deficient silver isotopes.

These experiments serve as a proof-of-principle of in-gas cell laser-spectroscopy measurements of reaction products from light- and heavy ion induced fusion evaporation reactions. In the next steps other isotopes around ^{100}Sn, including the indium isotopes, will be investigated, following the study of heavy isotopes starting with the neutron-deficient actinium isotopes.

Future Developments

Although the technique of in-gas cell laser spectroscopy is sensitive, measurements with production rates as low as a few ions per second have been performed, it suffers from a low-spectral resolution. This is mainly due to pressure broadening and, to a lesser extent, due to Doppler broadening. This results in a total resolution between 5 and 10 GHz. This limits the applicability of this technique to the heavy elements, where the hyperfine splitting and isotope shifts are large compared to the total spectroscopic resolution, or to specific elements like ,e.g., copper, silver and indium that have a large ground-state hyperfine splitting [2]. Ways to improve the spectroscopic resolution, the efficiency and the selectivity are under study. An interesting option is to perform laser-resonance ionization in the gas jet outside of the gas cell. By using a ‘de Laval’ nozzle as exit hole, a cold and homogeneous gas jet of over 5 cm long can be formed. By applying resonance laser ionization inside this jet (by counter propagating the laser beams) the atoms of interest are ionized and captured in the RF structure surrounding the jet. From there on the ions follow the same path towards the detection system as described above. By biasing the RF structure with a positive voltage relative to the gas cell, unwanted ions cannot escape from the gas cell and the selectivity increases by at least one-order-of-magnitude. Furthermore, the low-temperature and low-pressure jet decreases the spectroscopic resolution to about 200 MHz, again at least one-order-of-magnitude better compared to in-source spectroscopy. This technique, that has certain similarities with the so-called ‘Laser Ion Source Trap’ [5], is currently under investigation at LISOL and JYFL [6]

The final goal of the project is to couple the LISOL laser ion source at the focal plane of the Super Separator Spectrometer (S3) set-up of the SPIRAL-2 project at GANIL [7]. Superior heavy-ion beam intensities will be available to produce the most exotic nuclei including the so far poorly studied actinide isotopes. The reaction products will be separated from the primary beam using the S3 system and stopped in the buffer-gas cell system. Laser ionization inside the gas cell will be used to produce beams of refractory-type elements, not available at high-temperature target based ISOL systems. Laser spectroscopy measurements on nuclei around ^{100}Sn and in the actinide region will be performed using the in-gas jet spectroscopy system described above.

OPTIONS FOR EURISOL

Laser Spectroscopy at EURISOL

Laser spectroscopy studies deliver charge radii, nuclear magnetic moments and quadrupole moments, and spins in a model independent way, provided the atomic physics is well understood [3]. A strong program for these studies at EURISOL, including the study of neutron-deficient isotopes, should be foreseen. As the production of isotopes from refractory type elements will be hampered at EURISOL when using the high-temperature target-ion source systems, it is essential that other efforts as the one mentioned above are pursued. In this way complementary information will be gathered.

Resonance Ionization Laser Ion Sources

Resonance Ionization Laser Ion Sources (RILIS) will inevitably have to be part of the EURISOL facility. The ionizing cavity used is the simplest and most ruggedized ion-source system available for producing RIB's. RILIS are essential to deliver pure (or purified) radioactive ion beams and have the potential to produce isomerically purified beams [8]. Both aspects deliver interesting cases for the study of neutron-deficient isotopes along the N=Z line as well as in the heavier mass region. For example, the isomers in the odd-odd N=Z nuclei in the region between Z=28 and Z=50 could be probed and e.g. be prepared for transfer reaction or Coulomb excitation studies. The same holds for studies of shape-coexistence in the lead region where for example Coulomb excitation and transfer reactions on very neutron-deficient mercury isotopes/isomers will unravel the underlying mechanism that creates shape coexistence. Interesting to note here is that one assumes that shape coexistence in the lead region is driven by a limited number of specific proton orbitals, however so far no undisputable experimental prove for this assumption has been delivered. Transfer reactions should clarify this situation and the use of isomeric beams can play herein an important role.

RIB to Access the Actinide Region

The high intensity RIB of EURISOL will also allow to enter into the parts of the actinide region that can not be reached with stable beams for, amongst others, laser spectroscopy studies. The general concept would be very similar to the laser spectroscopy studies planned for S3, except that the stable beams from SPIRAL-2 will be replaced by the intense RIB from EURISOL. This challenging idea needs further investigation to identify the regions in the chart of nuclei that can not be reached with stable beams or where the lower beam intensity of the RIB is fully compensated by the larger cross section using RIB compared to stable beams.

In-Gas Cell Laser Ionization at EURISOL

The use of a gas cell with a ^{238}U fission target close to the spallation neutron source of EURISOL might create the possibility to produce beams from refractory-type elements. The fission products will be thermalised in the gas cell and will be treated in the same way as described above to, either obtain intense neutron—rich beams of refractory type elements or to perform laser spectroscopy studies on these isotopes. This option is, however, extremely challenging as the gas cell has to be operated in a harsh environment whereby plasma effects, created by the fission products and their radioactivity, and other neutron-induced reactions, might hinder proper gas cell operation.

A final idea would be to use the gas cell for thermalization of reaction products produced in the fragmentation of the high-intensity radioactive ion beams with energies that allow fragmentation reactions. These conditions would be ideally suited for proper gas-cell operation.

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Early Onset of Deformation in the Neutron-Deficient Polonium Isotopes Identified by In-Source Resonant Ionization Laser Spectroscopy

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GROUND STATE PROPERTIES FROM LASER SPECTROSCOPY

The technique of laser spectroscopy has provided in the last few years key information on the structure of the nucleus [1]. The study of the isotope shifts can be linked to the changes in the mean square charge radii $\delta\langle r^2\rangle$ in a nuclear-model independent approach. Furthermore in the case of isotopes with a nuclear spin higher than 0, laser spectroscopy also provides a direct measurement of the ground-state spin while the hyperfine structure gives the magnetic dipole moment μ and the electric quadrupole moment Q (for I>1/2). A striking case, where laser spectroscopy has solved a series of long-lasting debates, is that of the copper (Z=29) isotopic chain with many complementary studies that have clarified the spins and the configurations of the ground state and of a few long-lived isomers from N=28 to N=46 [2-8].

There exists however some limitations to the technique inherent to atomic physics. First of all, the extraction of the $\delta\langle r^2\rangle$ from the measured atomic isotope shifts depends on two main atomic parameters: the mass shift, which is independent of the charge distribution of the nucleus, and the field shift factor, which gives a proportionality relation between the measured quantity and the nuclear observable. More information on the formalism can be found in Ref. [1]. It is however important to note that those two parameters can only be analytically calculated for a system that involves a single *s* electron, limiting therefore the study to alkali atoms and alkali-like ions. For the more complicated systems, large-scale open-shell atomic calculations must be performed [9]. Such studies require high computing power and must be redone for each atomic transition of interest. The accuracy of those calculations has only recently been challenged [10,11] and some within the community still lack confidence in their use.

Furthermore, the study of the hyperfine structure only provides spin information if the resolution of the measurement is sufficient, *e.g.* the spins of the lead isotopes on which only limits could be placed by in-source laser spectroscopy in a hot cavity ISOL facility [12]. As such, two categories of experiments must be distinguished: collinear laser spectroscopy experiments, benefitting from the Doppler compression of the 50 keV beam, and in-source laser spectroscopy experiments, benefitting from the high sensitivity of the resonant ionization method. As the first technique will be more thoroughly described in the contribution from M. Kowalska, this contribution will focus on the in-source technique.

SELECTIVE RESONANT IONIZATION BY LASER IRRADIATION

The use of lasers in nuclear physics is not limited to the study of the atomic transitions, but it is also used as an efficient and selective ion source [13]. By overlapping a series of intense laser beams on an atomic sample, it is possible to resonantly excite a valence electron from a given element until an ion is formed. Such technique is now frequently used at hot-cavity and gas-catcher facilities [1].

A limit exists in this technique as non-resonant ions are not totally suppressed: elements with a low ionization potential (*e.g.* alkali) are ionized in contact with a hot surface while some ions may survive the neutralization processes in a gas catcher. In order to suppress those non-resonant contaminant, different approaches are currently under investigation, like the Laser Ion Source Trap LIST [14,15].

Moreover, it should be noted that selective nature of the resonant laser ionization process requires the developments to be redone for each element. As the transitions used are always element specific, a new element will require a new set of atomic transitions to be studied. Many laboratory are constantly researching new ionization schemes to increase the versatility of the resonant laser ion source (*e.g.* LARIS at CERN, LARISSA at Universität Mainz).

The polonium element (Z=84) is one of the elements that has been developed most recently. As there is no stable isotope of polonium, it is not possible to study it in off-line facilities like LARIS or LARISSA and the studies had to be performed on-line at ISOLDE. The knowledge of the atomic structure of that nucleus was very scarce but the test proved successful, resulting in the development of three different ionization schemes [16]. Although the absolute ionization efficiency is inferior to that of a hot plasma ion source, the contamination of the beams of ^{200}Po has been identified to be below 1%, which can never be achieved with the other non-selective ion source.

LASER SPECTROSCOPY OF POLONIUM

Using the newly developed ionization schemes for polonium, in-source laser spectroscopy of the polonium isotopes has been performed at ISOLDE, using spallation products from the impact of the 1.4 GeV proton beam from the CERN PSBooster on a thick depleted UC_x target. By measuring the production yields as a function of the applied laser frequency of one of the resonant transitions, the isotope shifts (with respect to ^{196}Po) and the hyperfine structures (odd-A isotopes only) of the isotopes $^{191\text{-}204,206,208,209\text{-}211,216,218}$Po where measured [11]. The ability to study isotopes over such a wide range of masses, of half lives ($T_{1/2}$=33 ms up to 102 years), and of production rates (from 10^{-2} to 10^{7} ions per second) can only be achieved thanks to the versatility of the ISOLDE facility and of the RILIS laser ion source.

By comparing the isotope shifts in the even-*A* isotope $^{200\text{-}210}$Po measured in this work with respect to those using another transition [17], a King plot analysis [1] could be performed, hereby checking the consistency of the large-scale atomic calculations performed on this complex atomic structure. This is the first experimental test of those calculations on such a complicated system. While the field shift factors were found to be satisfying, some discrepancy on the mass shift was identified. Those resulted in an overall systematic uncertainty in the extraction of the $\delta\langle r^2\rangle$ of similar magnitude than the statistical uncertainty. The extracted $\delta\langle r^2\rangle$ are shown in Fig. 1.

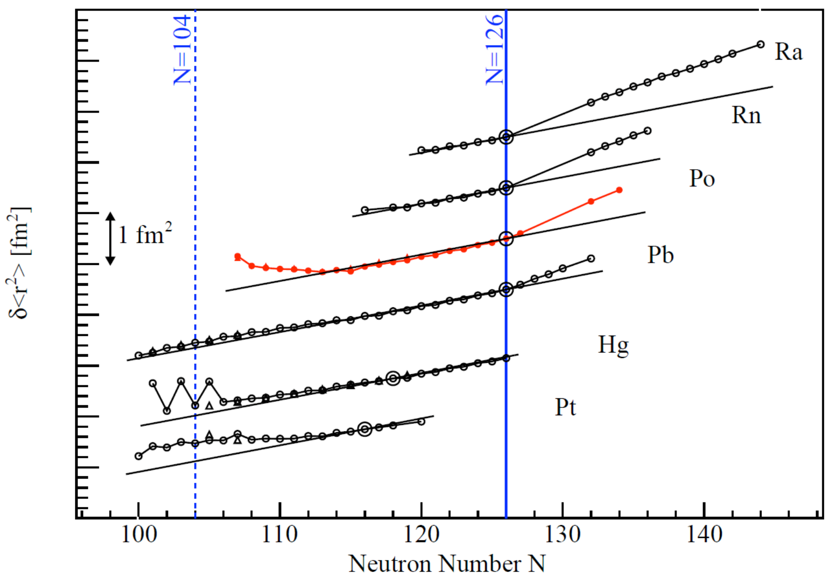

FIGURE 1. Changes in the mean square charge radii $\delta\langle r^2\rangle$ for the even-*Z* isotopes around Pb. See Ref. [11] and references therein. The offset between each isotopic chain is arbitrary and meant for better display. The reference isotope for each isotopic chain is identified by a larger circle.

The $\delta\langle r^2\rangle$ for the polonium isotopes show a clear departure from sphericity that starts at ^{200}Po and progresses very smoothly, in contradiction to what has been inferred from α-decay spectroscopy. Those $\delta\langle r^2\rangle$ are also compared to Beyond Mean Field calculations [11] which conclude that the departure for sphericity down to ^{192}Po results from a very soft nature of those nuclei with respect to deformation, while the isotopes remain on average spherical. Only isotopes with $A<192$ display a well-defined minimum, first with oblate deformation for ^{190}Po, then with prolate deformation for ^{188}Po and the lighter isotopes. The limitations in half lives and in production rates do not allow, however, for a measurement of those isotopes in order to assert those claims.

Concerning the odd-*A* isotopes, the inability to accurately measure the spin of the odd-*A* isotopes together with results that seem inconsistent with previous α-decay studies triggers some interrogations on the spin assignment of some of those isotopes. Further discussion on this issue and on the electromagnetic moments is under preparation [18].

COLLINEAR RESONANCE IONIZATION SPECTROSCOPY

In order to resolve the issue on the spin, greater resolution is needed. However, it is not possible to achieve the require sensitivity with conventional collinear laser spectroscopy methods, which are limited to beam intensities of 100 ions per second or higher. Nevertheless, a new method, currently under development at ISOLDE, could breach that gap by perform resonant laser ionization, benefitting from the high sensitivity, in a collinear geometry, hereby taking full advantage of the Doppler compression. This Collinear Resonance Ionization Spectroscopy (CRIS) technique should be able to study beams with intensities as low as 1 ion per second with a resolution close to that of the standard collinear laser spectroscopy technique [1,19,20].

This technique will first be developed to measure isotope shifts and hyperfine structures with radioactive atom beams. As a very sensitive and precise technique, it should definitely be considered for the next generation radioactive ion beam facilities. This technique operates at very low pressure ($<10^{-9}$ mbar) to suppress the background from non-resonantly ionized products. As such, it will produce highly purified beams and can be considered as a possible tool for providing clean beams at EURISOL. A variation on the technique also permits, for some elements, to work on the 1+ ion rather than on the neutral atom, hereby producing a 2+ ions, easily identifiable from the other elements in a mono-energetic beam. Although this approach requires further developments, it could prove very efficient.

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Rp-process-motived experimental initiatives at NSCL

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INTRODUCTION

Type I X-ray bursts are the most frequent type of thermonuclear explosion in the Galaxy. In such events, the neutron star in a binary system experiences a dramatic increase in brightness on a timescale of a few seconds. The explosion is powered by a thermonuclear runaway when the heating resulting from the accumulation of matter on the surface of the neutron star cannot be compensated by readjusting the stellar structure or by surface cooling[1]. This increase in temperature leads to higher nuclear reaction rates which result in a more rapid temperature increase. The resulting burst has a typically energy output of 10^{39-40} ergs (more than 1000 times more than the sun during the same period of time) and lasts typically 10-100 seconds. During the flash, it is expected that 90% of the previously accreted hydrogen and helium is transformed into carbon and heavier elements[2]. Observations of such events provide information about the properties of matter under extreme conditions by providing constraints in the system parameters such as neutron star properties, thermal state of the neutron star crust, accretion rate, ignition mechanism, etc.

X- ray bursts have been observed in approximately 90 sources that show a recurrence times of hours up to days[3]. Although X-ray burst have been observed since the 1970's, a dramatic increase over the last decade in observational data has led to new discoveries and large catalogues [4, 5] that allow for the first time a meaningful comparison between bursts (due to uniform and updated analysis procedures) and the study of bursters outside the typical burst behavior. Although much progress has been obtained in our understanding of these processes, several open questions remain. As an example the recent observation of short recurrence times (less than 10 minutes) do not agree with current X-ray burst models. The short recurrence time is too short for the accretion rate to accumulate enough fuel to burn in the burst. Although, this seems to indicate that unburned fuel from previous X-ray bursts is being used, the mechanism for halting burning once an X-ray burst starts is still unknown. Both stellar (fast rotation mixing, burning occurring in a hydrogen-depleted layer, etc.) and nuclear physics causes (nuclear waiting points)[3] may be responsible for halting and then re-igniting the short recurrence time X-ray bursts. In order to fully understand these and other observations (millisecond burst oscillations, burst dependence on accretion rate, superburst fuel origin, crust processes, multi-peaked bursts, change in burst behavior as a function of time), current nuclear physics uncertainties need to be reduced.

RP-PROCESS

Once the burst is triggered by the 3α reaction, the temperature of the exploding layer quickly increases triggering first a sequence of mainly (α,p)-(p,γ) reactions (the so-called αp-process) followed by hydrogen burning via the rapid proton capture process (rp-process). The rp-process is the main source of energy and determines the X-ray light curve. Quantitative comparison between X-ray burst calculations and typical X-ray bursts have shown excellent agreement[6] but have also shown that the nuclear physics of the rp-process are not sufficiently accurate to test X-ray bursts at the level provided by observations[13]. The αp-process path on the chart of nuclides follows a competition between (α,p) reactions (allowed by the increasing temperatures in the early phase of an X-ray burst) and proton captures up to mass $\approx$40. An effective way to avoid long β-decays (compared to the other rates) is by having an (α,p) reaction followed by a proton capture. The main sequence starts with ^{14}O(α,p)^{17}F(p,γ)^{18}Ne and continues until ^{38}Ca(α,p)^{41}Sc is reached. For heavier nuclei up to mass $\approx$64-100, the rp-process path is dominated by proton captures and β-decays.

NUCLEAR PHYSICS

In order to determine important uncertainties in current X-ray burst models, studies examining nuclear reaction sensitivities have been performed in the past[7, 8]. In those studies, key nuclear reactions whose uncertainties have the largest impact were identified. Since the direct measurements of most nuclear reactions are not feasible with current facilities (except in a few cases such as ^{13}N(p,γ)^{14}O[9, 10] at Louvain-la-Neuve and ^{21}Na(p,γ)^{22}Mg[11] at TRIUMF), indirect methods are usually employed. A few experiments have been performed to study (α,p) and (p,α) directly[12]. When the reaction has to be studied indirectly, knowledge of excitation energies, Q-values, spin assignments, single-particle strengths and spectroscopic information are required. Nuclear masses are needed for the determination of resonance energies, which enter exponentially in the reaction rates and have to be known to better than 10 keV when a few resonances dominate the reaction rate[1]. Such precision has been obtained for the Q-values of lighter nuclei (Z<23) in the rp-process path but only in some cases for heavier nuclei. In cases where the (p,γ) Q-value is small or negative, an equilibrium between proton capture and its inverse photo-disintegration is established. In those cases, the Q-value has to be known with a precision of better than 100 keV. Waiting points with a relatively long β-decay half-lives and a proton unstable neighboring $Z+1$ nucleus such as ^{68}Se and ^{72}Kr, are examples. These nuclei (along with ^{64}Ge) in particular are responsible for the rate of energy release and the long tails observed in some bursts[13]. Although the mass of the waiting point isotopes have been measured, the Q-values have been obtained from theoretical estimates since the p-capture nuclei are particle-unstable. A recent experiment at the National Superconducting Laboratory (NSCL) has been performed to address the nuclear physics uncertainty in the lifetime of ^{68}Se by measuring the β-delayed proton emission of ^{69}Kr. By measuring the proton emission from low lying β-decayed states in ^{69}Br, the proton separation of ^{69}Br can be constrained. Analysis of the experiment is currently underway.

Although considerable progress has been made, most of the reactions studied experimentally so far are limited to nuclei in the rp-process path close to stability. Most of the reactions used in X-ray burst models are theoretical estimates based on statistical Hauser-Feshbach calculations[14]. Shell model calculations[15, 16] are limited to available configuration spaces. Energies of individual states can be estimated with shell model calculations with a precision at best of around 100 keV which translates into many orders of magnitude uncertainties. For a review of recent measurements using both direct and indirect techniques see [1].

REA3 REACCELERATED BEAM FACILITY

The ReA3 reaccelerated beam facility currently under construction at NSCL will provide low energy rare isotope beams ideally suited for astrophysics studies. The beams produced by fragmentation will stop in a gas-stopper before being reaccelerated in a superconducting LINAC to energies from 0.3 to 6 MeV/u. ReA3 will provide rare isotope beams of many elements that are currently unavailable or chemically difficult to produce in other rare beam facilities. The possibility to measure nuclear reaction rates at the astrophysically relevant energies for nuclei directly in the rp-process path will provide exciting science opportunities. Figure 1 shows expected ReA3 intensities.

Scientific equipment currently under development that will be used for rp-process motived experiments include ANASEN and the Active Target Time Projection Chamber (AT-TPC). The AT-TPC is being built by a collaboration of researchers from MSU, University of Notre Dame, Western Michigan University, LLNL, LBNL, and St. Mary's University. The time projection chamber detector will be placed inside a large solenoid so once the beam particles enter the gas chamber, they can interact with the active target. The resulting products will be tracked within the gas vessel of the time projection chamber. It is planned to be used for the indirect study of reactions of astrophysical interest either by (d,p) or (^{3}He,d) transfer reactions. The Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN) is a charged-particle detector array being developed by Louisiana State University and Florida State University and it consists of silicon-strip detectors backed with CsI scintillators arranged in a barrel configuration, and an annular Si detector enclosing the downstream end of the barrel. A gas proportional counter is also planned. It will initially be used for proton scattering, (α,p), (p,α) and (d,p) reaction studies.

The Separator for Capture Reactions (SECAR) is a highly specialized device also planned to be used in ReA3. This recoil separator will be used for the direct measurement of (p,γ) reactions at astrophysically relevant energies. Although the focus will be on X-ray bursts and novae, it will also address reactions relevant for late burning stages and explosive nucleosynthesis in supernovae. Although with ReA3, SECAR will be fully operational and first direct measurements will be carried out, only the Facility for Rare Isotope Beams (FRIB) will provide the beam intensities needed for direct measurements of a wide range of reaction rates.

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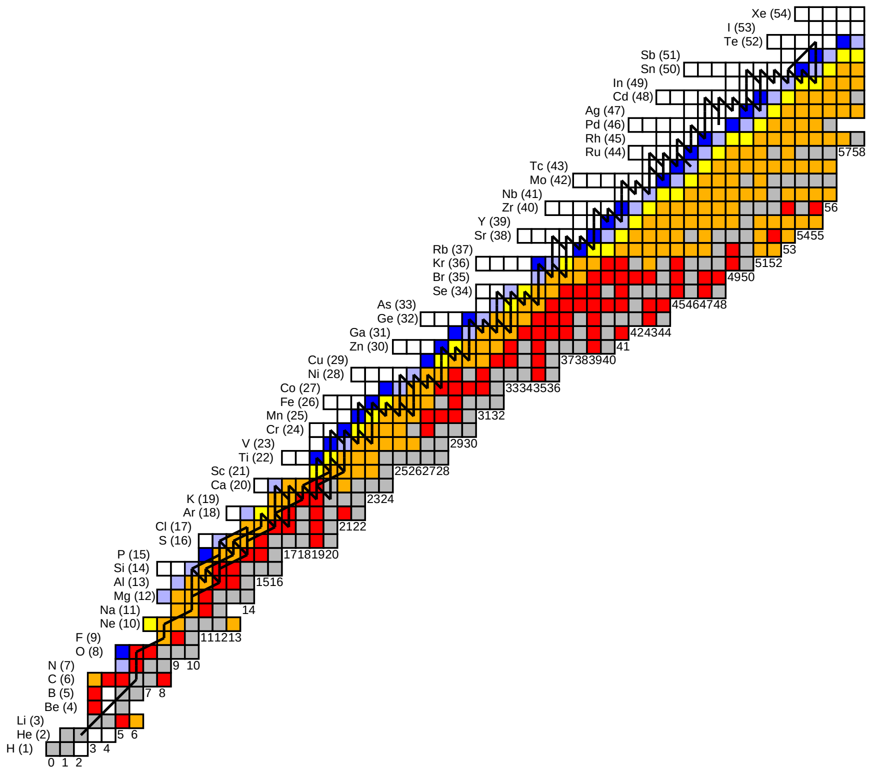

FIGURE 1. Expected ReA3 intensities and the main path of the r-process in a 1-zone rp-process model[17]. Stable nuclides are shown in gray, nuclides with intensities greater than 10^5 particles per second (pps) are shown in red, 10^4 pps in orange, 10^3 pps in yellow, 10^2 pps in light blue and 10 pps in dark blue.

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Explosive Hydrogen Burning Studied With RIB

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INTRODUCTION

Novae and X-ray bursts are astrophysical explosive phenomena. They are produced by the burning of hydrogen rich matter deposited onto the surface of a white dwarf star or a neutron star. Temperatures as high as $2x10^9$ K are reached during the X-ray bursts. Several nuclear reactions were identified as important cases to be studied, e.g. ^{18}F(p,α), ^{25}Al(p,γ), ^{30}P(p,γ), ^{14}O(α,p), ^{30}S(α,p)^{33}Cl …, since they could have a strong influence on measurable properties like light curve profiles, abundances or gamma ray flux. Many of these reactions involve radioactive nuclei. These reactions have been subject of many experiments, mainly indirect measurements, i.e. transfer reactions, resonant elastic scattering, beta decay studies…. In these experiments, the spectroscopic properties (energy, widths, spin) of resonances were measured and then used to calculate the rate of the reactions. Uncertainties still remain since not all states could be observed. In several cases, one of the most important uncertainties is the sign of interferences between some of these resonances, or between resonances and the direct capture contribution. This sign cannot be determined by indirect measurements nor predicted by theories. With the development of new intense radioactive beams of light neutron-deficient nuclei, the direct measurement of these nuclear reaction cross sections at low energy could be the unique way to obtain the final non-ambiguous reaction rates. It is certainly the most important goal and the most ambitious one. Let's take an example to illustrate this discussion.

THE CASE OF THE ^{18}F(p,α)^{15}O REACTION

The reaction ^{18}F(p,α)^{15}O is certainly the most studied reaction involving a radioactive nucleus. It provides a good example of what could be measured with the present means, and what could not be. This reaction is recognized as one of the most important reaction for nova gamma-ray astronomy [1]. However, its rate remains largely uncertain at novae temperatures [2]. In principle, the rate of this reaction can be calculated using the spectroscopic properties (excitation energies, partials widths, spin) of excited states in the intermediate compound nucleus ^{19}Ne or those of its mirror nucleus ^{19}F [3]. This objective triggered several studies but, despite a tremendous effort not all states known in ^{19}F could be observed in ^{19}Ne, and only a few partial widths could be measured [3,4]. Moreover, it was also discussed that the presence of interferences between several low-lying (l=0) 3/2+ states induces strong uncertainties in the calculation of the cross section at low energies (see Fig 1) [5]. This fact triggered several new studies with the objective to measure the cross section at low energy and so, to constrain the signs of the interferences. This could be achieved down to ~ 400 keV [5,6]. Once again, the conclusion is far to be clear since it was not possible to measure the cross section at a sufficient low energy and with a sufficient accuracy.

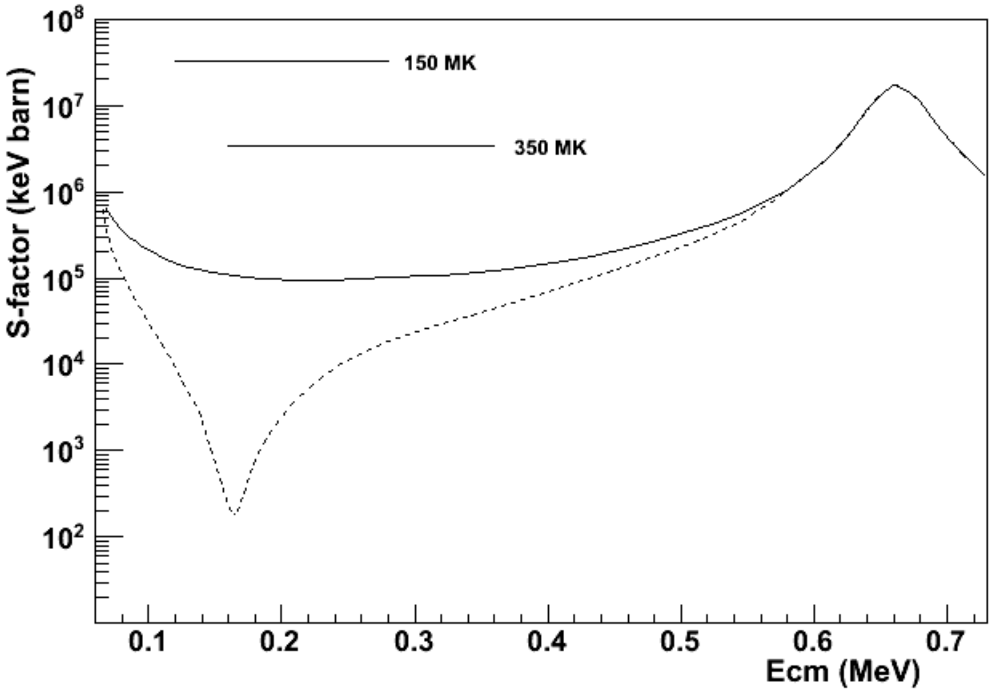

FIGURE 1. The calculated astrophysical factors of the reaction $^{18}F(p,\alpha)^{15}O$ are shown as a function of the center of mass energy (from [5]). Depending on the sign of interferences between several resonances, here calculated for two configurations (+ + +) (continuous line) and (+ + -) (dashed line), the cross section could be very different at low energies. The Gamow window is shown for different temperatures (top left horizontal lines in Mega Kelvin).

If a very intense radioactive beam of ^{18}F will be available in the future, a very important goal would be to expand these direct cross section measurements at lower energies, and so to determine non-ambiguously the rate of the reaction. Figure 2 shows the beam intensity required in order to measure a rate of 10 reactions per day using a total detection efficiency of 50 %. It shows that the measurement can be performed down to the energy of 200 keV if a beam of ~ 10^8 pps is available. A measurement performed at this energy would allow us to conclude definitively about the rate of this reaction.

Another important question is “How sensitive is the measurement to the incident energy?". In Table 1, the effect of a change of 1 % in the incident energy is presented for this reaction. It shows that the incident energy is not a major issue since a 1 % change in the incident energy results in a maximum 12 % change in the cross section.

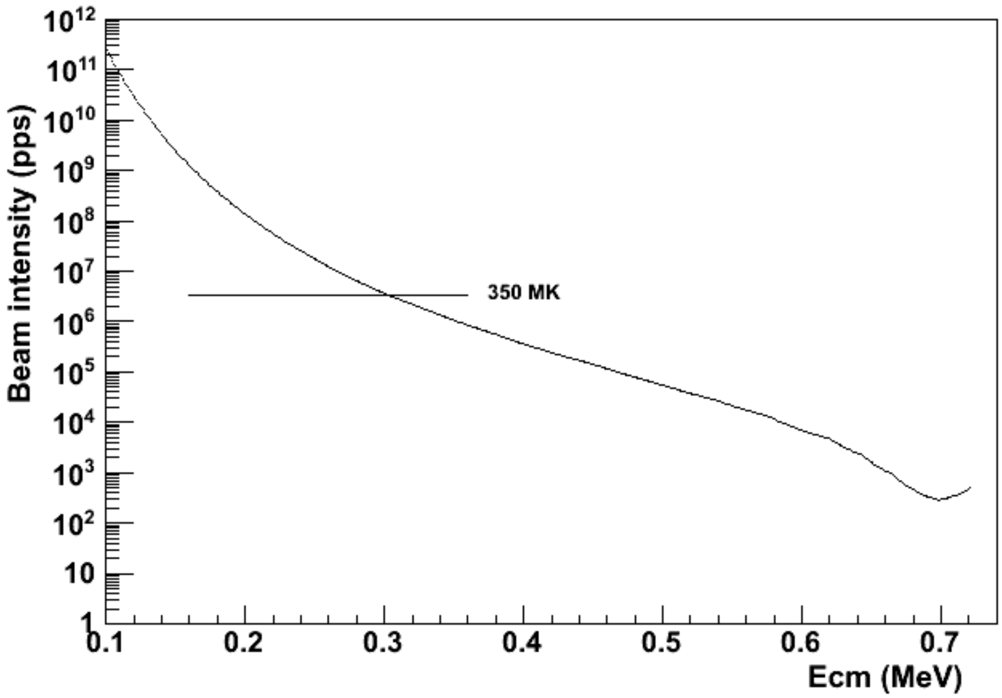

FIGURE 2. Beam intensity of ^{18}F radioactive ions required to measure 10 "counts" of the $H(^{18}F,\alpha)^{15}O$ reaction per day using a 50 % total efficiency detector shown as a function of the center of mass energy. At the energy of 200 keV it corresponds to about 10^8 pps.

TABLE 1. Effects of 1 % change in the incident energy on the $^{18}F(p,\alpha)^{15}O$ reaction cross section is presented for different energies. It shows that the accuracy of the incident energy is not a major issue.

Incident energy E_{CM} (keV)	**Effect on the cross section of 1 % difference in E_{CM}**
100	12 %
200	9 %
400	8 %
700	7 %

A good example of experimental setup can be found in the Ref [5] or [7]. The reaction products (α particles and ^{15}O ions) were detected using two position sensitive annular silicon detectors positioned downstream from the target. So, in this case there is no need for a recoil mass separator. A problem could come from the target, which should sustain the very high beam intensity. Moreover, in Ref [5] it is shown that a solid target could be a source of noise, since $\alpha + {}^{15}O$ coincidence events could be mixed with $^{18}F+^{12}C$ elastic scattering events. A good solution for the future could be the use a windowless gas target (~ 10^{18} atoms/cm2 is required).

THE GENERAL CASE

The good point about these reactions made in order to study the X-ray bursts and the novae is that the temperatures for these astrophysical sites are very high, which results in relatively high incident energies and high cross sections, the Gamow window being generally located above 100 keV. But, even in these good conditions, the low energy part of the excitation function will not always be accessible with reasonable radioactive beams. In general, the X(particle, particle)Y reactions cross sections are much larger than those for the X(particle, γ)Y reactions, which make the first one the easiest ones to be studied. In the first case, a simple ensemble of silicon detectors could be used to measure the charged particles. In the second case, the experimental setup is necessarily much more complicated. In general, it requires the use of a recoil mass separator in order to select the compound nucleus Y, and a gamma spectrometer to detect the gamma in coincidence (but not always necessary). A configuration where a Wien Filter is used as a recoil mass separator is studied at GANIL [8]. It could be an excellent option since the acceptance of this kind of separator could be very high. Another problem could arise from the purity of the beam. If the radioactive beam is polluted by another stable or radioactive beam, the cross section of one beam could overwhelm by the cross section of the other. Very efficient and selective source could be used; a resonant ionization laser (see for example [9]) is a promising option. Moreover, in general the angular distribution of the reaction products is not isotropic, it is also important to measure the evolution of the cross section as the function of the angle.

In principle, direct measurement of reaction cross sections at low energy for astrophysics is an excellent physics case for EURISOL. A detailed study of several reactions should be performed in order to determine the required experimental conditions and the limits of the measurements.

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Aluminum-26 Nucleosynthesis With Proton-Rich Exotic Beams

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INTRODUCTION

The origin of galactic ^{26}Al is a long-standing question in nuclear astrophysics, with important implications for galactic chemical evolution and stellar nucleosynthesis. The gamma ray line at 1.809 MeV – from the β^+ decay of the ^{26g}Al to the first excited state in ^{26}Mg – has been decidedly observed by orbiting telescopes such as COMPTEL [1], RHESSI [2], and INTEGRAL [3]. In determining the stellar source(s) of ^{26}Al, the global analyses of these gamma-emission maps has been complemented with a deeper understanding of specific nucleosynthesis sites with regard to their ^{26}Al production. The former indicate that Type II supernovae and Wolf-Rayet stars could be the dominant contributors of ^{26}Al to the measured gamma ray map [4], while present models of novae and AGB stars also suggest significant ^{26}Al production.

The present work focuses in particular on ^{26}Al nucleosynthesis in the context of explosive stellar environments. In novae, for example, the production of ^{26}Al happens in the Mg-Al (hydrogen-burning) cycles [5]. The ^{26}Al(p,γ)^{27}Si and ^{25}Al(p,γ)^{26}Si reactions are two processes in this cycle that strongly affect the ^{26}Al yield. The first has the obviously important role of depleting the yield of ^{26g}Al. The second reaction's impact is more subtle: the ^{26}Si produced in the reaction decays to ^{26}Al, but through its isomeric state (^{26m}Al) instead of its ground state, thus effectively reducing the flux of 1.8 MeV γ-rays. The impact of these reactions has been corroborated in a study that investigated the influence of rate uncertainties on nova nucleosynthesis [6]. (Another important reaction not discussed in my talk is the ^{26m}Al(p,γ)^{27}Si reaction.)

Both rates are dominated by narrow isolated resonances in the compound nuclei ^{27}Si and ^{26}Si, whose resonance energies and strengths need to be known. The ideal scenario is one in which a direct measurement of the reaction is performed. Since ^{25}Al and ^{26}Al are unstable, radioactive ion beams of high intensity are required, while lower intensities are useful in indirect approaches, such as elastic scattering or transfer reactions, to determine level parameters. In my talk, I surveyed some experiments that our McMaster group has carried out along these lines. For example, for the ^{25}Al(p,γ)^{26}Si reaction, a direct measurement remains a dream in the horizon (true also for the ^{26m}Al(p,γ)^{27}Si, and so indirect approaches have been explored [7]. In the following, in the interest of space and relevance to EURISOL, I will focus on a direct measurement of the ^{26}Al(p,γ)^{27}Si reaction with a ^{26}Al beam at TRIUMF-ISAC.

MEASUREMENT OF ^{26}Al(p,γ)^{27}Si WITH DRAGON

The dominant contribution to the ^{26}Al(p,γ)^{27}Si reaction rate at T ~ 0.1-0.4 GK is from a resonance located at excitation energy E_x(^{27}Si) = 7652 keV and with resonance energy E_r = 188 keV. The uncertainty in the rate at these temperatures was determined largely by the adopted range for the resonance strength of this state: $\omega\gamma$ = 64 μeV, with upper and lower limits of 290 μeV and 0.0099 μeV, respectively [8]. This strength had been previously measured to be 55 $\pm$ 9 μeV in an experiment with a radioactive ^{26}Al target, but the results remained unpublished [9].

In view of the wide range of uncertainty in the strength of the E_r = 188 keV resonance, the goal of our experiment was to perform a measurement of this strength, taking advantage of high-intensity ^{26}Al beams from the TRIUMF-ISAC facility and the DRAGON recoil separator. The latter was built specifically for measurements of radiative capture reactions of importance to nuclear astrophysics [10].

The ^{26}Al beam was produced with the Isotope Separation On-Line (ISOL) method, by impinging 70 μA of 500 MeV protons from the TRIUMF cyclotron onto a high-power SiC target. The long-lived ^{26}Al diffuses out of the target, and a laser ionization system (TRILIS) was utilized to improve the ionization selectivity and the beam intensity. The beam was accelerated through the ISAC RFQ-LINAC accelerator. For measurements on resonance, the beam energy was 201 keV/u with intensities of about 5×10^9 particles per second. The beam energy spread was ~ 1% FWHM.

The beam ions impinged on a windowless H_2 gas target, which is the first component of the DRAGON recoil (Figure 1). The beam energy and the target pressure are selected to ensure that the resonant reactions occur at the center of the gas target. The beam intensity is monitored by a silicon detector, inside the gas of the target, which detects protons from ^{26}Al + p elastic scattering. The target is surrounded by an array of BGO detectors, which detect gamma rays from the (p,γ) reactions. The ^{27}Si recoils, along with beam ions that did not react in the gas, emerge from the target with an equilibrium distribution of charge states and enter the electromagnetic separator, whose main purpose is the separation between recoils and beam ions at the level of about one part in 10^{9-10}.

The separator comprises two stages, each consisting of a magnetic dipole and an electrostatic dipole. One charge state (4^+) of the Si recoils and beam ions is selected after the first magnetic dipole. Most of this remaining beam is stopped at a set of slits immediately after the first electrostatic dipole. The second stage serves to remove additional beam ions that passed through the first stage. At the final focus of the separator, a double-sided silicon strip detector was used to measure the energies of the ^{27}Si recoils and of any remaining “leaky” beam ions. The latter are further suppressed by a coincidence requirement between gamma-ray and recoil detections. The time-of-flight through the separator (21m in length) for the recoils is also measured.

The right panel in Fig. 1 shows a two-dimensional histogram of time-of-flight versus energy for coincident events, in which a locus corresponding to the ^{27}Si recoils is seen. More than 100 recoil-gamma coincidence events for the E_r = 188 keV resonance were observed in the experiment. The main results of this study [11] are: (1) a resonance energy E_r = 184 $\pm$ 1 keV, which represents a small change, but is still

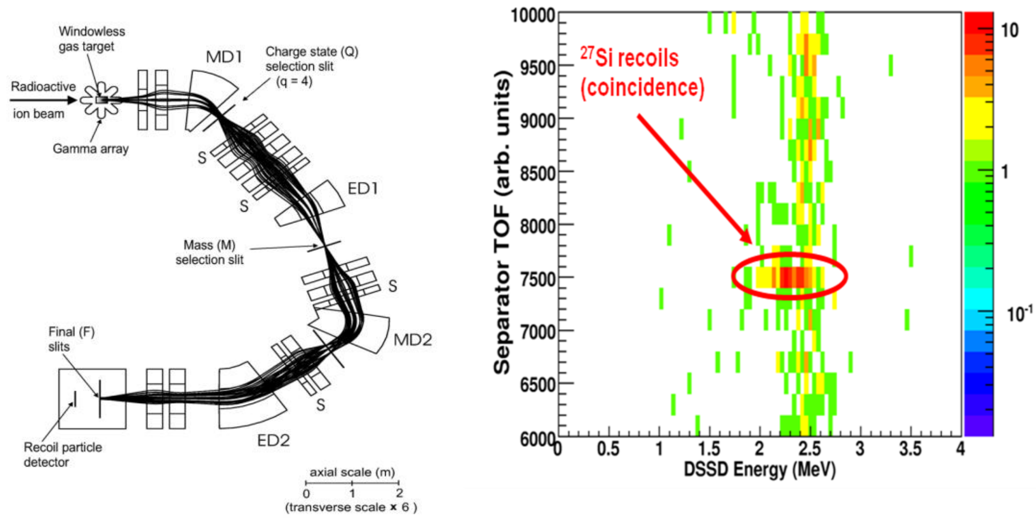

FIGURE 1. Left panel: Schematic of the DRAGON recoil separator. Right panel: Two-dimensional histogram of time-of-flight (TOF) vs. energy. The highlighted region circumscribes ^{27}Si events.

significant for the reaction rate; (2) a (p,γ) strength $\omega\gamma = 35 \pm 7$ μeV, which is only 64% of the unpublished value of Ref. [9] and demonstrates DRAGON's ability to measure weak strengths to 20%; and (3) a re-evaluated thermonuclear ^{26}Al(p,γ)^{27}Si reaction rate, resulting in more reliable estimates for ^{26}Al synthesis in classical novae.

CONNECTION TO EURISOL

The ^{26}Al(p,γ)^{27}Si reaction is the easiest to study, given the long half-life of ground-state ^{26}Al. For the ^{25}Al(p,γ)^{26}Si and ^{26m}Al(p,γ)^{27}Si reactions, however, achieving the required beam intensities of ^{25}Al and ^{26m}Al has presented significant challenges. EURISOL can contribute by (1) creating a dedicated program for the development of intense beams of these short-lived Aluminum isotopes, drawing on past experience at ISAC REX-ISOLDE; and by (2) including a recoil mass separator, similar to DRAGON (ISAC), in its suite of experimental facilities.

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Reactions with Neutron-Deficient Nuclei

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Direct measurements relevant for nuclear physics and nuclear astrophysics involving unstable nuclei are difficult for two reasons: a) targets (or projectiles at appropriate energies for inverse kinematics) of unstable nuclei are not easily available, if at all, and b) charged-particle reactions at the very low energies relevant for stellar processes are very difficult to measure due to Coulomb repulsion, which leads to very low reaction cross sections. Hence, few direct measurements have been done on proton-rich nuclei to date. This problem has led to the development and use of indirect methods using reactions in radioactive facilities. The list of indirect techniques that are used today includes measurement of elastic scattering, reaction cross sections, Coulomb dissociation, nuclear breakup, transfer reactions, knock-out reactions, fragmentation reactions, and other indirect techniques. But even with the advent of rare isotope facilities worldwide, many pieces of valuable information still will require a dedicated facility such as EURISOL. Below I will discuss some of the open problems when using indirect techniques with reactions involving proton-rich nuclei.

REACTIONS WITH NEUTRON-DEFICIENT NUCLEI

Proton targets

Elastic proton scattering has been one of the major sources of information on the matter distribution of unstable nuclei in radioactive beam facilities. This is possible for proton-rich projectiles at intermediate and high energy collisions, 50 MeV/nucleon and beyond, because the reaction mechanism is well understood in terms of the *Glauber theory*. At lower energies, the reaction mechanism is more complicated, with a strong dependence on the details of the optical potential and on coupled-channels.
(p,p') reactions are excellent probes of the excited states of the projectile nucleus, despite the inherent need of a structure model to account for *coupled-channels* and *polarization effects*.
Quasi-free (p,2p) reactions are good probes of nuclear structure projectile energies of (200-1000 MeV/nucleon) when the projectile proton knocks out a bound nucleon. The energy spectra of the outgoing protons provide information on the energy of the struck nucleon in the nucleus. The shape of the angular correlations of the outgoing particles, or the recoil momentum of the nucleus, determines the *momentum distribution of the knocked-out proton*. In the last four decades quasi-free scattering experiments have been performed with this basic purpose, mostly for reactions on

stable nuclear targets. The main theoretical problem with quasi-free scattering is a proper description of *multiple scattering* and *medium corrections* to the free scattering, whenever necessary. Very few experiments to date with quasi-free (p,2p) scattering has been done involving rare isotopes.

Transfer Reactions

Transfer reactions are well established tools to obtain spin, parities, energy, and spectroscopic factors of states in a nuclear system. For proton-rich nuclei, **(d,p) reactions** have appreciable cross sections and are particularly spectroscopic tools due to the simplicity of the deuteron. Transfer reactions $A(a, b)B$ are effective when a momentum matching exists between the transferred particle and the internal particles in the nucleus. Thus, beam energies should be in the range of a few 10-100 MeV per nucleon. Low energy *reactions of astrophysical interest* can be extracted directly from breakup reactions $A+a \rightarrow b+c+B$ by means of the **Trojan Horse technique**. If the Fermi momentum of the particle x inside $a = (b+x)$ compensates for the initial projectile velocity v_a, the low energy reaction $A + x = B + c$ is induced at very low (even vanishing) relative energy between A and x. The main theoretical challenges are the proper treatment of *off-shell effects* and the normalization of the extracted astrophysical cross sections.

The **Asymptotic Normalization Coefficient** (ANC) technique relies on fact that the amplitude for the radiative capture cross section $b + x \rightarrow a + \gamma$ is given by $M=\langle I^a_{bx}(\mathbf{r}_{bx})|O(\mathbf{r}_{bx})|\psi_i(\mathbf{r}_{bx})\rangle$, where $I^a_{bx} = \langle\phi_a(\xi_b, \xi_x, \mathbf{r}_{bx})|\phi_x(\xi_x)\phi_b(\xi_b)\rangle$ is the integration over the internal coordinates ξ_b, and ξ_x, of b and x, respectively. For low energies, the overlap integral I^a_{bx} is dominated by contributions from large r_{bx}. Thus, what matters for the calculation of the matrix element M is the asymptotic value of $I^a_{bx} \sim C_a^{bx}\, W_{-\eta a,1/2}(2\kappa_{bx}r_{bx})/r_{bx}$, where C^a_{bx} is the ANC and W is the Whittaker function. These coefficients can be extracted in transfer reactions when the *peripherality* of the reaction is dominant. It is not clear if the accuracy with which the peripherality condition in transfer reactions has been under control in previous experiments. As with other reaction types, a good knowledge of *effective interactions* among the nucleons and *clusters* is crucial for the extraction of the ANCs.

Coulomb and Nuclear Excitation and Dissociation

The (differential, or angle integrated) Coulomb breakup cross section for $a + A \rightarrow b + c + A$ is directly proportional to the *photo-nuclear* cross section $\sigma^{\pi\lambda}_{\gamma+a \rightarrow b+c}(\omega)$ for the multipolarity $\pi\lambda$ and photon energy ω. Time reversal allows one to deduce the *radiative capture* cross section $b+c \rightarrow a+\gamma$ from $\sigma^{\pi\lambda}_{\gamma+a \rightarrow b+c}(\omega)$. The method has been used successfully in a number of reactions of interest for astrophysics.

One of the main obstacles for extracting the radiative capture cross section information is the contribution of the *nuclear breakup* and of *higher-order effects* from the **Coulomb breakup** contribution. There are still many open questions related to the apparent inability of a good agreement between theory and some experimental data.

Knockout Reactions

Single-nucleon knockout reactions with heavy ions, at intermediate energies (≥ 100 MeV/nucleon) and in inverse kinematics, have become a specific and quantitative tool for studying single-particle occupancies and correlation effects in the nuclear shell model. The experiments observe reactions in which fast, mass A, projectiles collide peripherally with a light nuclear target producing residues with mass (A − 1). The final state of the target and that of the struck nucleon are not observed, but instead the energy of the final state of the residue can be identified by measuring coincidences with decay gamma-rays emitted in flight. **Two-nucleon knockout reactions** are also useful to extract information on nucleon-nucleon corrections in nuclei. Either for one or two-nucleon knockout there is still much discussion on the role of the medium modifications of the nucleon-nucleon cross sections and the role of off-shell effects.

Charge-Exchange Reactions

Charge exchange reactions induced in **(p,n) reactions** are often used to obtain values of Gamow-Teller matrix elements, B(GT), which cannot be extracted from beta-decay experiments. Not only (p,n), but (^{3}He,t) and heavy-ion reactions (A,A±1) also provide information on the Fermi, B(F), and Gamow-Teller, B(GT), transitions needed for astrophysical purposes.

This approach relies on the similarity in spin-isospin space of charge-exchange reactions and β-decay operators. As a result of this similarity, the cross section σ(p,n) at *small momentum transfer* q is thought to be closely proportional to B(GT) for strong transitions.This assumption, valid for one-step processes, was proven to work rather well for (p,n) reactions (with a few exceptions). For heavy ion reactions the proportionality might not work so well. Theoretical works support that multistep processes involving the physical exchange of a proton and a neutron can still play an important role up to bombarding energies of 100 MeV/nucleon. In fact, deviations from the small momentum transfer assumption is common under several circumstances. For important GT transitions whose strength is a small fraction of the sum rule, the direct relationship between σ(p,n) and B(GT) values also fails to exist. Similar discrepancies have been observed for reactions on some odd-A nuclei including ^{13}C, ^{15}N, ^{35}Cl, and ^{39}K and for charge-exchange induced by heavy ions.

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Exotic Excitations in Neutron-Deficient Nuclei

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Introduction

The multipole response of nuclei far from the _-stability line and the possible occurrence of exotic modes of excitation present a rapidly growing field of research [1]. Characteristic ground-state properties (weak binding of the outermost nucleons, coupling between bound states and the particle continuum, nuclei with very diffuse neutron densities, formation of skin and halo structures) will also have a pronounced effect on the multipole response of unstable nuclei. For instance, the dipole (E1) response of short-lived isotopes is characterized by the fragmentation of the strength distribution and spreading into the low-energy region, and by the mixing of isoscalar and isovector components. While in light nuclei the onset of dipole strength in the low-energy region is caused by non-resonant independent single-particle excitations of the loosely bound neutrons, several theoretical analyses have predicted the existence of the pygmy dipole resonance (PDR) in medium-mass nuclei, i.e. the resonant oscillation of the weakly-bound skin against the isospin saturated proton-neutron core. The interpretation of the dynamics of the observed low-energy E1 strength in nuclei with pronounced proton or neutron excess is currently very much under discussion.

The Proton Pygmy Dipole Resonance

Because the proton drip-line is much closer to the line of _-stability than the neutron drip-line, bound nuclei with an excess of protons over neutrons can be found only in the region of light $Z < 20$ and medium mass $20 < Z < 50$ elements. For $Z > 50$, nuclei in the region of the proton drip-line are neutron-deficient rather than proton-rich. In contrast to the evolution of the neutron skin in neutron-rich systems, because of the presence of the Coulomb barrier, nuclei close to the proton drip-line generally do not exhibit a pronounced proton skin, except for very light elements. Since in light nuclei the multipole response is generally less collective, all these effects seem to preclude the formation of the pygmy dipole states in nuclei close to the proton drip-line. Nevertheless, recent analyses have shown that proton pygmy dipole states can develop in light and medium-mass proton-rich nuclei [2].

In figure 1 the RQRPA dipole strength distributions in the $N = 20$ isotones ^{40}Ca, ^{42}Ti, ^{44}Cr and ^{46}Fe are shown, calculated with the fully consistent relativistic Hartree-Bogoliubov + QRPA model using the DD-ME2 plus Gogny D1S effective interactions

[2]. The strength distributions are dominated by the giant dipole resonance at ≈20 MeV excitation energy. With the increase in the number of protons, low-lying dipole strength appears in the region below the GDR and, for ^{44}Cr and ^{46}Fe, a pronounced low-energy peak is found at ≈10 MeV excitation energy. In the lower panel of figure 1 we plot the proton and neutron transition densities for the peaks at 9.98 MeV in ^{44}Cr and 9.33MeV in ^{46}Fe and compare them with the transition densities of the GDR state at 18.82MeV in ^{46}Fe. Obviously the dynamics of the two low-energy peaks is very different from that of the isovector GDR: the proton and neutron transition densities are in phase in the nuclear interior and there is almost no contribution from the neutrons in the surface region. As in the case of the PDR in neutron-rich nuclei, obviously the low-lying state does not belong to statistical E1 excitations sitting on the tail of the GDR, but could indeed represent a fundamental mode of excitation: the proton electric pygmy dipole resonance (PPDR).

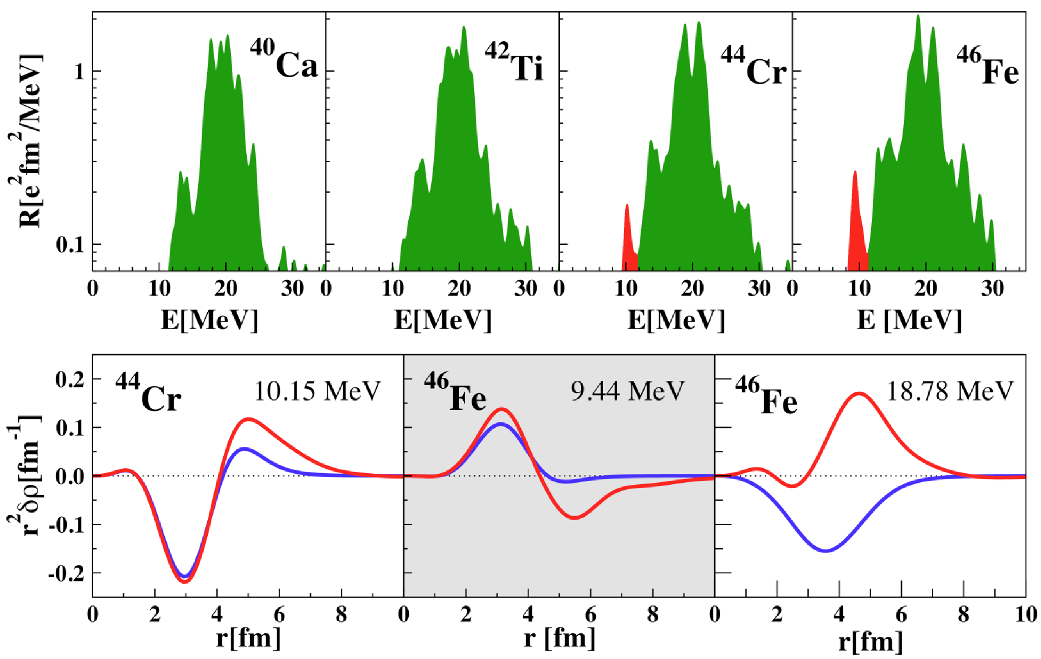

FIGURE1. The calculated isovector dipole strength distributions in the N = 20 isotones (upper panel). The proton and neutron transition densities for the low-lying states in ^{44}Cr and ^{46}Fe and for the IV GDR state in ^{46}Fe are shown in the lower panel.

Another example where a pronounced proton PDR can occur are the proton-rich isotopes of Ar. In the left panel of figure 2 we display the RHB + RQRPA electric dipole strength distribution in ^{32}Ar. In addition to the rather fragmented GDR structure at ≈20 MeV, prominent proton PDR peaks are calculated below 10 MeV. These peaks form the pygmy structure and exhaust 5.7% of the TRK sum rule. The right panel shows the mass dependence of the centroid energy of the pygmy peaks and the corresponding values of the integrated B(E1) strength below 10 MeV excitation energy. In contrast to the case of medium–heavy and heavy neutron-rich isotopes, in which both the PDR and GDR are lowered in energy with the increase in the neutron number, in proton-rich isotopes the mass dependence of the PDR excitation energy and B(E1) strength is opposite to that of the GDR. The proton PDR decreases in energy with the development of the proton excess. As nuclei become more proton rich, either by increasing the number of protons or decreasing the number of neutrons, due to the weaker binding of higher proton orbitals one expects more inert oscillations, i.e. lower excitation energies.

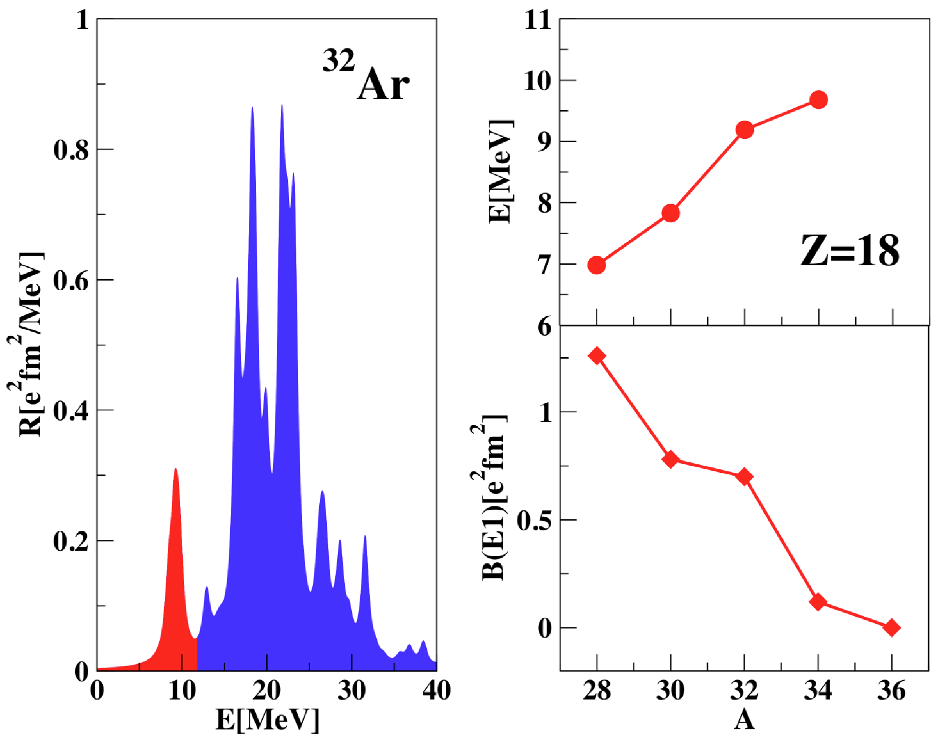

FIGURE 2. The isovector dipole strength distribution in ^{32}Ar (left panel). The mass dependence of the proton PDR centroid energy for Ar isotopes and the corresponding values of the integrated B(E1) strength below 12 MeV are shown in the right panel.

Isoscalar Dipole Compressional Mode

The isoscalar giant dipole resonance is a second order effect, built on 3h_, or higher configurations. It corresponds to a compression wave travelling back and forth through the nucleus along a definite direction. The isoscalar dipole strength distributions display a characteristic bimodal structure with two broad components: one in the low-energy region close to the isovector giant dipole resonance and the other at higher energy close to the electric octupole resonance. Theoretical analyses have shown that only the high-energy component represents compressional vibrations, whereas the broad structure in the low-energy region could correspond to vortical nuclear flow. Accurate data on compressional modes are becoming available also for lighter nuclei. In figure 3 we display the strength functions in ^{56}Fe and ^{58,60}Ni, for the isoscalar dipole operator. In all three nuclei the strength is strongly fragmented and distributed over a wide range of excitation energy between 10 and 40MeV, in agreement with experimental results. The strength is basically concentrated in two broad structures: one in the region 10 MeV < E < 20 MeV, and the high-energy component above 25 MeV. Only the high-energy portion of the calculated strength is sensitive to the nuclear matter compressibility of the effective interaction. The thick arrows denote the locations of the experimental centroid energies (m_1/m_0) in the low- and high-energy regions of the isoscalar strength. A good qualitative agreement is found between the calculated and experimental centroids at high energy, whereas in the low-energy region the theoretical centroids are systematically below the experimental values due to the presence of a pronounced low-energy mode.

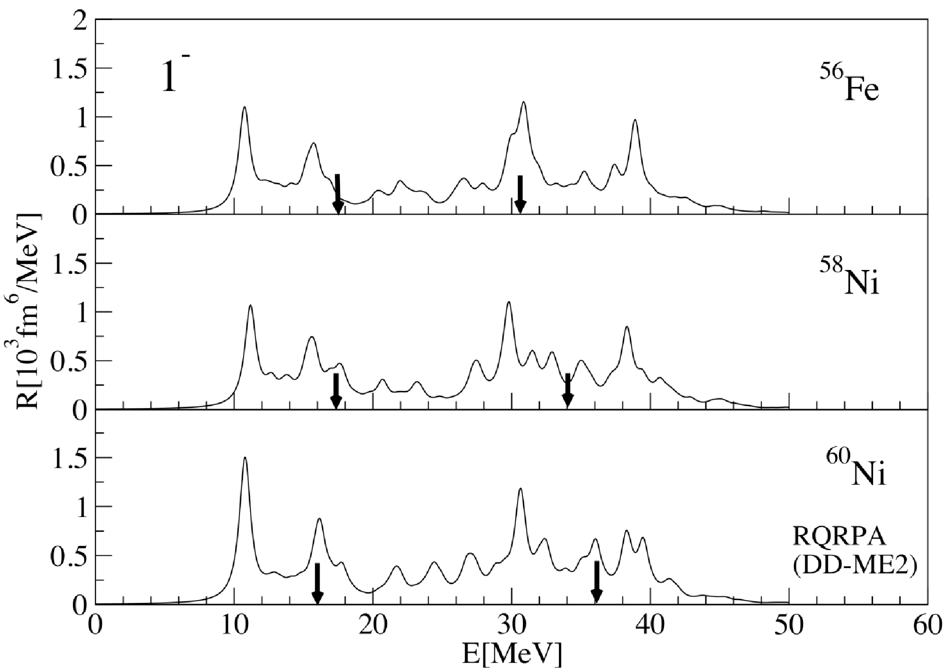

FIGURE 3. The isoscalar dipole transition strength in ^{56}Fe, ^{58}Ni and ^{60}Ni. The arrows denote the positions of the experimental centroid energies of the low- and high-energy components.

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Spectroscopy Of N~Z Nuclei: ^{100}Sn And Neighbours

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^{100}Sn is a unique case in the nuclear landscape, being doubly magic and the heaviest particle-stable N=Z nucleus. It is situated close to the proton drip line and thus the path of the rp-process runs close by. The beta-decay of ^{100}Sn is supposed to populate with a large Q-value essentially a single 1^+ state formed by a proton hole in the $g_{9/2}$ and a neutron particle in the $g_{7/2}$ shell. Thus it appears to be the best case to study the Gamow-Teller strength in nuclei. It has been produced [1,2] and studied [1,3,4] already in earlier experiments never identifying more than 14 events. With the improved intensities from the SIS at GSI an experiment with good statistics became feasible.

We have produced ^{100}Sn and nuclei in its neighbourhood by fragmentation of a 1 A·GeV beam of ^{124}Xe on a 4g/cm^2 Be target. The average intensity on target was more than 10^9 ions/s. Redundant measurements of energy loss, magnetic rigidity, and flight time in the second half of the fragment separator (FRS) allowed for a unique identification of the fragments as shown in Fig. 1 for the 15 days of data taking in a ^{100}Sn setting of the FRS. In addition to 259 nuclei of ^{100}Sn we identified for the first time the nuclides ^{93}Ag, ^{95}Cd, ^{97}In and most probably ^{99}Sn. Although we see some events at the location of ^{103}Sb, its half life must be at least a factor of 4 shorter than the flight time through the FRS of 200 ns, in contrast to the literature [5].

The fragments were stopped in a stack of Si detectors. For the correlation of implantation position and time with subsequent decays we used three large area position sensitive Si strip detectors (DSSD'S) with a total of 7200 pixels. Ten 1mm thick Si detectors in front and ten behind this implantation zone served as calorimeters to measure the β-spectrum and to determine its endpoint.

The implantation detector was surrounded by the 105 Ge detectors of the RISING array to observe isomeric decays as well as the γ-deexcitation following β-decays. A number of isomeric states was observed. As an example Fig. 2 shows a delayed γ-spectrum for ^{102}Sn, where we found a new isomeric γ-ray that we attribute to the 6^+-4^+ transition because it is coincident to the other two lines and shows a half-life consistent with that of the other two of 367(11)ns.

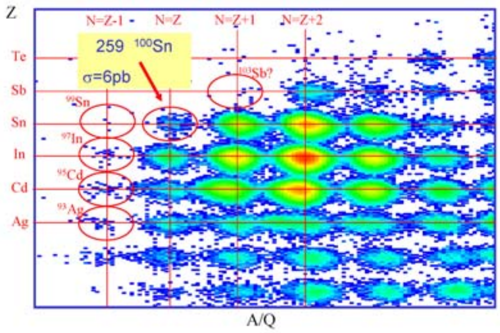

FIGURE 1. Nuclides identified in the FRS during the 15 days irradiation in the setting for ^{100}Sn.

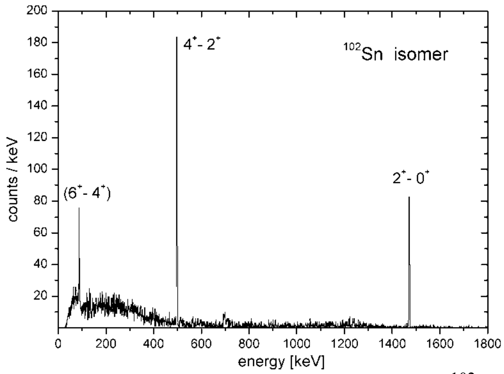

FIGURE 2. Delayed γ-spectrum for ^{102}Sn events. The low energy transition was hitherto unknown and could be interpreted as the 6^+- 4^+ transition.

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The β-decay of the implanted nuclei could be measured by observing an energy deposition in the same or in a neighbouring pixel of the DSSD's after the implantation. The sum of the energy depositions in an uninterrupted track in the Si-detectors gave the β-energy. The time correlation then yielded the decay curve. In Table 1 we list the preliminary results for the half-lives of extremely neutron deficient nuclei in the region of ^{100}Sn. In some cases the nuclei were not implanted and half-life limits are determined from their identification after the flight time of 200ns - or their much too low rate. Our results are considerably more precise than the literature values from GSI [3], MSU [4] and GANIL [6], if available. For the N=Z-1 nuclei even the candidate for prompt proton emission ^{97}In decays with a half-life compatible with the expectation for a pure Fermi- plus Gamow-Teller β-decay between mirror nuclei. Proton emission is certainly not the predominant decay mode.

We could for the first time measure a γ-spectrum following the β-decay of ^{100}Sn with five discrete lines. This spectrum supports the theoretical prediction that the β-decay of ^{100}Sn predominantly populates a single 1^+ state in ^{100}In. With this assumption we could fit the observed β-spectrum and extract a preliminary value for the endpoint energy of 3.29(20)MeV. With this endpoint and the half-life we calculate a value log(ft)=2.62(+0.13/-0.18). This is indeed the smallest value among all known β-decays.

For the Gamow-Teller (GT) strength we thus deduce a preliminary value of 9.1(+4.8/-2.3). This value has to be compared with the value 17.78 from the extreme single particle model, assuming that in ^{100}Sn the $g_{9/2}$ shell for the protons is completely filled and the spin-orbit partner $g_{7/2}$ for the neutrons is completely empty. Thus a 'superallowed' GT transition is possible to the $(\pi g_{9/2}^{-1} \otimes \nu g_{7/2})1^+$ state in ^{100}In. The reduction of the experimental value by about a factor of two reflects already the known quenching of the GT strength due to the short range correlations and leaves little room for reduction due to the truncation of the shell model space and long range correlations. It therefore appears that the structure of the ^{100}Sn ground state and the ^{100}In 1^+ state is extraordinarily well described by the simple shell model approach.

TABLE 1. Preliminary half-life values compared with values from the literature.

T_z=(N-Z)/2	Nuclide	$T_{1/2}$	Literature
-1/2	^{93}Ag	>200*ns*	-
-1/2	^{95}Cd	73(+53/-28)*ms*	-
-1/2	^{97}In	26(+47/-10)*ms*	-
-1/2	^{99}Sn	>200*ns*	-
0	^{96}Cd	0.99(13)*s*	1.03(+0.24/-0.21)*s*[4]
0	^{98}In	32(6)*ms*	32(+32/-11)*ms*[3] 47(13)*ms*[4]
0	^{98}In^{m}	0.86(21)*s*	1.2(+1.2/-0.4)*s*[3] 0.66(40)*s*[4]
0	^{100}Sn	1.16(20)*s*	0.94(+0.54/-0.27)*s*[3] 0.55(+0.70/-0.31)*s*[4]
1/2	^{101}Sn	2.10(10)*s*	1.7(3)*s* [5]
1/2	^{103}Sb	<50*ns*	>1500*ns* [6]

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Neutron Single Particle Energies in the ^{100}Sn region

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INTRODUCTION

The region around the double shell closure at ^{100}Sn is well known as a testing ground for the nuclear shell model. Recent work in this region has focused, to a large extent, on measuring the lifetime of some of the lowest lying excited states in a few selected isotopes. Beams produced by the ISOL as well as the fragmentation technique have been used and give similar results for sub-barrier as well as relativistic Coulomb excitation[1,2,3,4]. In the even-even Sn isotopes the measurements rather unanimously indicate a larger than expected reduced transition probability of the first 2^+ states as ^{100}Sn is approached. The lightest even-even Sn isotope for which such measurements have been performed as of now is ^{106}Sn (see fig. 1).

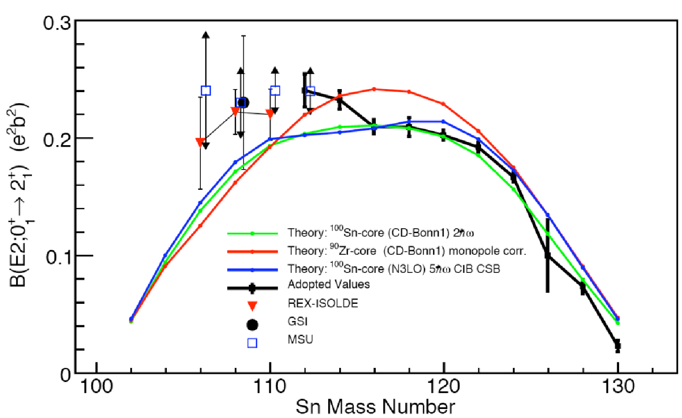

FIGURE 1. Recent experimentally deduced B(E2) values for the first 2^+ states in the even-even Sn istopes compared to results from large scale shell model calculations.

Large scale shell model calculations currently show a rather clear increase of the reduced transition probability at mid shell and a falling trend for isotopes closer to ^{100}Sn as well as ^{132}Sn. Theoretical treatises have e.g. attempted to increase the model space to allow for particle-hole excitations across the shell-gap but so far no general conclusive results have emerged to explain the experimentally observed trend [1]. On the other hand, some results from QRPA and RQRPA calculations [5] indicate a general trend with decreasing collectivity at mid-shell. Still those calculations have the complication that they either do not reproduce the measurements for the heavy even-even Sn isotopes well, or have till recently not been performed for the full shell between ^{132}Sn and ^{100}Sn.

Current Status of Neutron Single Particle Energies

As is well known, the two-body matrix elements and the single-particle energies can be considered as fundamental input parameters to a shell model calculation. An approach that uses a microscopic description of the nucleon-nucleon interaction and transforms it to an interaction in the medium is particularly attractive since it can connect fundamental physical processes to observable data. However, even if two-body matrix elements are calculated starting e.g. from the CD-Bonn or N3LO approach the single-particle energies are still best determined experimentally. In the ^{100}Sn region the ultimate goal would e.g. be to determine the energy of the neutron single-particle orbits in ^{101}Sn. Today only the spacing between the $g_{7/2}$ and $d_{5/2}$ neutron orbits is known in this nucleus, and there is some controversy surrounding the order of these two [6,7].

Even if determining the energy of the full set of neutron orbits above the N=50 gap appears to be out of reach experimentally for many years yet, it is still of considerable interest to investigate states in the odd Sn isotopes that are dominated by different single-particle orbits. Investigations of this kind have been performed in the past using transfer reactions on the stable even Sn isotopes. In particular, Cohen and coworkers have studied a set of odd Sn isotopes, between A=113 and A=125, using (d,p) and (d,t) reactions on even Sn isotopes, in normal kinematics and have from this deduced the filling of single particle-neutron orbits with neutron number [8].

Experimental information about the migration of the single-particle orbits for the light unstable Sn isotopes is still largely incomplete. Table 1 summarizes the current status of assumed single particle dominated states. A general comment is that it is often connected with significant experimental difficulty to feed many of the single-particle dominated states in beta-decay. Likewise the population of these states in fusion evaporation reactions do often not occur with high enough probability to allow for an experimental determination of the spin.

TABLE 1. Energy in keV of states dominated by single-particle neutron orbits above the N=50 gap [9]

Isotope/State	5/2+	7/2+	1/2+	3/2+	11/2-
111Sn	0	0	254	643	978
109Sn	0	135	545	925	1269
107Sn	0	151	-	1280	1667
105Sn	0	200	-	-	-
103Sn	0	168	-	-	-
101Sn	0?	172?	-	-	-

From the point of view of Q-values the (d,p) reaction seems to be most promising for initial studies at lower intensities. For this reaction the Q-value varies from ~5.5 MeV for ^{112}Sn to ~7.9 MeV for ^{102}Sn. The alternative (p,d) reaction that would produce the lighter exotic odd mass isotope has Q-values between ~ -8.5 MeV and -11.0 MeV for the same mass range. This corresponds to a common threshold energy of about 1000 MeV. The strongest populated states in (d,p) transfer on the stable isotopes are produced with maximum cross-sections of a few mb/sr but cross sectionsdrop significantly below this value for some cases.

Finally, an experimental challenge that needs to be addressed for these inverse kinematics reactions is a proper observation of the outgoing charged particles. For an inverse (d,p) reaction at 10 MeV/u in this mass region, an outgoing proton can have an energy up to ~ 70 MeV. Consequently, the angular range covered is important. The application of a separator in conjunction with charged particle and gamma-ray detection would also be advantageous.

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An Overview Of The SAGE Spectrometer

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The SAGE spectrometer combines the JUROGAM II germanium detector array with a highly segmented silicon detector and an electron transport system and allows simultaneous in-beam γ-ray and internal conversion electron measurements. SAGE can be coupled with the RITU gas-filled recoil separator [1] and the GREAT focal-plane spectrometer [2], as shown in Figure 1.

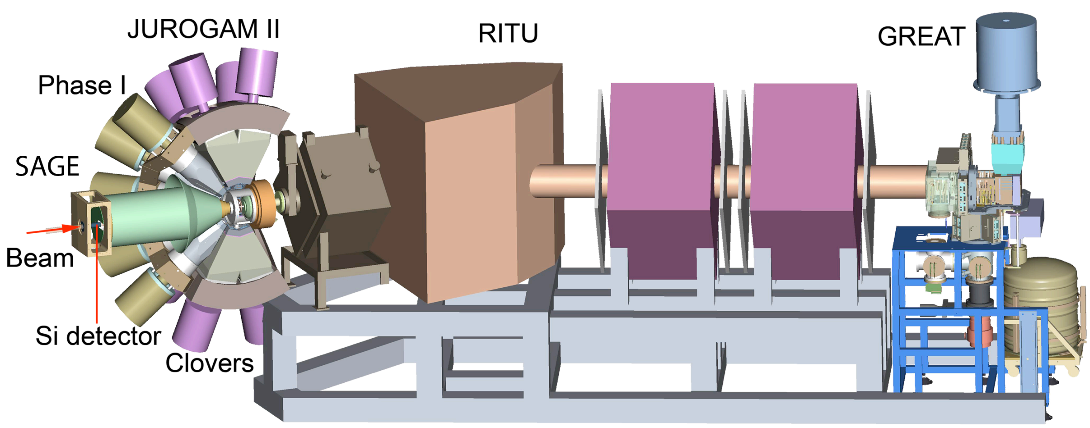

FIGURE 1. The SAGE spectrometer combined with RITU and GREAT. The germanium and silicon detectors can be seen.

JUROGAM II consists of 15 so-called Phase I Compton-suppressed germanium detectors [3,4] and 24 fourfold segmented Clover detectors [5]. The version of the array used as part of SAGE uses only 10 of the Phase I detectors and has a total γ-ray detection efficiency of 5.5% at 1332 keV.

The silicon detector is annular and segmented into 90 individual segments of varying size as shown in Figure 2. The detector is 1 mm thick and 50 mm in diameter. Even though the detector is highly segmented its total active area is approximately 96%.

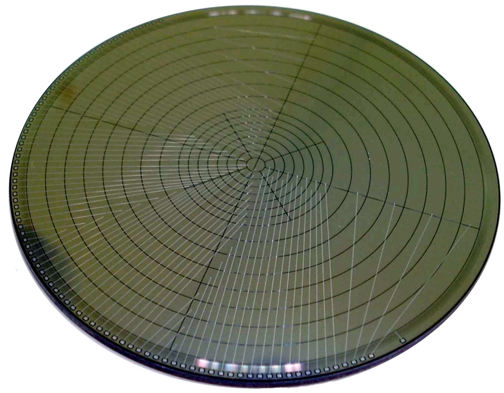

FIGURE 2. A photograph of the silicon detector used with SAGE. The individual segments are clearly visible with the signal tracks running across the surface of the detector connecting each pixel with one of the bonding pads situated on the outside part of the silicon.

The silicon detector is positioned 95.5 cm upstream of the target. This is required because the detector is sensitive to all types of radiation so if it was placed near the target region not only conversion electrons but also other charged particles, like delta electrons, protons and α particles would be detected, creating a significant background. A solenoid coil system is used to transport the conversion electrons towards the silicon detector. The maximum magnetic field produced on the solenoid axis is 0.8 T downstream of the target with the field having an average value of 0.6 T upstream of the target. Magnetic shielding is used to reduce the effect of the magnetic field on the photomultiplier tubes of JUROGAM II as explained in [6].

The electron transmission efficiency of SAGE is approximately 7% between 200 keV and 400 keV. At higher energies the efficiency gradually decreases and if the detection efficiency of the detector is taken into account it drops to about 3% at 600 keV. At lower energies the efficiency drops rapidly as most of the electrons are reflected by the electromagnetic fields.

A near collinear geometry between the beam and solenoid axes was adopted in the design. This helps to reduce Doppler broadening and additionally decrease the flux of delta electrons reaching the detector. Delta electrons are low energy electrons produced during the collisions of beam and target particles and are emitted primarily at forward angles [7,8].

To further reduce the delta electron background a high-voltage barrier is positioned in the region between the target and the silicon detector. Voltages of up to -50 kV can be applied to the high-voltage barrier.

SAGE uses the triggerless Total Data Readout (TDR) method [9]. In this system no common hardware trigger is applied to start the data collection but all the channels run independently and are associated in software to reconstruct the events. This virtually eliminates the dead time issues arising when a common hardware trigger is used and when wide time gates are applied at the electronics employed for the focal plane detectors. Lyrtech 16-channel VHS-ADC cards are used to provide the 196 channels of digital electronics required, 90 for the silicon and 106 for the germanium detectors.

In the ADC cards the outputs of the preamplifiers are directly digitised and then processed using the Moving Window Deconvolution method [10,11].

SAGE has been successfully commissioned in the beginning of 2010 in the Accelerator Laboratory of the University of Jyväskylä. The commissioning runs showed that the spectrometer works within the design criteria but further work was required in order to optimise the behaviour of the silicon detector.

The optimisation work took place in the University of Liverpool and resulted in significant improvements to the intrinsic resolution, stability and noise characteristics of the detector.

As proof of principle γ-ray and conversion electron spectra obtained using a ^{133}Ba source are presented in Figure 3 [12]. These spectra were obtained during the commissioning runs, before any optimisation work took place.

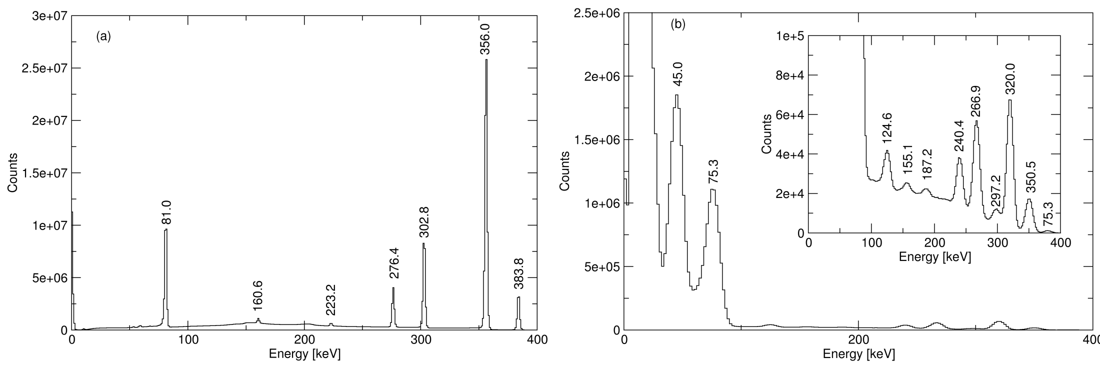

FIGURE 3. Total γ-ray (a) and conversion electron (b) spectra obtained with the SAGE spectrometer using a ^{133}Ba source. The labels over the peaks denote transition energies in keV. The inset in the conversion electron spectrum shows the said spectrum on a different scale.

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Fundamental research using the high intensity proton beams of MYRRHA at SCK•CEN

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Since 1995, SCK•CEN has been studying the coupling of a proton accelerator, a liquid PbBi spallation target and a PbBi-cooled sub-critical fast reactor core. The project, since 1998 named MYRRHA, has evolved to a larger installation, able to work in subcritical mode (as an Accelerator Driven System) and in critical mode. In March 2010, the Belgian federal government has committed itself to financing 40% of the total investment for MYRRHA. The difference needs to be financed by an international consortium that has to be set up in the coming years. MYRRHA is foreseen to be fully operational by 2024.

Apart from the experimental and irradiation possibilities in the subcritical reactor, the MYRRHA proton accelerator on its own can be used as a supply of proton beams for a number of experiments. In order to explore new research opportunities offered by the accelerator, a pre-study was carried out within the framework of the "Belgian Research Initiative on eXotic nuclei" (BriX) network of the Interuniversity Attraction Poles Programme of the Belgian State. This study was investigating unique possibilities for fundamental research using high-intensity proton beams with a fraction of the full 600-MeV proton beam during ADS operation (up to 200 μA). An interesting approach for fundamental research is the installation of an Isotope Separator On-Line (ISOL@MYRRHA) facility with a ruggedized target-ion source system, which is able to provide intense low-energy Radioactive Ion Beams (RIBs) for experiments requiring very long beam times (up to several months).

Because of the wide spectrum of different scientific programs using RIBs, the demand for beam time is extra-ordinary resulting in typical beam-time periods of one to two weeks per experiment. On the other hand, going more and more exotic is a driving incentive of several research programs. Thus even vigorous efforts to improve beam intensity and purity, and detection efficiency and sensitivity will not substantially decrease the demand of beam time. This limitation prohibits potentially very interesting programs, involving experiments which

- need very high statistics;
- need many time-consuming systematic measurements;
- hunt for very rare events;
- have an inherent limited detection efficiency.

These particular experimental programs can be addressed at ISOL@MYRRHA, given the availability of extended beam times with high intensity and given the high reliability of the MYRRHA accelerator.

Measurements with high-intensity beams and long/regular beam times are an important source of information for quasi all fields in science making use of RIBs, ranging from fundamental-interaction measurements with extremely high precision over systematic measurements for condensed-matter physics and production of medical radio-isotopes.

The figure below shows an overview of typical RIB research over different fields. Examples of ISOL@MYRRHA opportunities are indicated in yellow font.

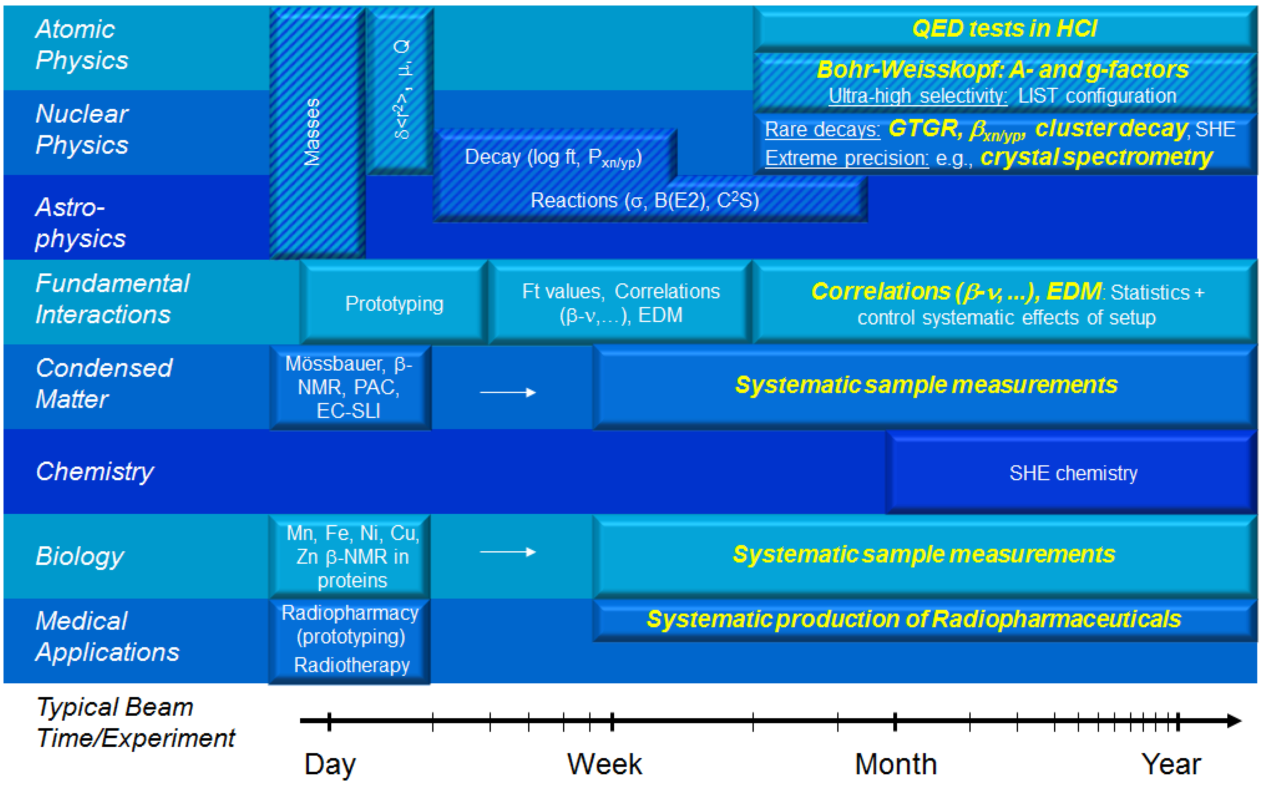

Figure 1: Illustration of the possible RIB research by exploiting the availability of long beam times at ISOL@MYRRHA. In yellow font are typical examples of experiments which can be addressed at ISOL@MYRRHA. The horizontal limits of each box are representative of the typical beam time per experiment.

These specific physics cases were included in the feasibility report, which was published on the ISOL@MYRRHA website http://isolmyrrha.sckcen.be. The report has been submitted for consideration to the different working groups of the NuPECC Long Range Plan 2010. As a result, the Technical Design Study for intense radioactive ion beams at ISOL@MYRRHA was included on the list of NuPECC recommendations for future facilities.

MYRRHA is foreseen to be in full operation by 2024 and it will be operated in the first years as an ADS. In a second phase, when the MYRRHA reactor will run as a stand-alone critical reactor, the full proton-beam intensity might be used for ISOL@MYRRHA or other applications. The detailed technical design study for ISOL@MYRRHA is planned for 2012-2015. The commissioning of the facility will begin in 2021.

Selective sensitivity of proton scattering to densities on the nuclear surface

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Abstract

Microscopic descriptions of nucleon scattering from nuclei depend on the matter distribution of their neutron and proton constituents. Additionally, the different behaviour of density-dependent effective interactions in the *pp* and *pn* channels offer a selective mechanism by which proton probes couple to proton and neutron distributions in the nucleus. Recent formal studies of the optical model potential have shown that intrinsic medium effects, i.e. nuclear mean fields and Pauli blocking, appear in the optical potential in the form of a the gradient of the density-dependent effective interaction. These properties set limits to the sensitivity of proton scattering to the matter distribution of proton-rich nuclei.

Microscopic optical model potentials (OMP) for nucleon-nucleus (NA) scattering usually take the form of a convolution of a two-body effective interaction with the target ground-state mixed density. Within the Brueckner-Bethe-Goldstone (BBG) g-matrix approach for the effective interaction, nuclear medium effects are made explicit by means volume integrals throughout the bulk of the nucleus. Even though these models account for a broad body of scattering data [1, 2], there remain puzzling limitations –specially at nucleon energies below 100 MeV– which require further investigation. This is particularly relevant considering the construction of the EURISOL and similar facilities, where radioactive isotope beams could be set to collide hydrogen targets. Thus, when the energy of these unstable beams reach 70A MeV, inverse kinematics tells us that the physics behind the collision is the same as that of NA scattering at 70 MeV, typical nucleon energies used in the seventies. Therefore, current trends involving radioactive beams provide stimulating grounds to revisit the challenges behind the interaction of nucleons with nuclei, to assess their structure as well as learn about the *in-medium* effective interaction itself.

The interaction between a nucleon with energy E and a composite nucleus can be described by means of an OMP, a one-body operator which in momentum space takes the general form

$$U(\boldsymbol{k}',\boldsymbol{k};E) = \int d\boldsymbol{p}'\, d\boldsymbol{p}\, \langle \boldsymbol{k}'\boldsymbol{p}' \mid \hat{T}(E) \mid \boldsymbol{k}\,\boldsymbol{p} \rangle_{\mathcal{A}}\, \hat{\rho}(\boldsymbol{p}',\boldsymbol{p}) \; . \qquad (1)$$

Here $\hat{T}$ is a two-body effective interaction which, in general, contains information about the discrete spectrum of the many-body system. The one-body mixed density in momentum space, $\hat{\rho}(\boldsymbol{p}',\boldsymbol{p})$, describes the ground-state of the target. A complete evaluation of the optical potential considering all these elements is far from feasible even with nowadays computing capabilities. Part of the difficulties can be avoided by treating separately the ground-state of the target and the NN effective interaction. A remaining difficulty is the account for the Fermi motion of the target nucleons implied by the $d\boldsymbol{p}\,d\boldsymbol{p}'$ integration.

As demonstrated in Ref. [3], intrinsic medium contributions can be disentangled from their free-space counterpart in $\hat{T}$ following a general analysis of its momentum-space structure. The matrix elements of $\hat{T}$ in coordinate space are denoted with $\langle \boldsymbol{r}'\boldsymbol{s}' \mid \hat{T} \mid \boldsymbol{r}\ \boldsymbol{s}\rangle$, where the 'prior' coordinates of each particle are denoted by $\boldsymbol{r}$ and $\boldsymbol{s}$, respectively, while $\boldsymbol{r}'$ and $\boldsymbol{s}'$ refer to the 'post' coordinates of the same particles. These vectors define the *mean coordinate* $\boldsymbol{z}$, given by the simple average of the prior and post coordinates:

$$\boldsymbol{z} = \tfrac{1}{4}(\boldsymbol{r}+\boldsymbol{s}+\boldsymbol{r}'+\boldsymbol{s}')$$

In momentum space, the $\hat{T}$-matrix elements are given by $\langle \boldsymbol{k}'\boldsymbol{p}' \mid \hat{T} \mid \boldsymbol{k}\ \boldsymbol{p}\rangle$, where $\boldsymbol{k}$ ($\boldsymbol{k}'$) and $\boldsymbol{p}$ ($\boldsymbol{p}'$) represent the projectile and struck-nucleon momenta prior (post) interaction, respectively. The two representations of the $\hat{T}$-matrix are related by means of Fourier transforms, which according to Ref. [3] can be expressed as

$$\langle \boldsymbol{k}'\boldsymbol{p}' \mid \hat{T} \mid \boldsymbol{k}\ \boldsymbol{p}\rangle = \int \frac{d\boldsymbol{z}}{(2\pi)^3}\, e^{i\boldsymbol{z}\cdot\boldsymbol{K}_\perp} g_{\boldsymbol{z}}(\boldsymbol{K}_\parallel; (\boldsymbol{k}'-\boldsymbol{p}')/2, (\boldsymbol{k}-\boldsymbol{p})/2)\ . \tag{2}$$

Clearly the *reduced interaction*, $g_{\boldsymbol{z}}$, is evaluated at the mean coordinate $\boldsymbol{z}$ and pair momentum $\boldsymbol{K}_\parallel = (\boldsymbol{k}+\boldsymbol{p}+\boldsymbol{k}'+\boldsymbol{p}')/2$. Here $\boldsymbol{K}_\perp = \boldsymbol{k}+\boldsymbol{p}-\boldsymbol{k}'-\boldsymbol{p}'$. Assuming that g_z depends only on the magnitude of the mean coordinate, $|\boldsymbol{z}| = z$, and that far away from the center of the nucleus g_z takes free-space t matrix form ($g_\infty = t$), then it can be shown [3] that

$$\langle \boldsymbol{k}'\boldsymbol{p}' \mid \hat{T} \mid \boldsymbol{k}\ \boldsymbol{p}\rangle = \delta(\boldsymbol{K}_\perp) g_\infty - \frac{1}{2\pi^2}\int_0^\infty z^3\, dz\, \frac{j_1(z\,K_\perp)}{z\,K_\perp}\,\frac{\partial g_z}{\partial z}\ . \tag{3}$$

What is curious about this result is that it disentangles very clearly the free-space contribution, the g_∞ term, from its medium-dependent counterpart. The medium dependence appears as the gradient of the reduced interaction, whereas the medium-independent contribution exhibits momentum conservation, as dictated by $\delta(\boldsymbol{K}_\perp)$.

After replacing the above expression for $\hat{T}$ into Eq. (1) for U we obtain the *unabridged* OMP, $U(\boldsymbol{k}',\boldsymbol{k};E) \equiv U_0(\boldsymbol{k}',\boldsymbol{k};E) + U_1(\boldsymbol{k}',\boldsymbol{k};E)$, with U_0 the full-folding optical potential based on the free t-matrix. The medium-dependent contribution U_1, in turn, is given by

$$U_1(\boldsymbol{k}',\boldsymbol{k};E) = \frac{1}{2\pi^2}\int d\boldsymbol{p}\, d\boldsymbol{p}'\hat{\rho}(\boldsymbol{p}',\boldsymbol{p})\int_0^\infty z^3 dz \frac{j_1(zK_\perp)}{zK_\perp}\left(-\frac{\partial g_z}{\partial z}\right)\ . \tag{4}$$

A realization of the optical potential is made if we model the reduced interaction g_z by means of the nuclear matter g matrix in the BBG theory. Here at each coordinate z with nuclear density $\rho(z)$, g_z is represented by the antisymmetized g matrix. As shown in Ref. [3], this model reproduces the *in-medium* folding model introduced by Arellano, Brieva and Love [4] if one assumes a Slater approximation for the mixed density. However, the above expression is general enough to allow the use of the full (off-shell) mixed density.

The medium-dependent term U_1 can be conveniently expressed as $U_1 = \int_0^\infty u(z)\, dz$, with u representing a potential density. Thus, by examining the behavior of $u(z)$ for selected matrix elements of U we can assess the importance of the various contributions to the OMP. To illustrate this feature we consider protons of mass m and energy $E = 40$ MeV colliding a given nucleus. We examine the forward on-shell ($\boldsymbol{k} = \boldsymbol{k}'$; $k = \sqrt{2mE}$) matrix elements of U. Here the targets are ^{40}Ca, ^{48}Ca, ^{48}Ni and ^{56}Ni. In the left panel of Fig. (1) we plot the real (solid curves) and imaginary (dashed curves) components of $u(z)$ as function of the radial distance z. This figure evidences quite neatly that intrinsic medium effects are confined to the region $4-6$ fm, with clear dominance of the coupling of the

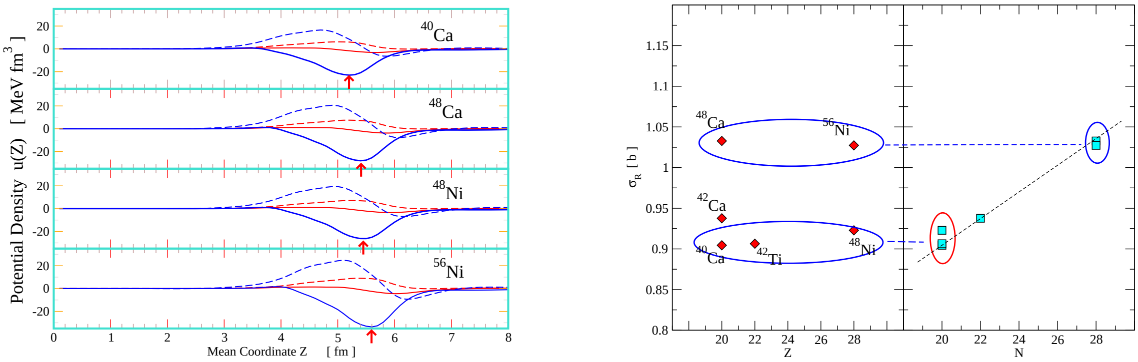

Figure 1: Left: Potential density $u(z)$ for selected targets as function of the radius z ($E = 40$ MeV). Right: Reaction cross sections as function of the proton (Z) and neutron (N) number of the target.

incoming proton to the target neutrons (blue curves) over that to protons (red curves). The strength of these contributions is dictated by the area under the curves. Hence, judging from these figures, the main sensitivity to intrinsic medium effects should come mainly from neutron densities. The sensitivity to proton densities come mainly from U_0, whose strength scales with the proton number Z.

To illustrate the above remarks, we have calculated OMP considering Hartree-Fock-Bogoliubov densities based on the D1S Gogny interaction [6]. The bare two-nucleon interaction is the Argonne v_{18} potential, from which off-shell g matrices are calculated at various densities. These matrices are then folded, without localization whatsoever, to obtain non-local optical potentials which are then used to evaluate scattering observables. In the right frame of Fig. 1 we show the reaction cross section σ_R as functions of the proton and neutron numbers. Clearly σ_R exhibits a uniform sensitivity with respect to the neutron number N, in contrast with a weak sensitivity to variations in Z.

In summary, based on formal properties implicit in the structure of the OMP, we are able to gauge –to some extent– the degree of sensitivity of NA scattering observables to proton and neutron distributions of the target. These features are energy- as well as channel-dependent. An analysis of reaction cross sections for Ca and Ni isotopes shows stronger sensitivity to the neutron number. Although not discussed here, this feature is generally true for medium energy proton scattering observables, being more sensitive to the details of the neutron than the proton density.

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The Farcos project

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INTRODUCTION

The study of correlations between particles emitted during a collision between two heavy ions provides information about the space-time properties and quantitative understanding of reaction dynamics. This in turn depends on the details of the nuclear interaction and the equation of state (EoS) of nuclear matter. The Eurisol facility will allow studying these problems with higher sensitivity to the isospin degree of freedom thanks to the capability of accelerating highly N/Z-asymmetric beams at intermediate energies. In this respect, detectors capable of detecting all reaction products on an event-by-event basis and measure their reciprocal correlations are mandatory [1,2]. Different observables need to be measured over a large solid angle coverage with high energy and angular resolution. The solid angle coverage guarantees a characterization of the collision event. The energy and angle resolution are important in order to measure the momentum vectors and kinetic energies of the detected particles and explore their correlations. Recent implementation of pulse-shape identification techniques promise to provide unique capabilities [3-5] that will allow studying nuclear dynamics even at low energies at facilities such as Spiral2 and Spes [6].

In this contribution we present the physics cases for the construction of a detector array meant to measure correlations between particles and fragments in coincidence with large solid angle arrays. The name of the project is Farcos, standing for Femtoscopy ARray for Correlations and Spectroscopy. It is expected to address topics in “femtoscopy” via intensity interferometry and spectroscopy with radioactive beams.

DYNAMICS AND TWO-PARTICLE CORRELATIONS

Heavy-ion collisions allow one to explore the properties of nuclear matter under extreme conditions. A clear understanding of the dynamics of heavy-ion collisions is required. Particles are emitted at different stages that are difficult to isolate. It is therefore important to disentangle particle and fragment emitting sources. Where and when are fragments produced? Understanding dynamics in heavy-ion collisions requires tracing-back particle and fragment emitting sources. Such challenge can be accomplished by using two-particle correlation function known to be sensitive to the space- time features of nuclear reaction mechanisms [7]. The shape of correlation functions probe important transport properties of nuclear matter and the density dependence of symmetry energy in the equation of state.

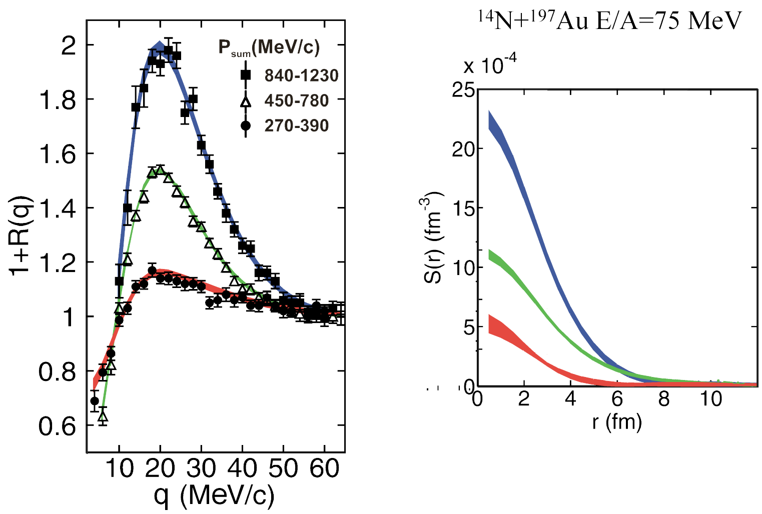


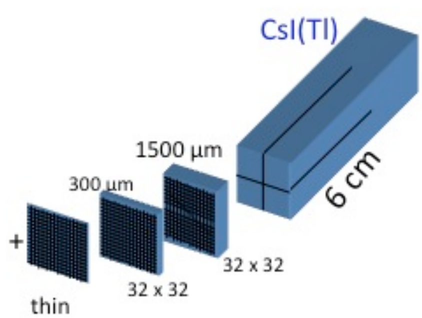
FIGURE 1. Left panel: Two-proton correlation functions measured in Ne+Au collisions at E/A=75 MeV. See Ref. [8] for details. Right panel: emitting source functions extracted by imaging.

Two-proton correlation functions, $1+R(q)$, is defined as the ratio between the two-proton coincidence and uncorrelated spectra, $Y_{coin}(q)$ and $Y_{unco}(q)$, respectively. q is the relative momentum between two protons in Y_{coin} and Y_{unco} spectra. Uncorrelated proton pairs are usually constructed by coupling protons from different events. Fig. 1 shows such a correlation function in the case of N+Au collisions at E/A=75 MeV [8]. The peak at q=20 MeV/c is due to the nuclear interaction between the two protons and determines the spatial extent of the emitting source, $S(r)$, defined as the probability of emitting two protons with a relative distance r recorded at the time when the second proton is emitted. Imaging techniques [8 and Refs. therein] have been successfully used to extract the emitting source function from the measured correlation function. This images represent sort of "space-time pictures" of the emission [7-9]. The right panel of Fig. 1 shows the source functions, S(r), extracted from the correlations represented on the left panel. The source function not only provides information about the size/volume of the emitting source, but also allows us to estimate the relative contributions between fast dynamical pre-equilibrium sources and slowly evaporating sources characterizing the later thermalized stages of the reaction [8]. This sensitivity of R(q) to the space-time features of the reaction becomes very useful as tool to explore transport properties of nuclear matter. Indeed microscopic transport models have shown sensitivity to the nucleon-nucleon (NN) collision cross section in the nuclear medium [9] and to the density dependence of the symmetry energy [10]. Such research program requires also the difficult task of measuring p-p, n-p and n-n correlation functions in the same experiment [10]. Coupling charged particle and neutron detectors is also a priority in this respect.

Extending these measurements to fragment-fragment correlation functions allows one to extract space-time information about the stage of heavy-ion collisions when nuclear matter at low density breaks-up into complex fragments possibly indicating the occurrence of a phase-transition [11] and carrying important signatures of the effects of the symmetry energy and its density dependence. The possibility of measuring fragment correlation functions is further enriched by the introduction of powerful pulse-shape capabilities that would allow identifying fragments at low kinetic energies [3,4]. These fragments can be identified only by a detailed study of the shape of the signal induced by their passage through the detector [2-4]. Another important application of intensity interferometry is represented by the study of correlations between unlike light particles, such as proton-alpha, deuteron-alpha, deuteron-^{3}He, etc. [7]. An extended study of all these correlation functions would allow a reconstruction of several emitting sources in the same reaction. These light particle correlations are usually characterized by the presence of several resonances and a precise measurement of their position and shape is mandatory in order to probe their emitting sources. High angular resolution is thus a key feature of an array meant to perform correlation measurements between light particles.

CORRELATION FUNCTIONS AS A SPECTROSCOPIC TOOL

During the dynamical evolution of the system several loosely bound nuclear species are produced for a very short time and decay. Their unstable states can be identified and explored by detecting all the products of their decay in coincidence. A typical example of this type of analyses has been shown in Ref. [12] where p-^{7}Be correlation functions were measured in order to study unbound states in ^{8}B nuclei and probe their spins [12]. In a more recent experiment, three- and four-particle correlation functions have been used to study highly lying unbound states in ^{12}C and ^{10}C nuclei [13]. Three-alpha particle correlation functions can be used to study the decay of internal states in ^{12}C. While two-alpha-two-proton correlation functions probe ^{10}C decay. In the case of ^{12}C these correlation studies allow one to disentangle the direct decay into three alpha particles from the sequential decay into ^{8}Be+alpha with a subsequent decay of ^{8}Be into two alphas. In the case of ^{10}C studies one can identify the decay sequence of unbound states that produce intermediate states in ^{6}Be, ^{8}Be and ^{9}B [13]. The techniques reported on Ref. [13] show that one single heavy-ion collision can provide access to some spectroscopic information of exotic unbound states. The availability of very proton-rich beams at Eurisol can enhance the possibility of producing even more exotic resonances and study their decay properties.



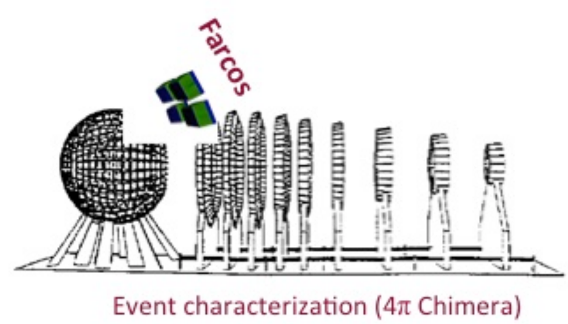


FIGURE 2. Left panel: Schematic view of the expected design of Farcos telescopes. Right panel: Coupling of the Farcos array to the Chimera detector at the LNS of Catania.

REQUIRED ARRAY FEATURES

Based on the physics cases outlined above, we plan to build an array of silicon strip and CsI(Tl) telescopes to be coupled to large detector arrays such as Chimera@LNS-Catania or Indra@GANIL. A minimum of about 15 telescopes is required in order to address a number of physics cases as outlined above. However a larger solid angle coverage would significantly increase the scientific reach of the project. The array will have a large geometric flexibility. Silicon strip detectors with thicknesses of 300 and 1500 μm (6.4 x 6.4 cm^2) will be followed by 6 cm –long CsI(Tl) crystals arranged in a square configuration 2 x 2 (each crystal will have a front face of 3.2 x 3.2 cm^2). This array will provide an angular resolution up to about 0.1^o at a distance of 1 m from the target. The left-end side of Fig. 2 shows a schematic view of the basic telescope. The geometry flexibility of the telescopes is expected to allow the use of an additional silicon strip detector aimed at lowering the identification threshold. Low thresholds will also be attained with pulse-shaping techniques [3-5]. Silicon nTD solutions are also under consideration to improve pulse-shaping capabilities. The required electronics will need to address the goal of obtaining high resolution, high dynamic ranges and high flexibility (programmability) in order to identify light and heavy fragments. Due to the large number of channels that will be employed in the array, an integrated electronics solution will be required. The right-end side of Fig. 2 shows a possible arrangement of the array inside the Chimera reaction chamber at the LNS of Catania. The use of the array in studying correlations between charged particles and neutrons is also envisioned and will require a specific study on the materials required in order to couple Farcos telescopes to neutron counters.

The high flexibility of the array will certainly allow applications at the Eurisol facility, especially when studying reactions induced by proton-rich beams. These beams will allow studying correlations between charged particles emitted by short-lived exotic nuclei abundantly produced close to the proton-drip line (two- and multi-proton emitters, etc.). Also, studying direct reactions induced by radioactive beams, such as (p,d), (d,p) etc. reactions, will be possible due to the envisioned high energy and angular resolution and to the geometric flexibility [14].

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Symmetries in proton-rich nuclei seen through ground-state properties

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Light proton-rich nuclei are valuable objects to investigate various symmetries in atomic nuclei. Recent investigations of nuclear ground-state properties using laser spectroscopy and Penning-trap mass spectrometry performed at ISOLDE/CERN addressed the symmetries in multiple ways: Magnetic moments of ^{21}Mg and ^{17}Ne allowed studying the isospin symmetry. Charge radii of both isotopic chains revealed a wealth of geometrical phenomena, from proton halos to alpha-clustering, when adding only a few neutrons. The mass of ^{35}K gave evidence for a breakdown of the isobaric multiplet mass equation, related also to the isospin symmetry. Finally, the precise mass of ^{22}Mg contributed to the determination of the V_{ud} element of the CKM matrix.

SYMMETRIES PROBED VIA GROUND-STATE PROPERTIES

The ground-state properties of atomic nuclei, such as mass, charge radius, spin and electromagnetic moments are extremely valuable to investigate the nuclear structure when going away from the valley of beta stability. Among others, they can be used to probe various symmetries present in nuclei: geometrical symmetries (i.e. shapes) and, relevant especially for proton-rich and Z=N nuclei: isospin (proton-neutron) symmetries, as well as fundamental symmetries (e.g. in superallowed decays).

The geometrical symmetries are revealed in quadrupole moments or changes in charge radii. The isospin symmetry can be probed with masses by using the Isobaric-Mass-Multiplet Equation (IMME) [1,2] which connects the binding energies of the analog states within a given isospin multiplet. One can use this equation to predict the position of analog states and attribute configurations to observed states, or conversely to test IMME by searching for terms beyond the quadratic term. Isospin symmetry can be also investigated via the magnetic moments of mirror nuclei by representing the moments in the isospin space [3,4]. If the average of the two moments is used, only the iso-scalar moment of the mirror pair remains, based on which it is possible to determine the so called "spin expectation value". This allows probing the isospin symmetry, comparing configurations of mirror nuclei, and testing terms which break isospin. Mass measurements, on the other hand, give also Q-beta values of the superallowed $0^+ \text{->} 0^+$ β-decays, which lead to the corrected comparative half-lives Ft [5]. These in turn can be used to test the conserved-vector-current (CVC) hypothesis and the unitarity of the CKM quark mixing matrix via the V_{ud} matrix element. Inversely, when assuming that the CKM matrix is unitary, tests of nuclear-structure corrections in the determination of Ft are possible [5].

EXPERIMENTAL TECHNIQUES

The main experimental methods devoted to studies of nuclear ground-state properties make use of atomic physics. They use Penning traps to measure atomic masses and laser spectroscopy to determine the nuclear electromagnetic properties.

The results discussed below were obtained at the ISOLDE facility at CERN [6]. Here, proton bunches of 1.4GeV energy impinge on thick targets to produce a large variety of radionuclides via spallation, fragmentation, and fission reactions. The produced atoms are then ionized, extracted and accelerated to 30-60keV and mass separated, before they reach the given experimental setup.

In the collinear laser spectroscopy (used at ISOLDE within the COLLAPS setup [7]) the ion beam is overlapped with a narrow-band cw laser which allows scanning across atomic resonances. The resulting precise measurements of hyperfine structures and isotope shifts give then access to the nuclear spin, magnetic and quadrupole moment, and differences in charge radii. The usual detection method is by fluorescence, but to optimize the signal to noise ratio, element- or isotope-specific methods are employed.

The other atomic method relies on Penning traps which give access to atomic masses of exotic nuclei, with ISOLTRAP [8] at ISOLDE being the pioneer in this field. Inside the trap, the ions are manipulated by rf fields which can purify isobaric, and even isomeric contamination. Finally, by determining the ion's cyclotron frequency, the atomic mass can be measured with up to (or even beyond) 10^{-8} relative precision.

RECENT RESULTS IN SYMMETRY STUDIES

The first example of symmetries accessible with proton-rich nuclei concerns geometrical symmetries seen in the charge radii and quadrupole moments. Using the COLLAPS setup, charge of Ne and Mg isotopes were recently investigated (Fig. 1). These reveal a wealth of phenomena. In the Ne chain one sees the onset of proton-halo formation in ^{17}Ne, the closed neutron shell in ^{18}Ne, clustering in $^{19\text{-}22}$Ne, and appearance of a new shell closure at N=14 [9]. For Mg isotopes, with two more protons than Ne, similar structures can be observed: clustering around ^{24}Mg, new shell closure N=14 or 16 and no closure at N=20 in the region of the island of inversion [10].

The isospin symmetry was tested at COLLAPS with the magnetic moment of ^{17}Ne and ^{21}Mg. In both cases the resulting isoscalar moments were compared to the extreme single-particle prediction and to the nuclear shell-model calculations (Fig 1). For ^{17}Ne-^{17}N, the determined isoscalar spin expectation value was within the empirical limit of unity given by the Schmidt values of the magnetic moments [11]. For ^{21}Mg-^{21}F it was significantly outside, but shell-model calculations taking into account isospin non-conserving effects were still in agreement with experimental results [12].

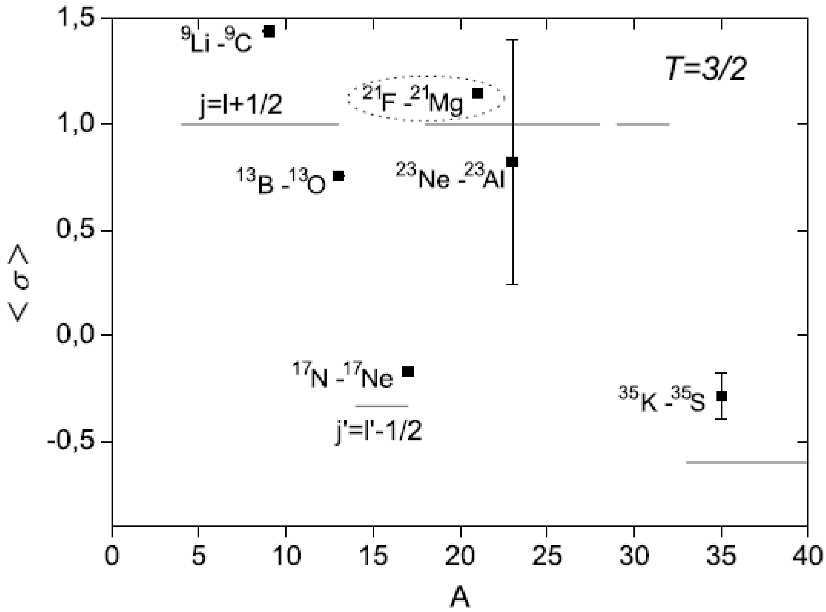

Fig. 1 Isoscalar moments for mirror pairs of the isospin 3/2 multiplet

The isospin symmetry has been also tested with mass measurements at ISOLTRAP. The measurement of ^{35}K gave evidence for a breakdown of the isobaric multiplet mass equation for the T = 3/2 isospin quartet. The non-zero cubic term in IMME showed the need of 2nd-order Coulomb effects, charge-dependent nucleon-nucleon interaction or many-body forces [13].

The last example was the mass of ^{22}Mg superallowed beta emitter, which led to the determination of the comparative half-life Ft, which agrees very well with other known cases [14]. ^{22}Mg belongs to superallowed beta emitters which require quite large nuclear-structure-dependent corrections and it is presently one of four best studied cases. Presently all measured cases are consistent with unitarity of the CKM matrix [15].

SUMMARY AND OUTLOOK

Ground-state properties on proton-rich nuclei are relevant (among others) for several symmetry questions, concerning isospin, shapes, or fundamental symmetries. The experimental studies in this area are lead by employing atomic physics methods, laser spectroscopy and Penning trap mass spectrometry, which give access to several properties at the same time (spins, radii, moments). Recent results from ISOLDE show how the symmetries were studied on relatively light systems, in Ne, Mg, and K chains.

In the future even more exotic proton-rich systems should be available, thanks to technical developments on the target and ion source side (more efficient ionization; new ISOL beams – B, C, O; new facilities) and due to increased sensitivity (thanks to bunched beams, ion-photon coincidence, new ion purifiers). This will give us access to ground-state properties of nuclei as ^{8}B, ^{9}C, ^{13}O, or ^{20}Mg.

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Shape coexistence in heavy nuclei

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A remarkable feature of the atomic nucleus is its ability to take on different mean field shapes for a small cost in energy. An excellent region for investigating such phenomena is in the neutron deficient nuclei around Z=82, such as ^{186}Pb where three different close-lying shape minima have been deduced on the basis of an alpha decay study [1]. There are many experimental avenues for investigating shape coexistence, and the problem has been attacked through many different spectroscopic techniques from alpha/beta spectroscopy to laser spectroscopy.

In-beam Spectroscopy

In terms of exploring shape coexistence at the very limits of stability, a highly successful technique over the past twenty years has been recoil-decay tagging where in-beam gamma rays are correlated with the alpha decay of exotic nuclei at the focal plane of a recoil separator. Very recently, it has been possible to identify excited states in the extremely exotic nucleus, ^{180}Pb using the RITU separator at the University of Jyvaskyla in conjunction with the JUROGAM array (see figure 1). This experiment represents the practical observation limit for such studies with a cross-section of only 10 nanobarns. The data are interpreted as showing that the prolate configuration in the light lead nuclei continues to move up on passing the neutron mid-shell. This is in good conformity with state-of-the-art mean field models [2].

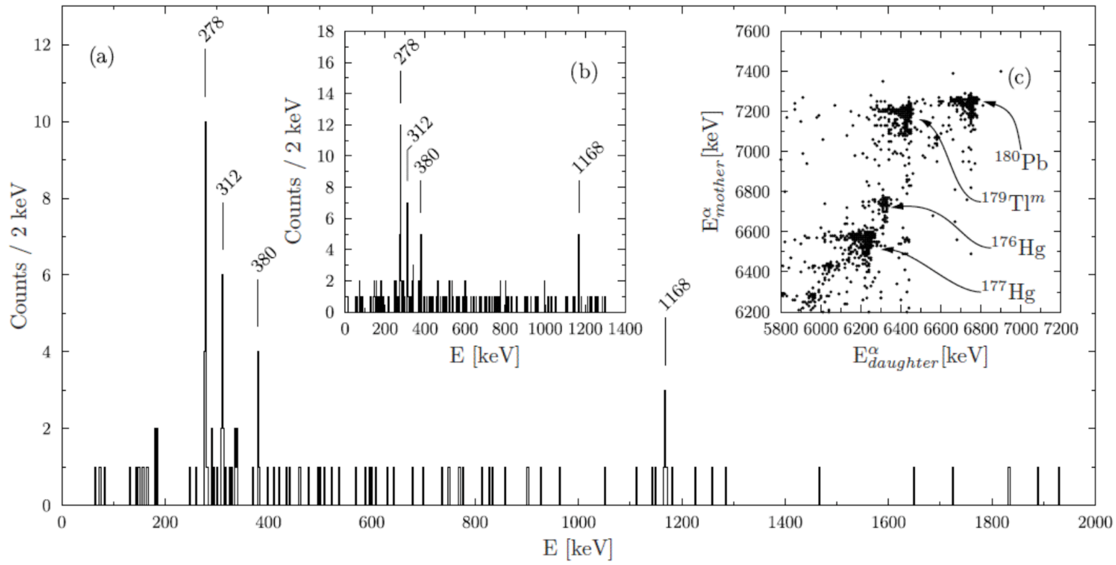

FIGURE 1. Spectrum of gamma-rays correlated with ^{180}Pb alpha decay at the focal plane of the RITU separator at University of Jyvaskyla. The inset shows the mother-daughter alpha decays recorded.

Coulomb Excitation with Radioactive Beams

In the last few years, the scope for investigating shape coexistence has been greatly expanded by the ability to carry out Coulomb excitation with radioactive beams. Coulomb excitation is an extremely useful technique for investigating shape coexistence as not only can it provide transition matrix elements but diagonal matrix elements can also be extracted which provide information on the sign of the spectroscopic quadrupole moment and, hence, the deformation.

The REX-ISOLDE facility, uniquely worldwide, is able to produce intense beams of proton-rich heavy nuclei using spallation reactions and re-accelerate these for Coulomb excitation studies. The first such heavy beams used were the light mercury isotopes, $^{182\text{-}188}$Hg, which are produced with high isobaric purity from a molten lead primary target. Latterly, the light radon nuclei were produced in isobarically pure form using a cooled transfer line and a ThC target, and, in the last year, neutron-deficient lead and polonium beams have also been produced. The apparatus used at REX-ISOLDE for Coulomb excitation comprises the MINIBALL array of 8 segmented germanium detectors in conjunction with a silicon CD detector for detection of scattered heavy ions. The present limitation of REX-ISOLDE to 3 MeV/u beams means that only the first excited state is strongly excited and the excitation of additional states is very low. Nevertheless, the experimental campaign has been very successful, and the analysis of the light mercury data is particularly advanced and close to submission for publication. In the future, it is planned to develop the technique further and obtain more sensitivity through alpha-tagged Coulomb excitation.

Complementary Measurements with Stable Beams

From the outset of the Coulomb excitation studies, it was clear that complementary measurements with stable beams could be of high value. In particular, plunger lifetime measurements have been carried out for the light mercury isotopes with the Cologne plunger and Gammasphere. These measurements can be used to deduce transition matrix elements in an independent way and, hence, constrain the Coulomb excitation measurements.

Shape coexistence is also commonly associated with prominent E0 transitions either 0+ -> 0+ transitions or E0 components of J-J transitions. Knowledge of these branches is important not only as an input to the Coulomb excitation analysis but also in its own right since E0 transitions are related to δr^2. The novel SAGE spectrometer at the University of Jyvaskyla has allowed conversion electrons to be detected in coincidence with gamma rays. It is also possible to tag individual reaction channels using the RITU recoil separator and SAGE spectrometer. Preliminary measurements of the light mercury and radon isotopes have been carried out with SAGE and this data is presently under analysis.

HIE-ISOLDE

The upgrade to HIE-ISOLDE will take place in two stages. The first stage where a beam energy of 5.5 MeV/u will be available for 2014, will be ideal for Coulomb excitation studies allowing multi-step excitation for all elements on a lead target. It is also intended to produce a system which will permit coincident detection of gamma rays and conversion electrons. The further stage of HIE-ISOLDE will see an upgrade to 10 MeV/u which will be a very suitable energy for single-particle transfer reactions such as (d,p) reactions. The extent to which shape coexistence is driven by occupation of intruder orbitals may be examined in this way. Similarly, two-proton adding or removal reactions are of high interest to investigate these important correlations. Possible reactions of this type include $^{184}Hg(^{3}He,n)^{186}Pb$. A letter-of-intent on such transfer reactions has been approved by the CERN INTC. It is presently unclear, however, what apparatus would be used for such measurements e.g. a conventional silicon barrel or a HELIOS-like device using a solenoidal field. It is also undecided as to whether a recoil separator would be needed for such measurements.

The work described here is part of a very large international collaboration based on experimental campaigns at REX-ISOLDE, the University of Jyvaskyla, Argonne National Laboratory and elsewhere. It is not possible to list all participants here but it is possible to point to the leading contributions of groups from Leuven, Liverpool, Jyvaskyla, CERN and York.

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Shape effects and beta decay: what can we learn from TAS experiments

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INTRODUCTION

Nuclear shapes and in particular nuclear deformation plays a key role in our understanding of nuclear structure. From the historical point of view it is interesting to see its evolution and how the concept become so necessary for our understanding of nuclear states. Actually it dates back to the 1950s when the interpretation of a large amount of accumulated nuclear data related to multipole moments, Coulomb excitation, large B(E2)-s, etc, leaded to the introduction of deformation and collectivity. An overview can be obtained from Aage N. Bohr's Nobel talk [1]. Since the 1950s, nuclear shape becomes a concept and an important tool for testing nuclear models.

But experimentally how do we deduce nuclear shapes? There are several ways and methods. We can obtain information on the deformation by means of measurements of nuclear electric quadrupole moments, which provide a direct measurement of the departure from sphericity. We can also determine the nuclear radii by scattering experiments and deduce the corresponding nuclear shape. The probes can be hadrons or charged particles and depending on that we can obtain information on the Coulomb radius or the mass radius. We can probe the shape by Muonic atoms or laser spectroscopy methods, which again can provide information on the departure from sphericity. The interpretation of nuclear spectroscopic data is also a source of shape information. From level lifetimes, B(E2)-s, etc., deformation can be deduced. More difficult is to obtain information on the sign of the deformation. One possibility is to obtain the sign of deformation from in-band multipole mixing ratios (from angular distributions). E0 transitions are also a "traditional" source of information, mainly related to shape changes and shape mixing. It is important to remember that shape is always model dependent in nuclear structure.

BETA DECAY and DEFORMATION

Beta decay can be a source of spectroscopic information, from which shape can be deduced. But there is also another alternative, based in the pioneering work of I. Hamamoto [2], and later followed by studies of P. Sarriguren *et al*. [3], Petrovici *et al*. [4] and references therein, which is related to the dependency of the beta strength distribution in the daughter depending on the assumed shape of the parent nucleus. This method can be used when theoretical calculations predict different strength distributions for the possible shapes of the decaying ground state (prolate, spherical, oblate). The procedure can be of particular interest since in some cases it can provide information on the shape for decaying 0^+ ground states.

DEFORMATION and THE TAS TECHNIQUE

The feasibility of this procedure depends on the precision of the experimental determination of the strength distribution. For these measurements total absorption is the most appropriate technique. This technique is based on the detection of the gamma cascades that follow the beta decay instead of detecting the individual gamma rays as we do in conventional Ge or high-resolution gamma spectroscopy. With the use of a highly efficient device, in essence a calorimeter placed around the source, efficiency close to 100 % for detecting gamma cascades can be achieved and then the so-called Pandemonium effect can be avoided.

This method has been applied successfully for example in the A~80 region, which is characterized by drastic shape changes and shape coexistence. In Nácher *et al.* [5], we confirmed that ^{76}Sr is one of the most deformed prolate N=Z nucleus in nature, and in Poirier *et al.* [6], we showed that ^{74}Kr is mixed in its ground state with this alternative technique. More recently we have extended these studies to the Pb region, where the beta decay of ^{188,190,192}Pb has been studied using the *Lucrecia* TAS spectrometer at CERN. Our preliminary results show, that even though the agreement between theory and experiment is not so spectacular compared with the A~80 region, the method can provide an alternative way for shape determination in the heavier domains [7]. We plan to continue this line of research for Hg, Po isotopes for which theoretical calculations are already available [8].

The future EURISOL facility, with beams of higher intensity for isotopes of interest for this application, can provide new opportunities for the study of nuclear shape effects using the total absorption technique.

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Neutron-Proton Pairing in N=Z Nuclei Studied through 2N Transfer Reactions

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INTRODUCTION

Pairing in exotic nuclei is a subject of active research in nuclear physics. Of particular interest is the competition between isovector (T=1) and isoscalar (T=0) Cooper pairs, expected to occur in N=Z nuclei.

Near ^{40}Ca and ^{56}Ni, earlier systematic analyses of two-neutron (L=0) transfer reactions [1,2] found the data consistent with a picture involving configuration mixing induced by simple pairing degrees of freedom of the valence neutrons. While providing evidence for isovector pairing in the form of pairing vibrations [2,3], the question of whether the isoscalar component generates collective modes is still an open one.

Direct reactions involving the transfer of an *np* pair from even-even N=Z nuclei could be excellent probes to study *np* correlations.

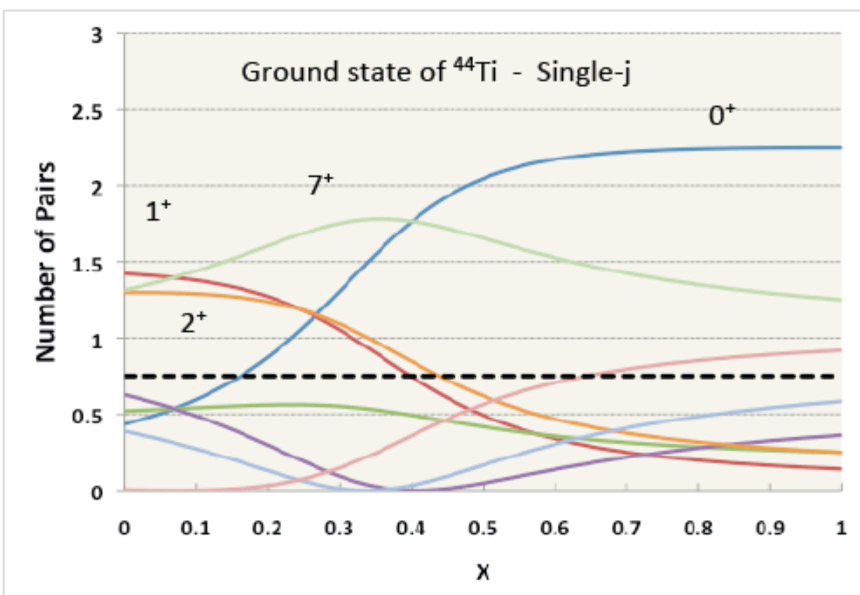

FIGURE 1. Number of pairs of a given spin in the ground state of ^{44}Ti as a function of the relative strength of T=0 vs. T=1 pairing, measured by the parameter x. Pure isoscalar corresponds to x=0 and pure Isovector x=1.

While absolute cross-section values are always desirable, we note that the ratio $\sigma(0^+)/\sigma(1^+)$ itself provides a clear measure of the pairing collectivity in the respective channels. This is illustrated schematically in **Figure 1**. showing the number of pairs of a given angular momentum J in the ground state of ^{44}Ti as a function of the parameter x, that measures the relative strengths of the T=0 vs. T=1 pairing forces. The calculations were performed following the formalism described in Ref. [4]. Note the strong (and opposite) dependence of the number of 0^+ and 1^+ pairs with x. Naturally, cross sections will scale with the number of pairs.

Of possible reactions such as (d,α), (α,d), (p, ^{3}He), (^{3}He,p), etc. we have chosen to study the latter one due to energy and kinematic considerations, but more importantly because both ΔT=0,1 are allowed. In this way both low lying 0^+,1^+ states in odd-odd self conjugate nuclei will be populated.

THE (^{3}HE,P) REACTION IN REVERSE KINEMATICS

With ^{40}Ca being the last stable N=Z nucleus, we started a program at the ATLAS facility in Argonne National Laboratory to study the (^{3}He,p) in reverse kinematics as required for radioactive beams. The experiments conducted so far included a proof of principle of the experimental technique, using the stable beams of ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca and the first successful application with a radioactive beam of ^{44}Ti. The setup, similar to that previously used in refs. [5,6], consisted of two annular Si strip detector (S1 type, 16 rings x 16 sectors) covering the angular range from 163^o to 148^o, a ^{3}He gas target cell (50 – 100 μg/cm^2) and the FMA.

The angular range covered by the Si detectors in the CM system is 8^0-18^0, where the L=0 transfer cross sections are favored. Because of its Q-value, the (^{3}He,p) reaction is extremely clean in the backward angles but the singles spectrum is dominated by charged particles emitted by compound reactions in the Ti windows of the gas cell.
In addition, the ^{44}Ti beam delivered by ATLAS contained also ^{44}Ca in a ratio ~2/1. Therefore, channel selection by a mass analyzer is required.

In our test run [7], the cross sections derived from the measurements in ^{40}Ca are in good agreement with previous work, performed in normal kinematics [8].

For the ^{44}Ti run, approximately 100μCi of ^{44}Ti were purchased from LANL and mixed with natural Ti, in oxide form, to make a cone for the sputtering ion-source of the ATLAS Tandem. Over a 3 day run, we had an average beam intensity of ~5x10^5 part/s

Preliminary results of the ^{44}Ti reaction are presented in **Figure 2.** The left panel shows the identification of ^{46}V using the FMA setup and the right panel the proton spectra observed on two groups of rings in the S1 detectors, obtained after kinematic correction of the proton energies.

With the intensity above, a target thickness of ~100μg/cm^2 and taking into account the FMA efficiency , we estimate a cross sections for the (^{3}He,p) reaction to the gs of approximately ds/dΩ~ 1mb/str at forward angles in the CM, in line with results in ^{40}Ca.

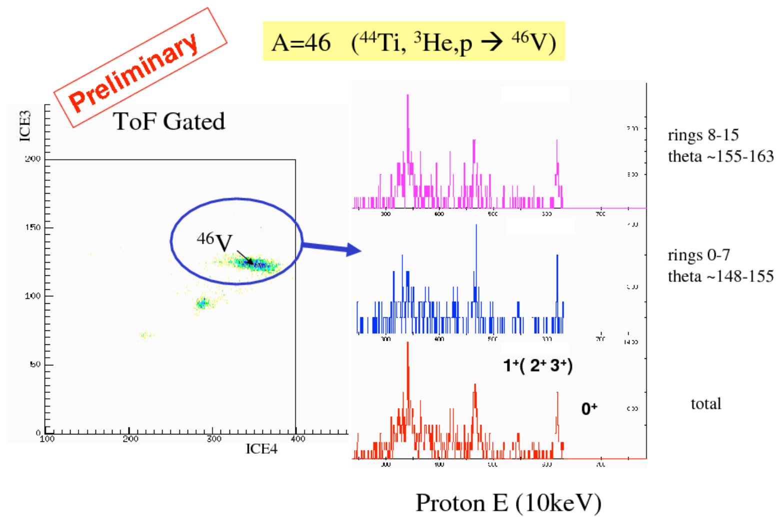

FIGURE 2. Proton spectra for the ^{44}Ti reaction. These are obtained by selecting ^{46}V recoils as seen by the FMA

As discussed earlier, we will concentrate on the ratio σ(0^+)/σ(1^+) . The systematic of this ratio for nuclei up to ^{40}Ca is shown in **Figure 3**. The trend of the experimental data is shown by the red line and as references, a "single-particle estimate" by the blue line and the superfluid limit for isovector pairing by the green line. The "single-particle estimate" includes (i) a spin statistics factor (2J+1), (ii) the probability of a t=0 or a t=1 *np* pair in ^{3}He, and (iii) a LS-jj recoupling coefficient that gives the amplitude of an L=0 pair in a pure j^2 configuration. The single particle estimate varies from 1/9 for an $s_{1/2}$ orbit to 1/3 in the limit of large j. It appears to be some enhancement of the T=1 over the T=0, and one could argue *loosely* that this arises from the T=1 extra-correlations.

The blue point is a preliminary result for the ^{44}Ti. The measured ratio lies close to the value expected within the vibrational scheme, for *n* –phonons [2,3]

$$\sigma(n \rightarrow n+1) = (n+1)\sigma(0 \rightarrow 1)$$

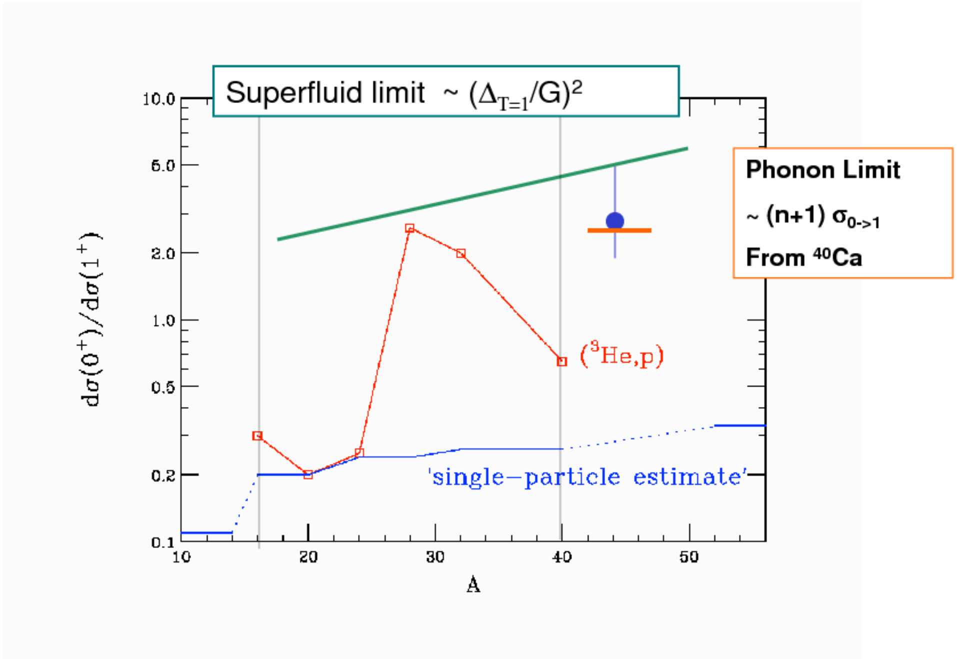

FIGURE 3. Sytematics of $\sigma(0^+)/\sigma(1^+)$ for nuclei up to ^{40}Ca. The preliminary result for the ^{44}Ti experiment is also shown. Single-particle and superfluid (T=1) limits are indicated as references.

With ^{44}Ti interpreted as a two phonon (T=1) state on the doubly magic ^{40}Ca, and from the observed ratios in ^{42}Sc we expect an enhancement $\sigma(0^+)/\sigma(1^+)_{46V} \sim 3\ \sigma(0^+)/\sigma(1^+)_{42Sc} \sim 2$.

SUMMARY

Direct reactions are unique tools in our experimental study of exotic nuclei. Following earlier studies of the (t,p) and (p,t) reactions, two nucleon transfers provide specific probes to study the amplitude of pairing collective modes.

In particular for *np* pairing, we believe the (^{3}He,p) reaction stands out as an ideal tool to study *np* correlations. The use of radioactive beams require inverse kinematics and we have carried out a proof of principle with stable beams and a successful first experiment with a ^{44}Ti beam at ATLAS.

Reactions like (d,α), (α,d) and (p, ^{3}He) will provide important complementary information and in fact, the (d,α) reaction is planned at GANIL.

The study of *np* pairing in N=Z nuclei using these reactions will constitute a unique program at FRIB/ReA12 and EURISOL. Based on current estimates of N=Z beam intensities at these facilities and improvements in the experimental setups over the pilot experiment described in this talk, one can envision approaching nuclei near ^{88}Ru, in the region where the most collective effects are expected.

Of particular importance for the success of such a program is a parallel development in reaction and structure theory to firmly elucidate this question.

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Aligned neutron-proton pairs in N~Z nuclei

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MOTIVATION AND CONTEXT

The study of nuclei with comparable numbers of neutrons and protons (N~Z) is one of the declared goals of radioactive-ion beam facilities. Several phenomena of interest, such as the breaking of isospin symmetry or the emergence of new collective modes of excitation, are predicted to become more pronounced as the mass number A=N+Z of the nucleus increases, and this constitutes the main argument for carrying out the difficult experiments to study heavy N~Z nuclei.

Arguably, the goal of most interest in this quest is the uncovering of effects due to isoscalar (T=0) neutron-proton pairing. In contrast to the usual isovector (T=1) pairing, where the orbital angular momenta and the spins of two nucleons are both anti-parallel (*i.e.*, L=0 and S=0), isoscalar pairing requires the spins of the nucleons to be parallel (S=1), resulting in a total angular momentum J=1. Collective correlation effects conceivably might occur as a result of isoscalar neutron-proton pairing [1] but have resisted so far experimental confirmation.

Recently, the idea of a different pair correlation effect was proposed by Blomqvist, as described in Ref. [2]. The proposal applies to situations where neutrons and protons are confined to a shell with high angular momentum j and it attempts a description of the structure of low-energy states of N~Z nuclei in terms of aligned neutron-proton pairs coupled to maximum angular momentum 2j. Blomqvist's idea is related to the so-called stretch scheme, which was advocated a long time ago by Danos and Gillet [3]. In the stretch scheme, shell-model states are also constructed from aligned neutron-proton pairs, treated in a quasi-boson approximation, which neglects anti-symmetry between the nucleons in different pairs. The latter approximation is absent from Blomqvist's approach in which anti-symmetry is fully taken into account.

This is an example of a neutron-proton pair correlation effect and as such one can imagine a simplified description by approximating the pairs as bosons. It is argued in this contribution that the interacting boson model of Arima and Iachello [4] indeed provides a natural framework to discuss neutron-proton pair correlations.

SUMMARY OF RESULTS

A full account of our analysis was given in Ref. [5] where it was shown that part of the low-energy spectroscopy of N=Z nuclei which have their valence nucleons confined to a single high-j orbit, can be represented in terms of an aligned isoscalar neutron-proton B pair with J=2j and is further improved by the inclusion of an isovector S pair coupled to J=0. This was proven explicitly for a four-hole system and indirectly, through a mapping onto a corresponding boson system, for six and eight holes. Some deficiencies were found in this approach. A first concerns states of the four-hole system with angular momentum J=2j which turn out to be poorly approximated with just S and B pairs. A second deficiency is more generic and pertains to the low-J states in odd-odd N=Z nuclei, the description of which calls for the inclusion of isoscalar neutron-proton pairs with low angular momentum. Nevertheless, it should be noted that the two isomers that have been observed so far in ^{94}Ag, (7^+) and (21^+), are adequately described in terms of B pairs.

These results were obtained for the $1g_{9/2}$ orbit and for three different choices of two-body interaction. To what extent are they valid in general and can they be considered as representative of a system of neutrons and protons confined to a high-j orbit? In essence, two ingredients, geometry and dynamics, determine the outcome of the present pair analysis. The geometry is defined by the coefficients of fractional parentage and, provided j is not too small, it is expected to evolve only slowly with j. The dynamics is determined by the two-body interaction, which in our study was varied significantly but within reasonable bounds. The matrix elements used were typical of what is obtained for a residual interaction with a short-range, attractive character and we may thus expect similar results when we move to orbits other than $1g_{9/2}$.

OUTLOOK

This work calls for further studies. The pair analysis of the shell-model wave functions should be extended to higher particle numbers, which can be achieved through an isospin-invariant formulation of the nucleon-pair shell model. Consequently, the present results require further confirmation at higher particle number but one is tempted to conclude at this point that a reasonable model can be formulated in terms of b bosons, which can be made more realistic by adding a further s boson. Due to its simplicity, such a model could be of use to elucidate the main structural features of N~Z nuclei in this mass region. These topics are currently under study but already now a qualitative idea can be given of the possible predictions.

The determination of energy spectra of N~Z nuclei approaching ^{100}Sn is within reach of present nuclear accelerator facilities, as witnessed by the results obtained for ^{92}Pd [2] and the experiments planned at GANIL [6] concerning ^{96}Cd. These experiments constitute a first test of the aligned-pair scheme. The energies of the first few levels in ^{92}Pd agree with the predictions in terms of aligned pairs while, on the basis of our results [5], it is to be expected that in ^{96}Cd this approximation breaks down for the yrast 8^+ level, as a consequence of the more seniority-like behaviour of this state.

The existence of known or probable isomers in the odd-odd nuclei ^{98}In, ^{94}Ag and (possibly) ^{90}Rh could be exploited to test the aligned-pair scheme. As argued in this contribution, a consequence of this scheme is that many states in the N~Z nuclei in this region can be approximated in terms of b bosons. For example, the 9^+ isomer, expected to exist in ^{98}In, can be identified directly with the b boson itself. The known 7^+ and 21^+ isomers in ^{94}Ag can be written as linear combinations (with only a few terms) of three-b-boson states. As a result, within the aligned-pair approximation, simple relations will exist between magnetic dipole and electric quadrupole moments of such isomers, and their measurement will provide thus an experimental test of this scheme.

Along the same lines, relations can be established between the matrix elements for the transfer of a deuteron. The basic matrix element for this transfer is between the ground state of ^{100}Sn and the (conjectured) 9^+ isomer in ^{98}In. Other matrix elements for the transfer of a deuteron, such as between the 7^+ isomer in ^{94}Ag and states in the nuclei ^{92}Pd and ^{96}Cd, can then be expressed in terms of this basic matrix element. The measurement of deuteron transfer cross sections would thus constitute a test of the aligned-pair scheme, provided aspects related to the reaction mechanism for the transfer of a deuteron are under control.

Thanks are due to Salima Zerguine, my collaborator in this study.

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Beyond mean-field description of exotic structure and decay of proton-rich nuclei in A~70 region

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Abstract of the talk given at the EURISOL topical meeting: *Neutron deficient exotic nuclei and the physics of the "proton rich side" of the nuclear chart*, February 21-23, 2011, Valencia, Spain

The interest for the investigation of proton-rich nuclei in the A~70 mass region exceeds the frontier of nuclear structure and dynamics.

Nuclei at or near the N=Z line are of particular interest as micro-laboratory for high precision tests of the Standard Model. The isospin symmetry breaking is also responsible for the mirror energy differences induced by the electromagnetic and charge-dependent strong interactions. Anomalies have been experimentally identified in the excitation energy of the analog states in the A~70 mass region. In this region small modifications in the Fermi surface induced by the Coulomb interaction can cause rapid changes in the nuclear shape altering the mixing of prolate and oblate components and may lead to different shapes in the ground-state configurations of nuclei belonging to the same isospin multiplet.

The properties of A~70 nuclei are relevant for nucleosynthesis and the simulation of many astrophysical objects requires the knowledge of decay rates of nuclei near the proton drip line. Changes in deformation of close-lying nuclei, with possible existence of long living shape isomers, can significantly affect the proton-capture rates and the beta decay strengths of the isomeric states and consequently the rp-process path.

Relevant for the Gamow-Teller (GT) beta decay of the waiting point nuclei could be the GT strength distributions for the low-lying excited states whose thermal population may result in a significant reduction of the effective lifetime at the high temperatures of X-ray bursts.

Shape coexistence and mixing, isospin mixing, significant neutron-proton pairing correlations competing with the like-nucleon ones, and competition between proton and neutron alignment have been identified as the main characteristic features of nuclei near the N=Z line in the A~70 mass region. The self-consistent treatment of exotic phenomena dominated by their interplay represents a challenge for the nuclear many-body models. The goal of the nuclear many-body approaches is not only to describe the properties of experimentally accessible nuclei, but getting predictive power for characteristics of nuclei remaining beyond the experimental reach. Moving towards a self-consistent theory with quantifiable error bars one expects predictive theoretical capability in nuclei. The description of phenomena where the nucleus serves as laboratory for fundamental effects requires particularly high accuracy of the nuclear structure models. On the other hand, particular components of the effective nucleon-nucleon interaction known to have direct relevance to spin-isospin properties play an essential role for the oblate-prolate competition and mixing in the A=60-90 mass region, too, as it is demonstrated in our studies within the Vampir models [1-5].

The VAMPIR approaches use Hartree-Fock-Bogoliubov (HFB) vacua as basic building blocks, which are only restricted by time-reversal and axial symmetry. The underlying HFB transformations are essentially *complex* and do mix proton- with neutron-states as well as states of different parity and angular momentum. The broken symmetries of these vacua (nucleon numbers, parity, total angular momentum) are restored by projection techniques and the resulting symmetry-projected configurations are used as test wave functions in chains of successive variational calculations to determine the underlying HFB transformations as well as the configuration mixing. Since for each new state of a given symmetry an independent variational calculation is accomplished drastic changes in structure with increasing energy are accessible by this model and the essential degrees of freedom for each particular state are automatically selected in the chain of variational calculations. The HFB vacua of the above type account for arbitrary two-nucleon correlations and thus simultaneously describe like-nucleon as well as isovector and isoscalar proton-neutron pairing. Furthermore the *complex* Excited Vampir model (EXVAM) allows the use of rather large model spaces and realistic effective interactions.

A self-consistent description of coexistence phenomena in the A~70 region was obtained within the beyond mean-field *complex* Excited Vampir variational approach using realistic effective interactions in large model spaces [1-5]. The mentioned open problems have been illustrated. More experimental information is needed in order to clarify the existing open problems and to provide valuable input for the theoretical models. Precise quadrupole moments and electromagnetic transition probabilities, clear assignments of spin and parities, Gamow-Teller strength distributions for the whole beta window represent real tests for the theoretical predictions and could help for improving the effective interactions and the strategy behind the different theoretical approaches.

The influence of the isospin mixing on the superallowed Fermi beta decay is superimposed on the effect of the shape mixing in this mass region as it is illustrated for the A=82 case, but the shape effect is expected to be stronger for A~70 nuclei. Experimental information on the non-analog branches could test the theoretical predictions.

Few examples concerning the mirror energy differences are presented and the anomalies identified in the A=70 case are discussed. Here data on the whole T=1 triplet would be very useful, as well as data concerning other triplets dominated by shape coexistence and mixing. The quadrupole moments for the involved low spin states would help to clarify the problem and to give support to the theoretical predictions.

Strongly connected with the shape mixing problem in the A~70 nuclei are the Gamow-Teller strength distributions for the beta decay of the nuclei playing an essential role in the astrophysical rp-process. Realistic predictions on the Gamow-Teller strength distributions and the influence of the shape isomers on the effective half-life of the waiting point nuclei at the high temperatures of the X-ray bursts require data for the nuclei which are in the experimental reach. A particular open problem for this mass region is the 'quenching issue'. Beyond mean field approaches and large model spaces are required from the theory and more data on Gamow-Teller strength distributions over the whole beta window from the experiment.

The discussed examples concerning the mentioned problems indicate that complex Excited Vampir is a robust model for describing the coexistence phenomena in the A~70 mass region. Some of the open problems require an increased model space and corresponding effective interaction. Currently we are involved in systematic investigations aiming to improve the effective interaction in larger model spaces.

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The drip-lines - a new paradigm for clustering

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CLUSTERING CLOSE TO STABILITY

The developments leading to our current understanding of clustering that appears in nuclei with *N*=*Z* (*N* even, *Z* even) can be traced to the earliest days of nuclear physics. The work by Hafstadt and Teller [1] crystallized the concept of clustering in alpha-conjugate nuclei. Their analysis is shown in Fig. 1. The linear relationship between the number of bonds between alpha-particles and the binding energy indicated that these nuclei could be described in terms of a close packed, geometric, arrangement of alpha-particle clusters. After 70 years this picture remains essentially correct, though it is now known that the alpha-particles do not retain their "free" nature in the ground-states as they overlap and the fermionic degrees of freedom become important in describing the structure. Nevertheless, the symmetries present in the geometrical picture remain. For example, ^{12}C is oblate in its ground state and the spectrum of excited states can be understood in terms of the triangular symmetry. Similarly, the arrangement of 4 and 5 alpha-particles in ^{16}O and ^{20}Ne would suggest spherical and prolate structures, respectively, as observed experimentally.

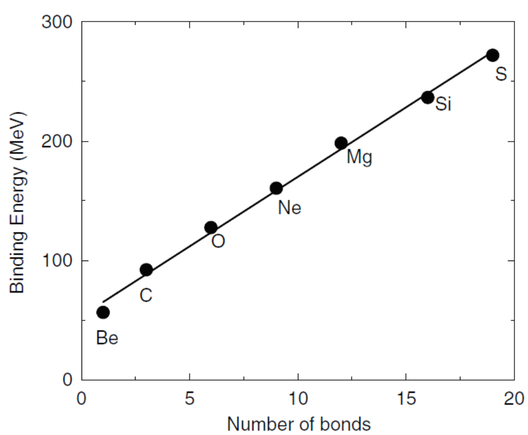

FIGURE 1. Binding energy per nucleon of $A = 4n$ nuclei versus the number of _–_ bonds. The analysis by Hafstad and Teller [1] suggested that the ground states of $A = 4n$, _-conjugate, nuclei could be described by a constant interaction energy scaled by the number of bonds. For 8Be there is one bond, 12C—3, 16O—6, 20Ne—9, 24Mg—12 and for structural reasons (the geometric packing of the _-particles) 28Si—16.

It was later realized by Ikeda et al. [2] that clustering is found explicitly close to the associated decay threshold. This resulted in the now famous Ikeda diagram (Fig. 2).

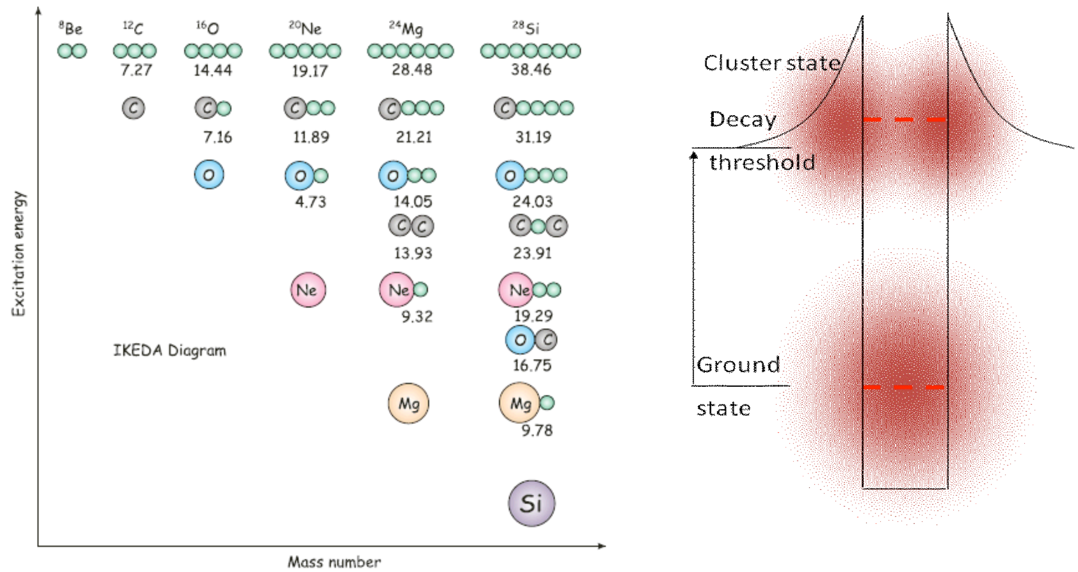

FIGURE 2 ***Left***) The Ikeda picture [2]. The diagram shows how the cluster degree of freedom evolves as the excitation energy increases. The important concept relayed by this diagram is that a cluster degree of freedom is only liberated close to a cluster decay threshold. Thus, for heavy systems the *N*_ degree of freedom only appears at the highest energies. *Right*) Illustration of the clusterisation which occurs close to the threshold.

The Ikeda diagram may be understood in terms of the transformation of the internal excitation energy into the equivalent mass-energy required to create the cluster partition. So at the threshold there is sufficient energy to create the clusters explicitly. This appearance of clustering at the decay threshold can also be understood from the perspective that close to the decay threshold the wave-function describing the system may tunnel into the barrier region reducing the kinetic energy – and enhancing the stability of the clustered system. It has long been known that the there is an optimal separation between the clusters which arises from the balance between the reduction of the potential energy as the clusters separate (negative sign) and the decrease in the kinetic energy (positive sign). It is however also clear that the coupling to the states above the barrier – the continuum – is also important in developing the evolution of the cluster structure. The combination of these effects results in the Ikeda threshold diagram being appropriate for the description of formation of cluster states for nuclei close to stability.

CLUSTERING CLOSE TO DRIP-LINES

As the drip-lines (proton or neutron) are approached then it is predicted that the driving forces related to clustering change. In stable nuclei the lowest energy decay threshold is typically the cluster decay threshold. However, near the drip-lines the lowest threshold will either correspond to neutron or proton decay. This changes both the nature of the continuum to which the bound system couples and hence the factors driving the formation of clustering. Fig. 3 illustrates the changing paradigm. The calculations shown on the left-hand-side are AMD calculations which treat all A nucleons as Gaussian wave-packets, with the nucleons interacting via an effective nucleon-nucleon interaction. It is seen that as the neutron drip-line is approached that the protons and neutrons become clustered. The cluster partition for ^{19}B is ^{11}Li+^{8}He, however the corresponding decay threshold is 13.0 MeV. It is the neutron-decay threshold (0.99 MeV) and the fact that ^{19}B is a 2n halo nucleus which turns out to be important.

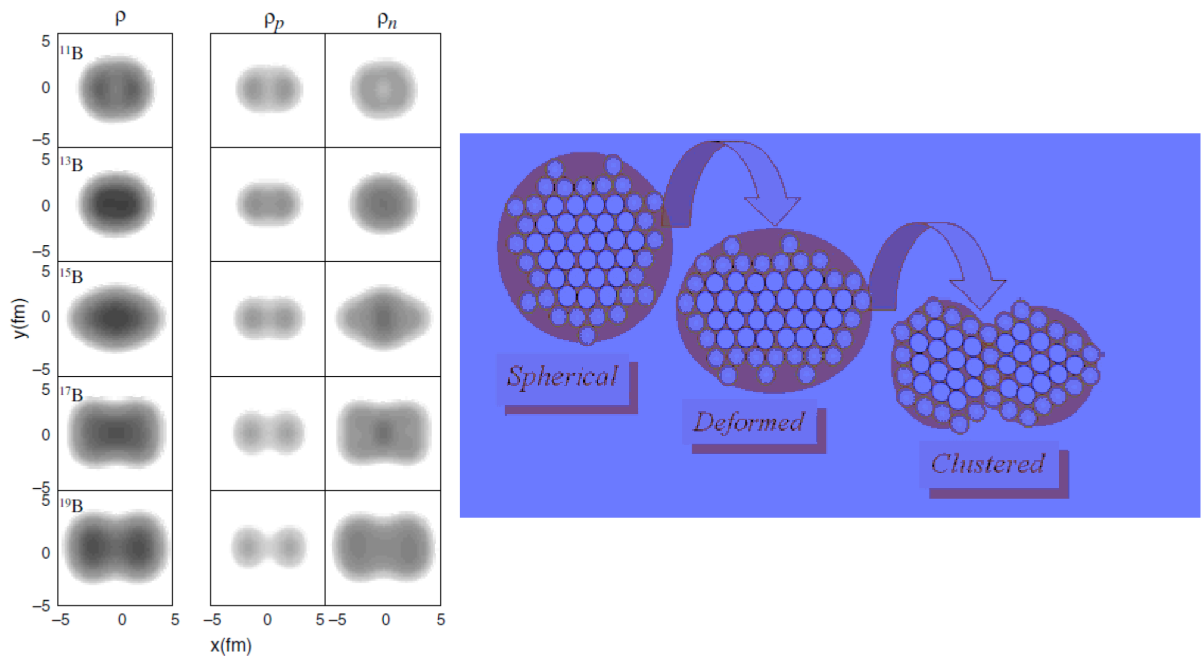

FIGURE 3 ***Left*)** Density distributions of boron isotopes, $^{11-19}$B. The densities of the protons and neutrons as well as their sum, _, are shown, from [3]. *Right*) A schematic of the evolution of cluster structure in the ground states of drip-line nuclei. The blue spheres represent nucleons associated with nuclear matter of normal isospin, whereas the red spheres are the excess valence neutrons. The transition from spherical through deformed to clustered permits a more even distribution of the valence neutrons

In order to attempt to understand the physics driving the formation of the clustering in ^{19}B the diagram on the right-hand-side of Fig. 3 should be considered. The halo neutrons being weakly bound can tunnel into the barrier region and hence have a reduced kinetic energy. In order to maximize the overall binding energy of the system the overlap of the valence neutrons with the core should be maximized. In the rather classical model shown this could be achieved by the nucleons entering the core, but this is energetically unfavourable as the states are Pauli-blocked. The alternative is to maximize the interaction with the core nucleons by either deforming, or optimally clustering, the core. Again, coupling to the continuum states is likely to be an important driving force in determining the structure of such systems at the drip-line.

Such an effect is not limited to neutron-rich nuclei, but in proton-rich systems where the valence protons are delocalized then similar effects should be present – the presence of the Coulomb barrier may reduce the magnitude of the effect, but from an experimental perspective it may be easier to reach the proton drip-line than the neutron drip-line. The question of how to probe such effects is an important one. One approach may be to use high energy (30 MeV/u +) fragmentation to observe the cross sections for the dissociation into various cluster partitions, as was done with the Beryllium isotopes in Ref. [4]. Alternatively, at lower energies measuring cluster spectroscopic factors using transfer studies may be effective, or even quasi-free scattering.

The transition between stable nuclei and those at the drip-lines is given by the behavior of molecular states. Here, protons or neutrons may be covalently exchanged between clusters (typically alpha-particles) [5]. Understanding the role of delocalized valence particles is key to understanding the structure of drip-line nuclei – this remains to be characterized for proton-rich nuclei.

CLUSTERING AND CORRELATIONS

It should be remembered that clustering is a manifestation of correlations which are seen as important drivers of nuclear structure in heavier systems, e.g. modification to shell structure, behavior of nuclei beyond closed shells, drivers of deformation and collectivity. In light nuclei the correlations are an appreciable contribution to the binding of the system and hence the effects of clusterisation are pronounced. As such, the phenomenon of clustering in light nuclei is central to the understanding of correlations across the full panoply of nuclei.

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