EURISOL User Group

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

Innovative Instrumentation for EURISOL

The Ron Cooke Hub, Heslington East Campus, University of York, York, UK,

15-17 July 2014.

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Programme

Tuesday 15 July

09:00-10:00	**Registration**
10:00-10:10	**Welcome-** Angela Bonaccorso, INFN, Pisa, Italy and Andrei Andreyev, University of York, UK
Session 1	**Chair - Angela Bonaccorso, INFN, Pisa, Italy**
10:10-10:35	**Current and future EURISOL activities** Yorick Blumenfeld, IPN Orsay, France
10:35-11:10	**HIE-ISOLDE : the project and the physics opportunities** Maria J G Borge, CERN, Geneva, Switzerland
11:10-11:35	**New instrumentation for the ALTO ISOL facility** Deyan Yordanov, Institut de Physique Nucléaire, France
11:35-12:10	**Coffee break**
Session 2	**Chair – Hans Fynbo, University of York, UK**
12:10-12:45	**Nuclear astrophysics with storage rings** Phil Woods, University of Edinburgh, UK
12:45-13:20	**The SPES exotic beam ISOL facility: Status of the project, technical challenges, Instrumentation, scientific program** Fabiana Gramegna, LNL-INFN, Italy
13:20-14:40	**Lunch and exhibition**
Session 3	**Chair – David Jenkins, University of York, UK**
14:40-15:15	**Ideas and instrumentation for ISOL@MYRRHA** Riccardo Raabe, KU Leuven, Belguim
15:15-15:40	**Spiral2 instrumentation** Adam Maj, Inst. Nucl. Phys., Kraków, Poland
15:40-16:05	**The future of fast-timing experiments with EURISOL** Oliver Roberts, University College Dublin, Ireland

16:05-16:30 **Coffee break**

Session 4 **Chair - Andrei Andreyev, University of York, UK**

16:30-16:55 **Latest development of recoil separators**
Herve Savajols, GANIL, Caen, France

16:55-17:20 Martin Sharratt AP Technologies

17:20-17:45 Hammamatsu representative

End of Day 1

Wednesday 16 July

Session 1 **Chair – Riccardo Rabbe, KU Leven, Belgium**

09:00-09:35 **ACTAR TPC: An active target and time projection chamber for nuclear physics**
Thomas Roger, GANIL, Caen, France, UK

09:35-10:10 **Polarized proton target for RI-beam experiments**
Tomohiro Uesaka, RIKEN, Japan

10:10-10:35 **Fast-timing studies at EURISOL**
Gary Simpson, University of the West of Scotland, UK

10:35-11:10 **Coffee break**

Session 2 **Chair – Robert Wadsworth, University of York, UK**

11:10-11:45 **The advanced nuclear Instrumentation of NUSTAR**
Juergen Gerl, GSI, Darmstadt, Germany

11:45-12:20 **Tagging around RITU: Instrumentation, methods and their applications**
Catherine Scholey, JYFL, Jyväskylä, Finalnd

12:20-12:45 **Detection of high-energy protons and gamma-rays using a novel LaBr3 (Ce)-LaCl3(Ce) phoswich array**
Enrique Nacher, Instituto de Estructura de la Materia - CSIC, Spain

12:45-14:00 **Lunch and exhibition**

Session 3 — Chair - TBA

14:00-14:35 **ELISe electron scattering off RIBs**
Haik Simon, GSI, Darmstadt, Germany

14:35-15:10 **The SCRIT electron scattering facility at RIKEN-RIBF**
Masanori Wakasugi, RIKEN, Japan

15:10-15:35 **Coffee break**

Session 4 — Chair – Andrei Andreyev, University of York, UK

15:35-16:10 **Advanced techniques for measuring nuclear moments, spin and charge radi**
Kieran Flanagan, University of Manchester, UK

16:10-16:45 **Precision spectrometry with ion traps for next-generation beams**
Susanne Kreim, CERN, Geneva, Switzerland

Workshop Dinner at 20:00 – Restaurant in City Centre

Thursday 17 July

Session 1 — Chair – Yorick Blumenfeld, IPN Orsay, France

09:30-10:05 **From solid-state to gaseous sensors for nuclear physics**
Emanuel Pollacco, CEA, Saclay, France

10.05-10:40 **Neutron detector arrays**
Johan Nyberg, Uppsala University, Sweden

10:40-11:05 **Conversion-Electron spectroscopy at EURISOL**
Gary Simpson, University of the West of Scotland, UK

11:05-11:40 **Coffee break**

Session 2 — Chair – Adam Maj, Inst. Nucl. Phys., Kraków, Poland

11:40-12:15	**Future prospects with scintillator arrays** David Jenkins, University of York, UK
12:15-12:40	**The GASPARD project: a 4pi array for direct reactions measurements** Marlène Assié, IPN, France
12:40-13:05	**SHARC: a versatile silicon array for use in radioactive ion beams** Gemma Wilson, University of York, UK
13:05-13:10	**Closing -** Angela Bonaccorso, INFN, Pisa, Italy
13:10	**Departure**

5th EURISOL TOPICAL MEETING

Innovative Instrumentation for EURISOL

15-17 July 2014, University of York, York, UK

Foreword

The 5th EURISOL Topical Meeting took place from July 15 to July 17, 2014, at the University of York (UK). It was the last in a series of topical meetings which included: "The formation and structure of r-process nuclei, between N=50 and 82 (including 78Ni and 132Sn areas)" (Catania, Italy, 2009), "Neutron-deficient nuclei and the physics of the proton-rich side of the nuclear chart" (Valencia, Spain, 2011), "Physics of light nuclei" (Lisbon, Portugal, 2012) and "Going to the limits of mass, temperature, spin and isospin with heavy Radioactive Ion beams" (Krakow, Poland, 2013). The meetings were initiated by the User Executive Committee of the EURISOL Users Group and supported by the European Commission via the EURISOL-NETWORK within the ENSAR contract. The local organisation of the meeting in York was provided by the Institute of Physics, and chaired by Prof Andrei Andreyev (University of York) and Dr Angela Bonaccorso (INFN Pisa). The aim of the meeting was to review the instrumentation and techniques presently used at the ISOL facilities and discuss the possible future ideas and developments for the EURISOL facility.

The programme focused on the following subjects:

- Instrumentation for beam handling: storage rings, separators, ion traps;
- Instrumentation for radiation detection: charged particles, γ-rays, neutrons, electrons;
- Spectroscopic techniques: electron scattering, fast timing, recoil decay tagging, measurement of ground-state properties.

In addition, the current status of the main ISOL projects for upgrades and new facilities was reviewed in a series of dedicated presentations.
This booklet collects the summaries of the contributions to the workshop, preceded by a short introduction organised according to the topics listed above. The full programme and the presentations are available at the workshop web site http://eurisol5.iopconfs.org/Home.

Upgrades and future facilities

This topic was addressed by Y. Blumenfeld, M. J. G. Borge, J. Gerl, F. Gramegna, A. Maj, R. Raabe, D. Yordanov.

The realisation of new radioactive ion beam facilities and the upgrade of existing ones has been recognised as an absolute priority by the nuclear physics community worldwide,

a priority triggered by the need of accessing reliable information on nuclei far from stability. In Europe, this fact was reflected in the recommendations of the 2010 NuPECC Long Range Plan, which identified as first objectives the completion of FAIR in Germany, SPIRAL 2 in France and SPES in Italy, alongside the upgrade of the REX-ISOLDE post-accelerator into HIE-ISOLDE. These facilities, in particular the ISOL facilities HIE-ISOLDE, SPIRAL 2 and SPES, can be seen, together with ISOL@MYRRHA, as intermediate steps of the route towards EURISOL.

Large collaborations have formed around the projects for the new facilities, with the aim of designing new detection instruments and, in some cases, re-think the associated detection techniques, in order to take full advantage of the forthcoming opportunities. Two elements were important to avoid duplication of the efforts: on one hand, groups working around similar detection concepts (or with similar technologies) for different facilities were closely collaborating, sharing ideas, and often also sharing manpower. The Activities and Networks in ENSAR were an important factor in this process. On the other hand, many new instruments were designed from the start with the idea of being portable, and thus having the possibility of being installed at different facilities.

Presentations at the York workshop gave overviews of the status of HIE-ISOLDE, ALTO at Orsay, SPES, SPIRAL 2, NUSTAR and ISOL@MYRRHA. They showed indeed an impressive large range of newly-developed instruments, but also revealed the synergies existing among the groups working on those instruments. Such synergies will be of course crucial in the future, for the realisation of instruments for EURISOL.

Instrumentation for beam handling

This topic was addressed by S. Kreim, H. Savajols, T. Uesaka, P. Woods.

The possibility of using storage rings to perform nuclear reactions on an internal target has been tested at the ESR ring at GSI. The test measurements could take advantage of the large experience accumulated at the ESR about beam handling and detection technologies in rings. Although several challenges have to be overcome, positive results indicate the feasibility and potential of this technique, which exploits the recirculation of the radioactive beam to compensate for the reduced target thickness. The project to install a storage ring at HIE-ISOLDE would open new horizons in this respect, not limited to nuclear reactions but also for laser spectroscopy, decay spectroscopy and atomic physics.

Related to nuclear reactions are the developments in recoil separators and spectrometers. New technologies and ideas have emerged recently: the use of multipoles to compensate for aberrations in large-acceptance instruments, which could in this way retain a high efficiency while at the same time achieve an effective spatial separation of the beam species; the techniques for ion separation at low energy, which employ laser ionisation and multi-reflection time-of-flight (MR-TOF) separators to achieve a very high beam purity.

The latter two techniques are now being used in combination with ion traps to achieve a

fast and effective mass purification, with resolving powers comparable to that of Penning-trap techniques and time scales one order of magnitude smaller. This has now pushed further the limits of ion analysis in high-precision ion traps towards shorter-living species, allowing for example mass measurement with single-ion sensitivity for nuclides with a very low production rate and strong contaminants. Thanks to their beam-analysis potential, MR-TOF devices will be incorporated in the Target-and-Ion-Source Development (TISD) programmes, such for example at ISOLDE.

Related to ion handling are the developments of new targets for reaction experiments. The polarised-proton target at RIKEN is a fine example, and the outlook towards obtaining such a device at room temperature opens important possibilities for detailed spectroscopy through reaction studies using the intensities available for exotic beams at the forthcoming facilities.

Instumentation for radiation detection

This topic was addressed by M. Assie, L. Pollacco, T. Roger, G. Wilson, J. Nyberg, D. Jenkins, E. Nacher.

The latest developments in the detection of charged particles and neutrons, and improvements of scintillators for γ-ray radiation, were reviewed in a number of presentations.

The use of an active target – a gaseous time-projection chamber, where the detection gas is at the same time the target of the reaction to be studied – for spectroscopic reaction studies has been already successfully employed in a number of cases. The development of the new-generation detectors of this kind (in Europe, the ACTAR TPC project) holds important promises for the exploitation of the most rare and weak beams at the new facilities. For the detection of charged particles, Si detectors have so far played the most important role with many set-ups present at all radioactive ion beam facilities worldwide (a dedicated presentation of SHARC at TRIUMF was a representative example). Such devices will continue their role thanks to important steps forward in the technique especially concerning particle identification, as shown by the GASPARD project. Several important challenges remain for both kind of detectors, as the demand for dynamic range, count rates, resolution, efficiency, and a very large number of channels to be handled in small spaces, all increase when dealing with rare events to be selected in a potentially high-polluted sample. In this respect it was suggested that it would be beneficial for our community to look in other directions, to the needs and developments present in other domains around these problems.

The realisation of the NEDA array for neutron detection summarises the characteristics of devices designed to work at the new-generation facilities: modular, portable, with a particular attention to integration with other detection arrays. At the same time, NEDA represents a significant step forward in detection efficiency, neutron-γ and neutron cross-talk discrimination and count-rate capability. The development of new organic scintillator materials is followed closely by the collaboration.

Similarly, inorganic scintillators have made very important progress in the last ten years thanks to the development of new materials. Performances of $LaBr_3$(Ce) are between those of traditional scintillators and Ge crystals. The drawbacks of $LaBr_3$(Ce) (high internal radioactivity and high cost) are being countered by the research on other materials which may achieve similar performances. These exciting developments are coupled with new techniques for light collection and translation such as avalanche photodiodes, possibly organised in arrays as in silicon photomultipliers. The new-design array such as PARIS and CALIFA take advantage of these materials using them in phoswich arrays for the efficient detection of high-energy γ-rays and protons.

Spectroscopic techniques

This topic was addressed by H. Simon, M. Wakasugi, O. Roberts, G. Simpson, C. Scholey, K. Flanagan.

Combining the developments in technology to improve established research methods, was the subject of a number of presentations.

The possibility of bringing electron scattering to the domain of radioactive nuclei is the aim of two projects. The ELISe project at FAIR uses a geometry with two colliding beams. SCRIT at RIKEN combines instead the principles of storage rings and ion traps to build an internal ion target in an electron storage ring. A proof-of principle measurement has demonstrated the feasibility of this technique.

The state-of-the-art and future improvements in well-established methods such as fast-timing, electron conversion and recoil-decay tagging were reviewed. The use of new detection materials (in particular fast and efficient scintillators) and the conditions to be expected at new facilities, all the way to EURISOL, are considered in the design of the new detection arrays.

Similarly, a review of methods to measure nuclear moments, spin and charge radii pointed out how the developments in laser methods have achieved ultra-high sensitivity (collinear spectroscopy) and energy resolution (with laser trapping techniques). For these reasons, laser techniques will very likely play a fundamental role in the study of the properties of the most exotic nuclei. It was however noticed that, in the years that separate us from EURISOL, introduction of completely new technologies is not to be excluded. Such sudden shifts have been observed in the past, and have taught us that new exciting developments may sometimes force us to re-think our methods completely.

HIE-ISOLDE: the Project and the Physics Opportunities

M. J. G. Borge

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Abstract. The ISOLDE Facility at CERN produces pure and intense radioactive beams of 1300 different nuclei of 75 elements by the ISOL-method. Since more than a decade it offers the largest variety of post-accelerated radioactive beams in the world today. In order to broaden the scientific opportunities beyond the reach of the present facility, the on-going HIE-ISOLDE (High Intensity and Energy) project will provide major improvements in energy range, beam intensity and beam quality. A major undertake of the project is the increase of the final energy of the post-accelerated beams to 10 MeV/u throughout the periodic table. The first stage will boost the energy of the current REX LINAC to 5.5 MeV/u where the Coulomb excitation cross sections are strongly increased with respect to the previous 3 MeV/u and many transfer reaction channels will be opened. The first stage of HIE-ISOLDE will start for physics in the autumn of 2015. The physics cases approved expand over the wide range of post-accelerated beams available at ISOLDE with more than six hundred shifts approved for day one physics. In this contribution the HIE-ISOLDE project will be described together with a panorama of the physics cases addressed.

Keywords: ISOL-Type Facility, Post-accelerated beams
PACS: 29.20.-c, 29.20.Ej, 29.38.Gj,

INTRODUCTION

The On-Line Isotope Mass Separator ISOLDE is the CERN facility dedicated to the production, study and research of nuclei far from stability. Exotic nuclei of most chemical elements are available for the study of nuclear structure, nuclear astrophysics, fundamental symmetries and atomic physics, and for applications in condensed-matter and life sciences. The radioactive nuclei are produced in reactions of 1.4 GeV proton pulse of 3×10^{13} particles in thick targets. More than 20 different target materials and ionizers are in use. Ionization can take place in hot plasma, on a hot surface or by laser excitation. Chemical selectivity is obtained by the right combination of target-ion sources giving rise to a selective production of more than 1300 isotopes of 75 different chemical elements, of which more than 700 different species have been studied. The ions are extracted from the ion-source by 30-60 kV acceleration voltages and directed towards one of the two electro-magnet where they are separated according to their mass, one the so-called General Purpose Separator (GPS) with a mass resolving power, M/ΔM, of more than 1000, and the other, a High Resolution Separator (HRS), which mass resolution is larger than 5000. The GPS and the HRS separators are connected to a common beamline system. This allows for the optimization of the space and the flexibility of operation as the ions can be produced from two different target-ion source units.

The post-accelerator, REX-ISOLDE, in operation since 2001, has opened new fields

of research in particular in reaction studies of light-medium mass nuclei with energies up to 3 MeV/u. The singly charged ions from ISOLDE are captured and bunched in a large acceptance Penning trap (REXTRAP) and charge bred in the REXEBIS ion source to an A/q ratio between 2 and 4.5. The higher charge of the beam allows it to be efficiently accelerated in a compact linear accelerator. A thorough technical description of the REX accelerator can be found in [1]. REX is being upgraded (HIE-ISOLDE) to provide an energy of 4.3 MeV/u in October 2015 for A/q = 4.5 and 5.5 MeV/u in the Spring of 2016. The post-accelerated radioactive beams will allow multi-step Coulomb excitation studies for a wide range of nuclei. In a second phase of HIE-ISOLDE energies up to 10 MeV/u for the radioactive beams will be obtained.

ISOLDE UPGRADE: HIE-ISOLDE PROJECT

The HIE-ISOLDE upgrade (HIE stands for High Intensity and Energy), intends to improve the experimental capabilities at ISOLDE over a wide front [2]. The main features are to boost the energy of the beams, going in steps from currently 3 MeV via 5.5 MeV to finally 10 MeV per nucleon, and a roughly sixfold increase in production expected due to an increase in intensity and energy of the proton beam. In addition improvements in several aspects of the secondary beam properties such as purity, ionization efficiency and optical quality are addressed in the project.

The major project components include a new superconducting (SC) linear accelerator (LINAC) based on Quarter Wave resonators (QWRs) for the post-acceleration and the necessary 4.5 K cryogenic station for helium. The decision to keep the existing experimental hall has imposed severe constraints on the LINAC, so it has been necessary to design and build accelerating cavities with a very high voltage gradient of 6 MV/m and low heat dissipation. The superconducting accelerator is based on two QWR geometries: twenty high-β and twelve low-β cavities cooled by helium and installed in six cryomodules providing a total effective acceleration voltage of 39.4 MV. The transverse focusing is achieved using eight superconducting solenoids housed inside the cryomodules maximising the transverse acceptance. The high-β cavities are grouped into four cryomodules of five cavities and one solenoid each. The high-β cavities based on 101.28 MHz niobium-sputtered copper (Nb/Cu) Quarter Wave Resonators have recently surpassed the foreseen specification of 6 MV/m at 10 W and they are at series production. The first two cryomodules with five high-β cavities each will permit to increase the energy to 5.5 MeV/u for A/Q = 4.5 and constitute the first phase of the project. The three stages of the project are schematically shown in Fig. 1.

The beam transfer line is designed to deliver beams of a large variety of energies from 0.45 MeV/u to 10 MeV/u to three experimental stations. The three experimental beam lines are designed to be identical and are placed at 90° degrees to the Linac. In each beam line two magnetic dipoles bend the beam 45° with a quadrupole in between to steer the beam through 90° double-bend-achromat lattices towards the experimental stations.

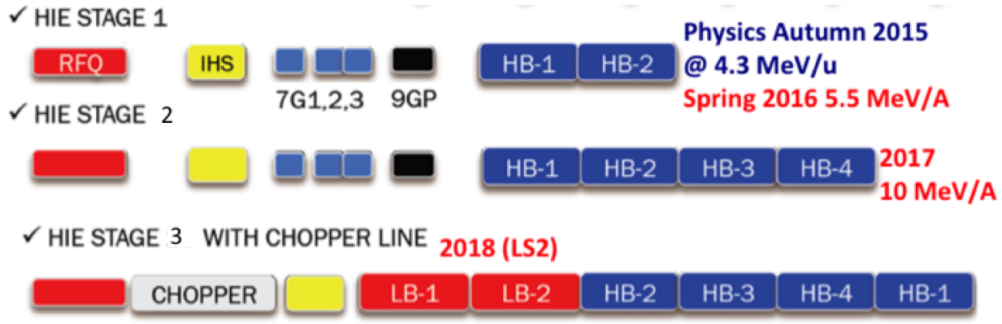

FIGURE 1. Schematic description of the elements and implementation phases of the accelerator part of the HIE-ISOLDE project. The present accelerator (from RFQ till 9GP) will be connected to the high-β cavities (HB-1-4) to increase the energy up to 10 MeV/u. The present accelerator with me replace replace by two low-β cavities (LB-1-2) in the third stage and a chopper line will be added.

PHYSICS CASES AT HIE-ISOLDE

The first call for proposals was made in October 2012. So far twenty seven experiments have been approved with more than six hundred 8h shifts allocated for day-one physics. The physics cases approved expand over the wide range of post-accelerated beams available at ISOLDE, where the increase in energy of the radioactive beams will enhance the cross section in most of the cases and the accessibility to detailed nuclear structure information at higher excitation energy.

In the light nuclear region, reaction studies of astrophysical interest such as the search for high-excited states in ^{8}Be is planned to address the cosmological ^{7}Li problem. Nuclear structure studies are planned to characterise cluster structure in ^{10}Be by transfer reaction or unbound states in the proton-rich nucleus ^{21}Al to check isospin conservation beyond the drip line by resonance elastic and inelastic scattering using the active target MAYA. For middle mass nuclei, the validity of a shell model description around ^{78}Ni will be studied and shape coexistence in the region A = 70-80 will be determined with high precision. Statistical properties of warm nuclei will be investigated by the low-energy enhancement of the gamma strength function of neutron rich nuclei. For heavier mass nuclei, quadrupole and octupole collectivity will be addressed in the neutron rich Te, Xe and Ba isotopes by Coulomb excitation, lifetime measurements and magnetic moment determination. Collective effects around the double magic ^{132}Sn will be studied. For the heavier nuclei, shape coexistence in the light Pb isotopes will be explored. Measurements of octupole collectivity in the Rn and Ra nuclei using Coulomb excitation will continue after the success in the determination of octupole character of ^{224}Ra and the octupole vibrator character deduced for ^{220}Rn [4]. In the quest of super-heavies, it is proposed to investigate the influence of the predicted shell closures at Z = 120 and N = 184 by probing the height of the fission barrier. This will be achieved by exploring the contributions of quasi-fission and fusion-fission reactions; in particular the deformed ^{95}Rb beam on a ^{209}Bi target is expected to permit the study of these features. The nuclei chosen for day one physics at HIE-ISOLDE are shown in red in the chart of the nuclides displayed in Fig. 2.

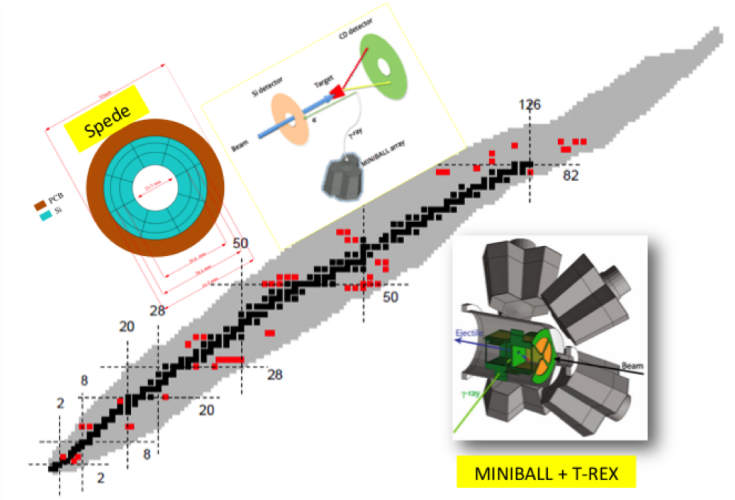

FIGURE 2. Layout of the ISOLDE facility.

The proposed studies will be realised with the most frequently used devices the MINIBALL γ-array [5] and he charged particle Si-detector array, T-REX [6], plus new instrumentation for transfer reaction studies such as the active targets MAYA [7] and the future ACTAR, a new general purpose scattering chamber, the two arms CORSET setup from GSI,...etc. The MINIBALL γ-array will be complemented with an electron spectrometer, Spede, to realise Coulomb excitation studies of odd-heavy nuclei where many highly converted transitions are expected.

The implementation of a storage ring [8] is highly supported by the CERN management. We intend to setup the heavy-ion, low-energy ring TSR from Heidelberg. Such a device will allow the realization of experiments with stored secondary beams, which will be unique in the world. The physics programme with the TSR is rich and large in scope expanding from investigations of nuclear ground states properties and reaction studies of astrophysical relevance to unique investigations with highly charged ions and pure isomeric beams.

SUMMARY AND OUTLOOK

The future of ISOLDE is bright. ISOLDE has restarted the first of August 2014 with the low energy physics program. With more than 45 years of operation ISOLDE remains as the pioneer ISOL-installation both at the level of designing new devices and production of frontier Physics.

The first phase of HIE-ISOLDE will start for Physics in the autumn of 2015. The physics cases approved expand over the wide range of post-accelerated beams available at ISOLDE . With this upgrade ISOLDE will be the place of choice for any experiment requiring a post-accelerated radioactive beam. We expect to complete phase two in a near future after that.

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The SPES Exotic Beam ISOL Facility: Status of the Project, Technical Challenges, Instrumentation, Scientific Program

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Abstract. SPES (Selective Production of Exotic Species) is the INFN project for a Nuclear Physics facility with Radioactive Ion Beams (RIBs). It is in advanced construction in Legnaro, with several technological innovations and challenges foreseen, comprehensive of new achievements and improvements. SPES will provide mostly neutron-rich exotic beams, derived by the fission fragments (10^{13} fiss/s) produced in the interaction of an intense proton beam (200 μA) on a direct UCx target. The expected SPES beam intensities, their quality and, eventually, their maximum energies (up to 11 MeV/A for A=130) will permit to perform forefront research in nuclear structure and nuclear dynamics, studying a region of the nuclear chart far from stability. This goal will be reached by coordinating the developments on the accelerator complex and those of the experimental set ups. A huge upgrading of the Linac ALPI post-accelerator is being performed. For what it concerns the instrumentation, some set ups are already installed at the Legnaro National Laboratory and they are regularly upgraded. Further efforts are devoted to new developments, which are very innovative and challenging. The new instrumentation is mostly related to international collaborations and it will be available for the experimentation at SPES. Several Letter of Intents have been presented at the Scientific Advisory Panel during the 2nd SPES International Workshop (26-28 May 2014). The presented themes represent a quite large and up-to-date scientific program to be discussed and studied in the forthcoming years, which will prepare the road towards EURISOL.

INTRODUCTION

The SPES exotic beam facility is being constructed at the Legnaro National Laboratory (LNL) in Italy. The Radioactive Beam project is mainly related to the development of an ISOL facility for neutron-rich element production

by means of an intense proton beam (of the order of few hundreds of μA), directly sent onto a sliced UCx target, with the aim of producing up to 10^{13} fissions/s [1].

The proton driver, which is a very innovative cyclotron able to produce up to 70 MeV proton intense beam (up to 750 μA beam current), can deliver two beams simultaneously. This opportunity gives the possibility of performing also interdisciplinary physics studies and appliance, especially devoted to material analysis, neutron production and medical applications (like, for example, the production of radio-isotopes)[2].

Four different independent phases have been proposed with separate financial budgets:

- the α–phase, which is related to the construction of the new building, to the development, set-up, installation and commissioning of the proton-driver and, finally, to the development and installation of the RIB production target areas and set-ups;
- the β–phase, which is related to the RIBS transport and post-acceleration performed with the upgraded ALPI Linac post-accelerator;
- the γ–phase, related to medical applications and radioisotope production.
- the δ–phase, which is dealing with a dedicated area for proton and neutron beam irradiation facilities;

The SPES project

The SPES ISOL facility bases on a commercial, newly designed, 70 MeV Cyclotron as proton driver produced by the BEST Theratronics Company [3]. The proton driver will provide a beam intensity up to 750 μA, with variable energy ranging between 35 and 70 MeV. The cyclotron is a compact four-sector machine, energized by a pair of room temperature conducting coils. Two independent extraction channels are positioned at 180° and can provide two proton beams simultaneously. The H^- beam is provided by an external ion source with a current of about 15-20 mA, which is necessary to deliver the 750 μA designed current at the exit of the cyclotron. The accelerator is under construction and test in Ottawa (Canada). It will be transported and commissioned at LNL in the late fall 2014. The proton beam will impinge on a direct multi-foil target (mainly UCx) in order to reach the designed number of fissions (10^{13} fissions/s). Different Target-Ionization Sources systems (TIS) are being developed and will be used to optimize the extraction efficiency of the desired isotopes, while minimizing the beam contaminants. The radioactive beams (RIBs) will be selected through a High Resolution Mass Spectrometer (HRMS), before being transported towards the Charge Breeder stage. A cross section of the SPES layout is displayed in Fig.1: the Cyclotron area is shown on the right part. The area dedicated to applications is also visible on the very right part of the layout, while, just on the left side of the Cyclotron area, the two RIB target bunker are displayed.

The target-ion source system is one of the key elements of the SPES project: the target is based on a multi-foil structure design (7 thin UCx disks for a total of 30g of Uranium). Considering a 40 MeV high intense proton beam (200 μA), the power on target is 8 kW. The resulting power density on target is such to maintain the temperature well under the UCx melting point (2350 °C) [4]. The proposed target geometry have demonstrated to support much higher currents with respect to the compact configuration [5]. Test on target materials have been performed at ORNL (Tennessee, USA) [6] and at iTHEMBA Lab (CapeTown, South Africa) [7]. Besides UCx, further target materials (SiC, B_4C, ZrC, Al_2O_3, CeS, LaCx, TaC etc.) are under development to produce some neutron deficient beams. The production target is part of the TIS system (Target-Ion Source). Different kind of sources have been developed to optimize the extraction procedure and to minimize the contamination: among them the Surface Ionization Source (SIS), the Plasma Ion Source (PIS) and the Laser Ionization Source (LIS). The hot-cavity ion source chosen for the SPES project is based on that one designed at CERN (ISOLDE) [8]. In particular, the Surface Ion Source has good efficiency and selectivity for the elements as Rb, Cs, Ba. Using a similar hot cavity cell, the laser resonant photo-ionization, is a powerful method to achieve sufficiently selected exotic beams for most of the elements [9]. However, in order to ionize elements with high ionization potential like the rare gasses, the plasma source is needed: even though this source easily ionize many elements, it has the drawback of not being selective at all. Both surface and plasma sources have been developed and in operation at the offline test-bench laboratory. The laser ionization technique is under development aiming at producing the most pure beams as possible (chemical selectivity) also for metal isotopes. For this purpose, a new laser Laboratory has been installed at LNL.

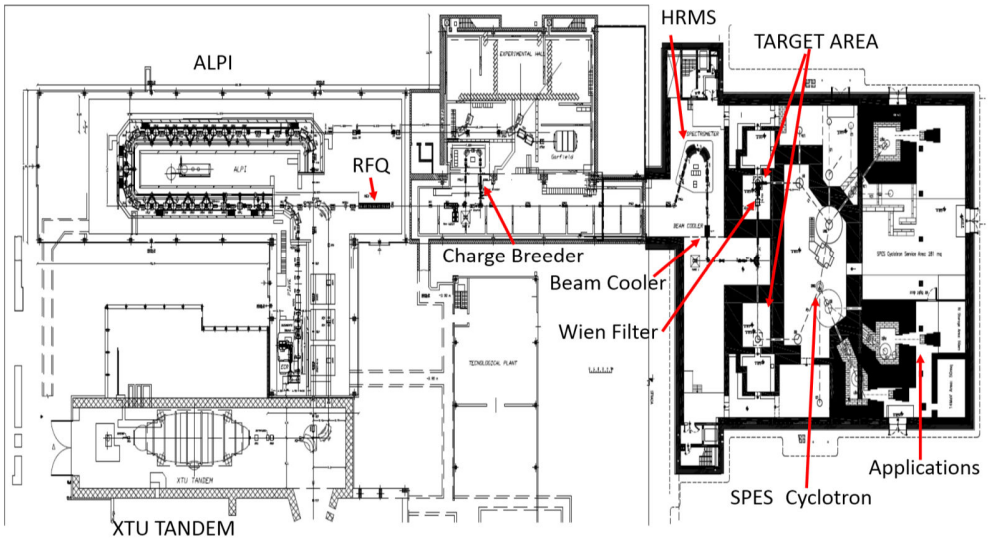

Figure 1. The SPES Layout

Just at the exit of the TIS system a Wien Filter and a first series of Dipoles and short Triplets magnets perform the first selection (ΔM/M =1/200). The transfer line is designed to pass through a Beam Cooler stadium, which is necessary to properly inject the beam into a High Resolution Mass Spectrometer. The Spectrometer (HRMS) is conceived to reach an effective mass resolution of at least ΔM/M =1/20000. To reach this goal, the HRMS physics design in the SPES configuration is made so to reach a resolution of ΔM/M =1/40000, value which is constrained by values of 3π mm mrad in emittance and 1.3 eV in energy spread. A by-pass line is also foreseen with the double aim either to by-pass the high resolution stadium, when required, or to transport back the exotic beams to the low energy area as shown in Fig.2. As shown in the layout, at the exit of the HRMS or after the by-pass, the transport line continues until the Charge Breeder, after which a further selection is provided by a Medium Resolution Mass Spectrometer MRMS (ΔM/M =1/1000). This is necessary to clean up the beam from contamination deriving by the breeding stadium. A new normal conductive RFQ injector is being designed to properly inject the RIBs into the Linac ALPI for the post-acceleration. The ALPI post accelerator is undergoing a major upgrading in terms of transmission properties, i.e. intensities, and maximum energies.

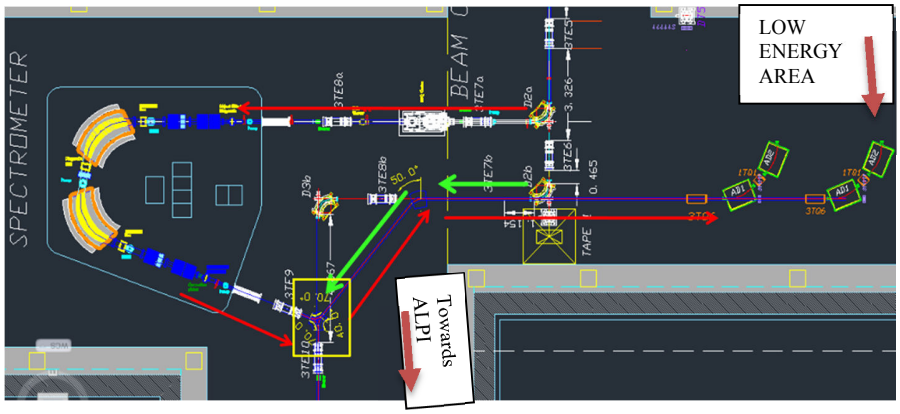

Figure 2. The High Resolution Mass Spectrometer and the By-pass line.

Finally, the selected exotic beam will reach the experimental area where the secondary target, provided by the user for the proposed experiments, will be set up.
The new building design has been approved and the construction is in an advanced phase as shown in Fig. 3. The operation of the cyclotron has already been authorized, comprehensive of the extraction and interaction of 5 μA proton beam on UCx target, for the *first day* experimental activity.

Figure 3. The SPES Construction Site

The SPES performances in terms of beam intensities at the production/extraction point (after the ionization source 1^+) and at the secondary target (experiment) position (post-accelerated intensities) have been evaluated and they are reported in ref. [8].
The SPES scientific program is under discussion based on the long-standing experience in nuclear structure and dynamics studies of the LNL and LNS international user communities. In particular, one of the traditional fields is the study of nuclei under extreme conditions, that is the study of the evolution of nuclear structure towards the region far from stability in terms of excitation energy (decay and behavior of hot nuclei), high spin states (highly rotating nuclei), and, finally, high isospin (high N over Z ratio). Large efforts are devoted to the upgrading of installed experimental set-ups (PRISMA [12], GARFIELD [13] etc.). The developments of new instrumentation (GALILEO, AGATA, ATS_ACTAR, FAZIA, NEDA, PARIS, TRACE, SPIDER etc.) are also performed within international collaborations in order to carry out up-to-date experimentation at SPES, as it was recently discussed in the 2nd International SPES Workshop (May 26-28 2014), where about 40 Letter of Intents have been presented and discussed [10].

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Ideas and instrumentation for ISOL@MYRRHA

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Abstract. ISOL@MYRRHA at SCK•CEN in Mol, Belgium, is a project for an Isotope Separation On-Line (ISOL) facility that would use a fraction of the proton beam of the MYRRHA accelerator to produce radioactive nuclei for fundamental and applied research. The facility will prioritise experiments requiring extended beam times and stable operation conditions. The physics case and associated instrumentation of ISOL@MYRRHA is addressed in a number of dedicated workshops taking place yearly at SCK•CEN.

Keywords: ISOL method, radioactive nuclei, nuclear spectroscopy
PACS: 29.25.Rm,29.38.-c,29.40.-n

THE ISOL@MYRRHA PROJECT

The Belgian Nuclear Research Centre in Mol (SCK•CEN) has been working for several years on the multi-purpose irradiation facility MYRRHA [1, 2]. The facility is conceived as an accelerator driven system (ADS), with a fast-spectrum research reactor (50-100 MW_{th}) capable of operating both in sub-critical and critical modes, driven by a 600-MeV, 4-mA linear proton accelerator. ISOL@MYRRHA [3] is a project for an Isotope Separation On-Line (ISOL) facility that would use a fraction of the proton beam of the MYRRHA accelerator to produce radioactive nuclei for fundamental and applied research. In the current conceptual design an average 100- to 200-μA beam would impinge on a ruggedised target-ion source system, which would allow the use of a range of materials (including actinides) dissipating the high power deposited. A two-stage mass separator incorporating a radio-frequency cooler and buncher would deliver high-quality and -purity radioactive ion beams (RIBs) at an energy around 60 keV. The projected yields at ISOL@MYRRHA were extrapolated from data collected at ISOLDE-CERN (Switzerland) and ISAC-TRIUMF (Canada) [4]. An increase of up to two order of magnitude for fission fragments may be reachable.

Currently a full technical design of the facility is being prepared at SCK•CEN. The project is supported through the Belgian Research Initiative on Exotic Nuclei (BriX), a network of the Interuniversity Attraction Poles (IAP) Programme, which brings together the Belgian expertise on nuclear physics, nuclear astrophysics and accelerator-driven systems. ISOL@MYRRHA and MYRRHA have several aspects of interest for the EURISOL project. To exploit possible synergies, a Belgian Eurisol Consortium (BEC[1]) has been created in 2013 to coordinate the ISOL-related R&D programmes in Belgium. In 2014 the BEC has then joined the EURISOL Collaboration.

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[1] The BEC partners: SCK•CEN, Universiteit Gent, KU Leuven, Vrij Universiteit Brussel, Université Libre de Bruxelles, The von Karman Institute for Fluid Dynamics, Bel V.

THE PHYSICS CASE

An important requirement of the MYRRHA linear accelerator is reliability over long periods: the goal is to limit beam failures (i.e. beam missing for more than 3 seconds) to less than one every ten days, on typical cycles of three months of operation followed by one month maintenance. This will allow stable operation of the ISOL@MYRRHA target-ion source for extended periods of time. The physics programme will take advantage of this feature prioritising experiments which require extended beam times and operation in very stable conditions. Thus experiments that:

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

The availability of very long beam times is of interest for most of the research fields employing RIBs. Examples include high-precision measurements for fundamental interaction studies, very high-resolution spectroscopy for nuclear structure, and long systematic studies on samples for condensed matter and biology applications [5].

A series of workshops is organised around the specific topics, with the aim of detailing the physics cases, build a users community and collect information that will help in the design of the final layout of the facility. Three of these workshops have already taken place on fundamental interactions (October 2011), detailed decay spectroscopy (April 2012) and RIB production and high-power target stations (September 2013, jointly organised with CERN-ISOLDE, GANIL-SPIRAL2 and TRIUMF-ARIEL). A topical day on medical applications of ISOL@MYRRHA is taking place in November 2014.

In the workshop on fundamental interactions [6] a number of experimental observables were identified, which would greatly benefit from the long beam times needed to collect the required high statistics, and investigate systematic instrumental effects by performing repeated reference measurements to characterise the setups. For example, experiments aiming at measuring the beta-neutrino correlation, probing the structure of the weak interaction; the beta-asymmetry parameter, searching for tensor-type weak interactions; atomic-parity violation; tests of Lorentz violation; precision mass measurements; precision half-life and beta-branching measurements, would all take advantage of very stable conditions on a long time base.

During the workshop on detailed spectroscopy [7] it was pointed out how, besides information on the most exotic systems, present-day nuclear structure theory needs complete, systematic and very precise information on a number of key cases, identified also in nuclei near the valley of stability. This emerges from a number of studies where it was shown that even very weak signals can call into question well-established nuclear models, forcing to invoke new mechanisms to explain the newly-acquired data. For example, see Refs. [8, 9] concerning the picture of β-vibrations and the true nature of low-lying 0^+ states. "Complete" spectroscopy implies that the largest possible number of observables of a nuclear system have to be determined: spins, parities and lifetimes of levels, but also the multipolarity and strength of transitions, including $E0$, with attention to weak, low-energy branches revealing cross-band transitions; but also magnetic and

quadrupole moments, which entail different detection techniques altogether. This sort of approach is in line with the profile of the ISOL@MYRRHA facility.

INSTRUMENTATION

Indications concerning the instrumentation that should equip the ISOL@MYRRHA facility have emerged from the previous workshops, and will be further integrated with the information from the forthcoming ones on laser and atomic physics and applications.

Measurements that concern research on fundamental interactions, as well as several other experiments, involve ion and atomic traps, i.e. electrostatic, Paul, Penning and magneto-optical traps (MOT). To achieve high-precision measurements, a complete characterisation of the setups is necessary. This implies that the setups should be permanent ones, with the floor plan of the facility organised accordingly. For the same reason, the data-acquisition system should have a high degree of diagnostics to identify and eliminate all experimental effects.

Concerning the beam characteristics, a high purity is necessary prior to the injection in a trap to avoid space-charge issues due to contaminants. Some of the measurements (beta-asymmetry parameter, tests of Lorentz violation) require polarised samples in traps, a technique that has been pioneered at TRIUMF and is being implemented at other laboratories (for a review see Ref. [10]).

Operation in multi-user mode would be desirable considering the long beam times planned for each experiment at ISOL@MYRRHA. Fundamental interactions studies in particular are well-suited for such a scheme, because they tend to use a limited set of isotopes that could be shared by running experiments in parallel, and because of the low duty cycle typical of such measurements. Such schemes have been considered at other facilities but rarely implemented in practice so far; at ISOL@MYRRHA, however, this becomes even more important for the reasons illustrated above.

The importance of "complete" spectroscopy for detailed nuclear structure studies has been mentioned in the previous section: the decay spectroscopy setups at ISOL@MYRRHA should reflect this need. Several examples have been presented and discussed at the dedicated workshop in 2012, with indications on possible critical points and suggested improvements. The importance of a reliable tape system for sample transportation at decay stations was underlined. The tape system should interfere as little as possible with the detector arrangement, preserving a high-efficiency detection that would combine, for example, γ-ray and electron-conversion spectroscopy. The conversion-electron detectors should be segmented, to cope with high rates. The γ-ray detectors may combine high-resolution elements for detailed spectroscopy with fast-timing elements for the measurement of half lives. Still, the setup should retain a certain degree of simplicity and symmetry in order to avoid complex effects due to multiple scattering of radiation. For example, it is desirable that β-tagging elements have a one-to-one correspondence with high-resolution γ-ray detectors, to place anti-coincidence gates and eliminate spurious signals due to high-energy β's.

For some specific physics cases complementary information is obtained from additional detection arrays. A neutron array becomes important when the nuclei to be investigated approach the neutron drip line and delayed emission appears. Such an array has

specific requirements in terms of floor space, with free surrounds to minimise neutron scattering background. Total-absorption spectroscopy (TAS) provides unmissable information on the complete and correct strength distributions within the decay window. The decay pattern is also an indicator of nuclear shapes [11], while the measurement of the decay Q-value can be used to determine the energy of isomers [12].

A crystal spectrometer [13, 14] would enable γ-ray detection with ultra-high resolution. The detailed study of γ-line shapes can be used for the measurement of strength distributions and half lives [15]; additionally, weak transitions can be separated in multiplets. The extremely high resolution of a crystal spectrometer (up to 10^{-6}) comes at the price of a very low efficiency. Using a single-bent crystal instead of a double-flat crystal geometry would improve the efficiency, preserving a significantly better resolution than HPGe detectors. A very promising outlook is the recent development of γ-ray lenses [16] which would boost the efficiency significantly. An important factor of these detection devices is the space requirement, as a long baseline is needed to separate the diffracted γ rays.

ACKNOWLEDGMENTS

This work summarizes some of the activities of members of the ISOL@MYRRHA Collaboration, whose contributions are here acknowledged, in particular those of the authors of Refs. [6, 7]. The workshops around the physics at ISOL@MYRRHA have been organised jointly by SCK•CEN and the members of the nuclear physics group of the KU Leuven (Profs M. Huyse, G. Neyens, N. Severijns, P. Van Duppen, and RR). The list of the participants to those workshops, whose ideas contributed to the shaping of the physics cases and the facility itself, is too long to be reported here, and can be found on the websites of the meetings [3]. They are all warmly thanked for their efforts.

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A Fast-Timing Array for Measuring Sub-nanosecond Half-lives

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Abstract.
A fast-timing γ-ray spectrometer aimed at measuring sub-nanosecond half-lives in exotic nuclei using $LaBr_3$(Ce) detectors is presented. The array will be used to exploit high intensity radioactive beams at future in-flight and ISOL facilities such as FAIR and SPIRAL2, respectively. The fast-timing array will be used with other novel and existing charged particle and neutron detector arrays, such as AIDA to measure implant-decay correlations. The final design of the fast-timing array was determined using the full-energy peak efficiencies of various detector geometries, calculated using the Monte-Carlo simulation package GEANT4. Timing precisions were then calculated based on the results of the simulated efficiencies for each configuration. As a result of this work, an array of 36 ø3.8x5.1 cm cylindrical crystals was determined to be the best configuration.

Keywords: GEANT4, Simulations, Fast-timing, $LaBr_3$(Ce)
PACS: 21.60.Ka, 29.30.Kv, 29.40.Mc

MOTIVATION

The Facility for Anti-proton and Ion Research (FAIR) [1] will include a new synchrotron, and in-flight separator (Super-FRS) [2] capable of delivering a large number of high intensity, rare iostope beams. In addition to this 'next generation' radioactive-ion beam in-flight facility, other facilities such as HIE-ISOLDE [3] and SPIRAL2 [4], promise intense beams of fisson fragments as well as high intensity radioactive ion and stable beams using the ISOL technique.

In order to exploit these beams, a setup focusing on the decay spectroscopy of very short-lived nuclei at the extremes of exsistence [5, 6] is envisaged, comprising a modular high-efficiency γ-ray spectrometer of $LaBr_3$(Ce) crystals that will be used to measure the half-lives of sub-nanosecond excited states by taking the time difference between the γ rays feeding and de-exciting the level of interest using $\gamma\gamma$ coincidences [7]. This array will work alongside the Advanced Implantation Detector Array (AIDA) [8], which consists of a stack of 20 8x8 cm double-sided silicon strip detectors (DSSDs), each with a thickness of 0.1 cm, and neutron detector arrays [9] in cases of β-delayed neutron emission.

TABLE 1. The crystal types used in the simulations along with their measured timing resolutions at 1.3 MeV. The coincidence timing precisions (TP) were normalised to the ø2.5x2.5 cm detectors.

#	Dimensions (cm)	CRT_{FWHM} (ps) at 1.3 MeV	*Relative TP* at 1.3 MeV	*Relative TP* at 4 MeV
8	ø5.1x5.1	300 [7]	0.34	0.21
10	ø3.8x5.1	210 (measured)	0.34	0.24
10	ø3.8x3.8	180 [7]	0.41	0.30
13	ø2.5x2.5	150 [12, 7, 13]	1.00	1.00
13	ø2.5x3.8xø3.8 (conical)	160 [13]	0.44	0.37
13	ø1.9x4.7xø3.8 ('hybrid')	-	0.10	0.04

MONTE-CARLO SIMULATIONS

The Monte-Carlo simulation package GEANT4 [10] was used to determine the full-energy peak (FEP) efficiencies of cylindrical crystals with dimensions; ø2.5x2.5 cm, ø3.8x3.8 cm and ø5.1x5.1 cm, which were compared with conical and 'hybrid' crystals. The 'hybrid' crystal is defined as a truncated cone with front and back diameters of ø1.9 and ø3.8 cm, attached to a cylinder with dimensions of ø3.8x4.7 cm. The conical crystals have front and back diameters of ø2.5 and ø3.8 cm respectively, and a length of 3.8 cm.

The AIDA implantation point was treated as a point source, which emitted 10^6 γ-ray events with energies from 0.1 to 4 MeV. The simulations also included the aluminium can around AIDA, which has dimensions of 10x10x50 cm and a thickness of 0.2 cm. The minimum radius for which an integer number of each detector type can be tiled into a ring around the AIDA implantation plane, was calculated to be 8.3 cm. The number of each detector type needed in one ring around AIDA is presented in the first column of Table 1 along with their typical coincidence resolving times (CRTs) at full-width half maximum (FWHM) in the second column.

The FEP efficiencies for one ring of each of the proposed detector types were simulated, with a ring of 13 hybrid crystals found to have the highest efficiency for $E_\gamma \geq 0.2$ MeV. The ø5.1x5.1 cm crystals were found to have more dead space between the adjacent detectors when tiled around the implantation point than the hybrid detectors due to the lack of truncation at the front of the crystals. For $E_\gamma \geq 0.2$ MeV, this resulted in a lower efficiency for the ø5.1x5.1 cm crystals than the hybrid crystals. For $E_\gamma \leq 0.2$ MeV, the hybrid crystals have an efficiency comparable to that of the ø3.8x5.1 cm crystals due to the smaller diameter at the front of each crystal. A ring of eight ø3.8x5.1 cm crystals has the third highest FEP efficiency ($\sim$5 % for E_γ=0.5 MeV). The FEP efficiencies of the remaining geometries (ø2.5x2.5 cm and conical crystals), were found to be lower than the other simulated configurations.

Timing Precisions

A coincidence timing precision can be calculated using the timing response and efficiency of coincident detectors, defined by Mach [11] to be:

$$Timing\ \ Precision\ (TP) = \frac{CRT_{\mathrm{FWHM}}}{\sqrt{N}}, \tag{1}$$

where CRT_{FWHM} is the coincidence response time at FWHM and N is the total number of coincidences in the time spectrum.

The last two columns of Table 1 show the results of calculations that used the CRT at 1.3 MeV, along with the simulated FEP efficiencies for a ring of each detector type. The timing precision for a ring of conical detectors at 4 MeV was approximated using the CRT of the conical detectors at 1.3 MeV, along with their simulated efficiencies at 4 MeV. The timing precision for a ring of hybrid detectors was approximated using the measured CRT of the ø3.8x5.1 cm detectors. All the detectors used their simulated efficiencies at 4 MeV along with their CRT at 1.3 MeV to get an approximate value for the timing precision at 4 MeV.

Table 1 shows the ø5.1x5.1 cm and ø3.8x5.1 cm detectors to be factors of $\sim$5 and $\sim$2 better than the ø2.5x2.5 cm and conical detectors at 4 MeV respectively. Consequently, these detectors along with the hybrid detectors were found to perform the best. Table 1 shows little difference in the coincidence timing precisions for both the ø5.1x5.1 cm and ø3.8x5.1 cm crystals. Thus in order to maintain the need for a modular array and minimise costs, the ø3.8x5.1 cm and hybrid detectors were selected for further consideration.

Full Array Configuration

The right panel of Fig. 1 shows two of the full array configurations that were simulated; a cross configuration of 24 detectors with 12 additional detectors at 45° (‘cross+45°’) and a ‘ball’ configuration of 36 detectors. The simulations of these configurations included 2 mm of lead shielding around each detector in order to increase the peak-to-background ratio by minimising Compton scattering between the adjacent crystals. The FEP efficiencies for multiplicity one γ rays up to 4 MeV are shown in the left panel of Fig. 1. The hybrid detector array of 36 detectors has a higher FEP efficiency than an array of 36 ø3.8x5.1 cm crystals in both configurations [14]. This is likely to be due to the increase in the solid angle coverage due to the tapering of the hybrid detectors. However, due to the lack of concrete data currently available in the literature for these detectors, 36 ø3.8x5.1 cm crystals in a ‘cross+45°’ configuration was chosen as the best design [14, 15]

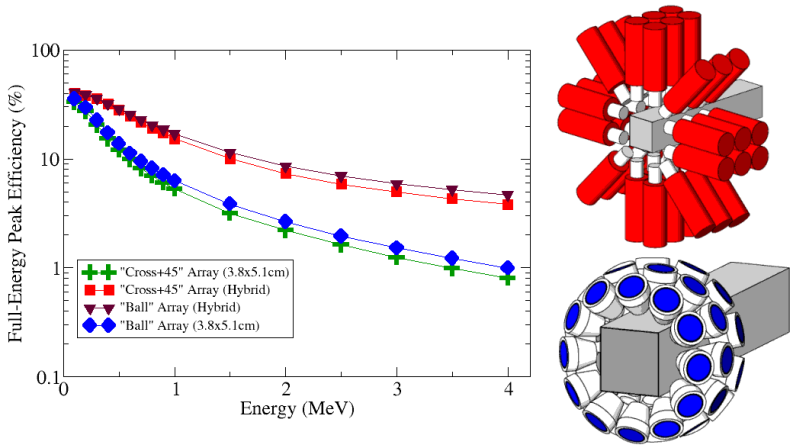

FIGURE 1. Left: The FEP efficiencies of 36 hybrid and ø3.8x5.1 cm crystals in two configurations; the 'cross + 45°' and 'ball' setups. The statistical errors are smaller than the data points. Right: The 'cross + 45°' and 'ball' configurations of 36 ø3.8x5.1 cm $LaBr_3$(Ce) and hybrid crystals, each housed in aluminium cans around AIDA. The PMT housing is also shown in the top figure.

FUTURE AND OUTLOOK

Based on the results of these simulations, 31 3.8x5.1 cm $LaBr_3$(Ce) detectors were subsequently bought and characterised. These detectors will be used to augment existing HPGe arrays in prospective experiments. The GEANT4 simulation code will be developed in order to determine how a distributed source of γ rays will affect the timing precision that can be obtained, and will be the subject of a future paper.

ACKNOWLEDGMENTS

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A Fast-Timing Array for Measuring Sub-nanosecond Half-lives

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Abstract.
A fast-timing γ-ray spectrometer aimed at measuring sub-nanosecond half-lives in exotic nuclei using $LaBr_3$(Ce) detectors is presented. The array will be used to exploit high intensity radioactive beams at future in-flight and ISOL facilities such as FAIR and SPIRAL2, respectively. The fast-timing array will be used with other novel and existing charged particle and neutron detector arrays, such as AIDA to measure implant-decay correlations. The final design of the fast-timing array was determined using the full-energy peak efficiencies of various detector geometries, calculated using the Monte-Carlo simulation package GEANT4. Timing precisions were then calculated based on the results of the simulated efficiencies for each configuration. As a result of this work, an array of 36 ø3.8x5.1 cm cylindrical crystals was determined to be the best configuration.

Keywords: GEANT4, Simulations, Fast-timing, $LaBr_3$(Ce)
PACS: 21.60.Ka, 29.30.Kv, 29.40.Mc

MOTIVATION

The Facility for Anti-proton and Ion Research (FAIR) [1] will include a new synchrotron, and in-flight separator (Super-FRS) [2] capable of delivering a large number of high intensity, rare iostope beams. In addition to this 'next generation' radioactive-ion beam in-flight facility, other facilities such as HIE-ISOLDE [3] and SPIRAL2 [4], promise intense beams of fisson fragments as well as high intensity radioactive ion and stable beams using the ISOL technique.

In order to exploit these beams, a setup focusing on the decay spectroscopy of very short-lived nuclei at the extremes of exsistence [5, 6] is envisaged, comprising a modular high-efficiency γ-ray spectrometer of $LaBr_3$(Ce) crystals that will be used to measure the half-lives of sub-nanosecond excited states by taking the time difference between the γ rays feeding and de-exciting the level of interest using $\gamma\gamma$ coincidences [7]. This array will work alongside the Advanced Implantation Detector Array (AIDA) [8], which consists of a stack of 20 8x8 cm double-sided silicon strip detectors (DSSDs), each with a thickness of 0.1 cm, and neutron detector arrays [9] in cases of β-delayed neutron emission.

TABLE 1. The crystal types used in the simulations along with their measured timing resolutions at 1.3 MeV. The coincidence timing precisions (TP) were normalised to the ø2.5x2.5 cm detectors.

#	Dimensions (cm)	CRT_{FWHM} (ps) at 1.3 MeV	*Relative TP* at 1.3 MeV	*Relative TP* at 4 MeV
8	ø5.1x5.1	300 [7]	0.34	0.21
10	ø3.8x5.1	210 (measured)	0.34	0.24
10	ø3.8x3.8	180 [7]	0.41	0.30
13	ø2.5x2.5	150 [12, 7, 13]	1.00	1.00
13	ø2.5x3.8xø3.8 (conical)	160 [13]	0.44	0.37
13	ø1.9x4.7xø3.8 ('hybrid')	-	0.10	0.04

MONTE-CARLO SIMULATIONS

The Monte-Carlo simulation package GEANT4 [10] was used to determine the full-energy peak (FEP) efficiencies of cylindrical crystals with dimensions; ø2.5x2.5 cm, ø3.8x3.8 cm and ø5.1x5.1 cm, which were compared with conical and 'hybrid' crystals. The 'hybrid' crystal is defined as a truncated cone with front and back diameters of ø1.9 and ø3.8 cm, attached to a cylinder with dimensions of ø3.8x4.7 cm. The conical crystals have front and back diameters of ø2.5 and ø3.8 cm respectively, and a length of 3.8 cm.

The AIDA implantation point was treated as a point source, which emitted 10^6 γ-ray events with energies from 0.1 to 4 MeV. The simulations also included the aluminium can around AIDA, which has dimensions of 10x10x50 cm and a thickness of 0.2 cm. The minimum radius for which an integer number of each detector type can be tiled into a ring around the AIDA implantation plane, was calculated to be 8.3 cm. The number of each detector type needed in one ring around AIDA is presented in the first column of Table 1 along with their typical coincidence resolving times (CRTs) at full-width half maximum (FWHM) in the second column.

The FEP efficiencies for one ring of each of the proposed detector types were simulated, with a ring of 13 hybrid crystals found to have the highest efficiency for $E_\gamma \geq 0.2$ MeV. The ø5.1x5.1 cm crystals were found to have more dead space between the adjacent detectors when tiled around the implantation point than the hybrid detectors due to the lack of truncation at the front of the crystals. For $E_\gamma \geq 0.2$ MeV, this resulted in a lower efficiency for the ø5.1x5.1 cm crystals than the hybrid crystals. For $E_\gamma \leq 0.2$ MeV, the hybrid crystals have an efficiency comparable to that of the ø3.8x5.1 cm crystals due to the smaller diameter at the front of each crystal. A ring of eight ø3.8x5.1 cm crystals has the third highest FEP efficiency ($\sim$5 % for E_γ=0.5 MeV). The FEP efficiencies of the remaining geometries (ø2.5x2.5 cm and conical crystals), were found to be lower than the other simulated configurations.

Timing Precisions

A coincidence timing precision can be calculated using the timing response and efficiency of coincident detectors, defined by Mach [11] to be:

$$Timing\ \ Precision\ (TP) = \frac{CRT_{\mathrm{FWHM}}}{\sqrt{N}}, \tag{1}$$

where CRT_{FWHM} is the coincidence response time at FWHM and N is the total number of coincidences in the time spectrum.

The last two columns of Table 1 show the results of calculations that used the CRT at 1.3 MeV, along with the simulated FEP efficiencies for a ring of each detector type. The timing precision for a ring of conical detectors at 4 MeV was approximated using the CRT of the conical detectors at 1.3 MeV, along with their simulated efficiencies at 4 MeV. The timing precision for a ring of hybrid detectors was approximated using the measured CRT of the ø3.8x5.1 cm detectors. All the detectors used their simulated efficiencies at 4 MeV along with their CRT at 1.3 MeV to get an approximate value for the timing precision at 4 MeV.

Table 1 shows the ø5.1x5.1 cm and ø3.8x5.1 cm detectors to be factors of $\sim$5 and $\sim$2 better than the ø2.5x2.5 cm and conical detectors at 4 MeV respectively. Consequently, these detectors along with the hybrid detectors were found to perform the best. Table 1 shows little difference in the coincidence timing precisions for both the ø5.1x5.1 cm and ø3.8x5.1 cm crystals. Thus in order to maintain the need for a modular array and minimise costs, the ø3.8x5.1 cm and hybrid detectors were selected for further consideration.

Full Array Configuration

The right panel of Fig. 1 shows two of the full array configurations that were simulated; a cross configuration of 24 detectors with 12 additional detectors at 45° (‘cross+45°’) and a ‘ball’ configuration of 36 detectors. The simulations of these configurations included 2 mm of lead shielding around each detector in order to increase the peak-to-background ratio by minimising Compton scattering between the adjacent crystals. The FEP efficiencies for multiplicity one γ rays up to 4 MeV are shown in the left panel of Fig. 1. The hybrid detector array of 36 detectors has a higher FEP efficiency than an array of 36 ø3.8x5.1 cm crystals in both configurations [14]. This is likely to be due to the increase in the solid angle coverage due to the tapering of the hybrid detectors. However, due to the lack of concrete data currently available in the literature for these detectors, 36 ø3.8x5.1 cm crystals in a ‘cross+45°’ configuration was chosen as the best design [14, 15]

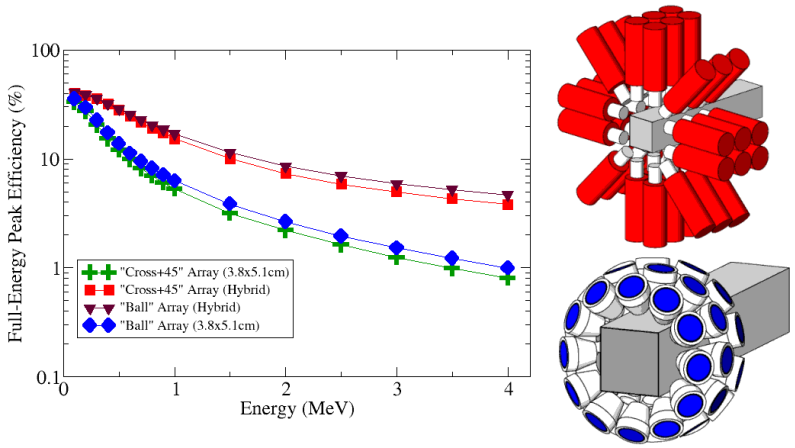

FIGURE 1. Left: The FEP efficiencies of 36 hybrid and ø3.8x5.1 cm crystals in two configurations; the 'cross + 45°' and 'ball' setups. The statistical errors are smaller than the data points. Right: The 'cross + 45°' and 'ball' configurations of 36 ø3.8x5.1 cm $LaBr_3$(Ce) and hybrid crystals, each housed in aluminium cans around AIDA. The PMT housing is also shown in the top figure.

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Based on the results of these simulations, 31 3.8x5.1 cm $LaBr_3$(Ce) detectors were subsequently bought and characterised. These detectors will be used to augment existing HPGe arrays in prospective experiments. The GEANT4 simulation code will be developed in order to determine how a distributed source of γ rays will affect the timing precision that can be obtained, and will be the subject of a future paper.

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Production of Proton Spin Polarization in a Low Magnetic Field and at High Temperature

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Abstract. A technique based on an electron polarization in photo-excited triplet states of aromatic molecules can provide us with a uniques opportunity to polarized protons in a solid material under a condition of a low magnetic field of 0.1–0.3 T and temperature higher than 100 K. We have applied the technique to a polarized proton target specialized to radioactive nuclear beam experiments and succeeded in measuring analyzing power in the p-^{6,8}He elastic scatterings. We present an overview of the target system and recent progress towards a high proton polarization at room temperature.

Keywords: Proton polarization, photo-excited triplet states, nuclear reaction
PACS: 29.25.Pj, 76.70.Fz, 24.70.+s

INTRODUCTION

Recent experimental and theoretical studies have revealed that spin degrees of freedom play a vital role in exotic nuclei. Tensor force effects on the evolution of shell and possible occurrence of p-n pairing in the proton-rich region are good examples of manifestations of spin degrees of freedom. In exploring the spin effects in exotic nuclei, scattering with polarized protons should be a powerful tool.

We have constructed a novel polarized proton solid target[1, 2], aiming to shed light of polarization on the physics of exotic nuclei. A distinguished feature of the target system is that it works under a low magnetic field of 0.1–0.3 T and a high temperature of > 100 K, which exhibits a striking contrast to standard dynamical nuclear polarization (DNP) targets working in extreme conditions of several Tesla and sub-Kelvin.

OVERVIEW OF THE TARGET

A key feature that singles out the target system among many spin-polarized solid proton targets developed worldwide[3] is operation conditions of a low magnetic-field

and high-temperature. In particular, the low magnetic field is mandatory in RI-beam experiments where detection of low-energy recoil particle produced by reactions is of practical importance. On the other hand, high temperature operation free one from using high-performance cryogenic devices which requires sophisticated techniques. The polarization in a low magnetic field and at high temperature can be produced with a technique based on an electron polarization in photo-excited triplet states of aromatic molecules. The electron polarization in a photo-excited triplet state of pentacene can be as large as $\sim$70% and depends neither on a magnetic field strength nor temperature. Protons in a naphthalene, or *p*-terphenyl, crystal doped with a small amount of pentacene (0.001–0.01 mol%) can be polarized by transferring the electron polarization by means of a cross polarization technique[4]. The method is called as "Triplet-DNP". We have constructed a polarized target system based on the technique and applied it to p-^{6,8}He elastic scattering experiments at RIPS, RIKEN[5, 6, 7]. Recently the target system was used in the $(\vec{p}, 2p)$ knockout reactions experiment for unstable oxygen isotopes at RI Beam Factory[8]. Details of the target system can be found in Refs.[1, 2]

TOWARDS ROOM-TEMPERATURE POLARIZATION

It has always been a dream to produce a high proton polarization in solid materials at *room temperature*. The room-temperature operation will definitely expand the applicability of the proton polarization. One promising direction is to apply the polarized target to low-energy RI-beam experiments. Polarization observables in low-energy reactions such as transfer reactions and proton resonant scatterings[9] are known to be good signatures of spin-dependent nuclear structure, The sensitivities are hardly available otherwise. At present, the target material is cooled down to $\sim$100 K by keeping it in cold nitrogen gas atmosphere. The room-temperature operation absolves us from use of the nitrogen gas ($\sim$40 mg/cm^2) and films to separate beam-line vacuum and the nitrogen atmosphere which are serious obstacles in low-energy experiments[10]. Another stimulating example is an application of the polarization to magnetic resonance imaging with a spin-polarized biomolecules, which will be discussed in the next section.

To achieve a high proton polarization at room temperature, we have to suppress nuclear spin relaxation rate and/or to increase photo-excitation efficiency. It should be noted that, at room-temperature, it is beneficial to use *p*-terphenyl ($C_{18}H_{14}$), instead of naphthalene. It is because one can dope pentacene in a *p*-terphenyl crystal with one-order of magnitude higher concentration ($\sim$0.1 mol%) than in naphthalene, which results in a higher efficiency in polarizing protons provided that sufficiently intense laser is available.

Recently, Tateishi and his collaborators reported that they have succeeded in suppressing nuclear spin relaxation rate at room temperature by (partially) deuterizing *p*-terphenyl and pentacene[11]. They replaced 4 out of 14 protons in a *p*-terphenyl (*p*-terphenyl-d_4) and all the protons in pentacene (pentacene-d_{14}) by deuterons. It was found that the spin-relaxation rate is reduced by a factor of $\sim$4. For the partially deuterized sample, they achieved a proton polarization of 34%.

To achieve high proton polarization in a material with a reasonably large volume, we need a high-power laser that satisfies requirements summarised in Table 1. Although

different lasers, an Ar-ion laser[12], a dye laser[13], and a disk laser[14] has been tested, none of them satisfies all the requirements.

TABLE 1. Specifications required for a laser to be used in pentacene excitation

Wavelength [nm]	590(, 545, 510)
Pulse width [μs]	$\sim$1
Repetition rate [Hz]	$\sim$ 1000

We started to construct a new laser system which satisfies the requirements and fits best to the pentacene excitation. The laser system consists of LD-drived YAG lasers with output wavelength of 1064 nm and 1319 nm and a sum frequency generator crystal to convert light from infrared into 589-nm light which has a sum energy of the 1064- and 1319-nm photons. Test experiments by a prototype laser are found to be quite promising[15]: at 0.6 T and at room temperature, a proton polarization of $\sim$41 % has been achieved in a sample of *p*-terphenyl-d_4 doped with pentacene-d_{14} for a pulse width of 126 nm and a repetition rate of 1 kHz (Fig. 1).

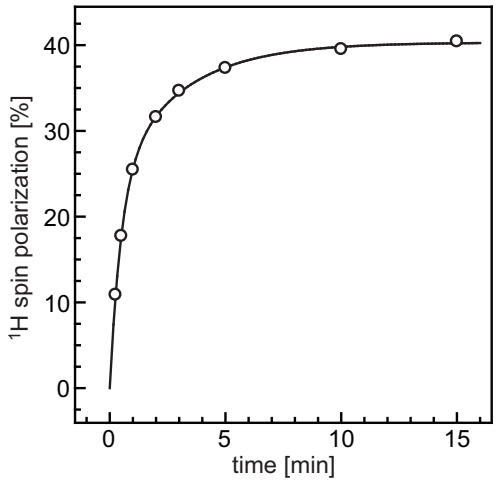

FIGURE 1. Proton polarization at 0.6 T and at room temperature. The new 589-nm laser with a pulse width of 126 nm and a repetition rate of 1 kHz is used.

CHALLENGES FOR FUTURE MEDICAL APPLICATIONS

Medical application of dynamical nuclear polarization is attracting a great deal of attention from researchers in biological and medical sciences[16]. Namely, enhanced polarization of ^{13}C, ^{15}N, ^{19}F isotopes in biomolecules (such as amino acids, lipid, DNA) produced by a DNP method can be used to achieve unprecedented sensitivity in NMR spectroscopy and *in vivo* MRI. Especially, dissolution DNP based on an electron polarization produced in a high magnetic field and at low temperature is accepted as a standard method[17] and substantial efforts are being devoted to broaden the application. Although the dissolution DNP is a secure method, low temperature ($\sim$ 1K) used in the methods requires costly devices and may limit application to some molecules.

The room temperature polarization demonstrated above has a potential to be an alternative to the dissolution DNP. A practical merit of the triplet DNP is that both apparatus and running cost is probably less than the dissolution DNP. At present, the proton polarization can be produced only in aromatic molecules and transfer to other molecules requires challenges. The Osaka University group, recently, reported that ^{19}F polarization in 2,3,4-trifluorobenzoic acid and 5-fluorouracil can be enhanced in glassy matrices codoped with pentacene, at 0.4 T and 120 K[18]. High polarization at room temperature requires further efforts and ideas. We are planning to try several approaches, ex. different mediums to transmit the polarization, super-molecules to interface a pentacene to the target molecules to make the medical application successful.

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Fast-timing Measurements at EURISOL

G.S. Simpson
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Abstract.
The fast-timing method relies on the excellent time resolution of fast scintillator detectors to perform direct timing measurements of lifetimes in the ps-ns region. Cascades of interest are selected with the aide of Ge detectors, to compensate for the moderate energy resolution of the scintillators. The fast-timing technique can be used in a range of setups including β-decay, in-beam and isomer studies. Recent instrumentation and data analysis developments are described.

Keywords: fast timing, lifetimes

INTRODUCTION

A lifetime measurement can directly give information on the properties of a state, for example, the degree of collective or single-particle behaviour present. Fast-timing is a well established experimental technique for measuring lifetimes in the ps–ns time region. It is a direct timing method, relying on the excellent time resolution of scintillator detectors and their associated electronics. The technique was first applied in the picosecond regime to the study of excited states populated following β decay, by Mach and collaborators [1]. The exponential decays in time spectra can be fitted to extract lifetimes upwards of $\sim$100 ps and the centroid-shift method can be used for lifetimes down to just a few picoseconds [1]. These measurements relied on the selectivity of Ge detectors and the fast time response of BaF_2 and plastic scintillators. The development of cerium-doped $LaBr_3$ scintillators, with energy resolutions of $\sim$3 % has rejuvenated these studies in the last decade [2].

Recent developments in fast-timing instrumentation and techniques will be outlined, along ongoing technical developments, within the NuPNET framework.

LIFETIME MEASUREMENTS FOLLOWING β DECAY AT ISOL SOURCES

Lifetimes of excited nuclear states in around 100 radioactive nuclei have been measured using the technique outlined in [1]. It used mass-separated radioactive beams, produced by ISOL or IGISOL sources. The detection setup consisted of a Ge detector, a thin plastic scintillator, for β-particle detection and one or two BaF_2 scintillator γ-ray detectors, which have moderate energy resolution but good timing properties (resolution $\sim$100 ps). The high energy resolution Ge detector selects only a fast γ-ray transition feeding a state of interest. Time measurements are then taken using the signals from constant-

fraction discriminators of plastic (β) and a BaF_2 scintillator detectors. A gate is set on the γ rays decaying from the state of interest in the BaF_2 detectors. In recent years the BaF_2 scintillator detectors have been superseded by $LaBr_3$(Ce) ones, which offer a factor of $\sim$3 better energy resolution, with only slightly worse timing properties [2]. The fast-timing technique allows lifetimes to be measured with low statistics (few tens of recorded coincidences) making its application ideal to beams of the most exotic nuclei generated by EURISOL.

IN-BEAM FAST-TIMING

The fast-timing technique has been used with mixed arrays of BaF_2 and the Ge detectors of the Jurogam array at JYFL by Mach *et al.* for in-beam studies measuring the lifetimes of states populated following fusion-evaporation reactions. A mixed array of $LaBr_3$(Ce) scintillators and the Ge detectors of the ROSPHERE array of the IFIN-HH, Romania have also been used more recently [3]. The advantage of such setup is that the, unlike in plunger experiments, thick targets may be used, giving access to lifetimes in nuclei with small cross-sections. At the IKP Cologne fast-timing measurements have also been made using $LaBr_3$(Ce) scintillators and an "orange" electromagnetic conversion-electron spectrometer, allowing lifetime measurements to be performed for low-energy states in heavy nuclei [4].

Very recently 16 $LaBr_3$(Ce) from the FATIMA array have been used together with 8 Clover Ge detectors of the EXOGAM array to measure lifetimes of excited states in nuclei populated in neutron-induced fission at the ILL reactor, Grenoble [5]. Two targets with thick backings were used in this experiment, one containing 0.8 mg of ^{235}U and the other of 0.3 mg of ^{241}Pu. The fission rates of these targets was $\sim 10^5$ fissions/s. The use of prompt γ-ray spectroscopy gives access to intermediate- and high-spin states in $\sim$100 neutron-rich, heavy nuclei. States with intermediate and high spins are rarely populated following β decay. First results are published in [5] and show the applicability of the fast-timing technique to the study of exotic nuclei with high rates of β-decaying background transitions. Hence, a similar setup can be envisaged at EURISOL.

LIFETIME MEASUREMENTS USING ISOMER SPECTROSCOPY

The use of spectrometers to select and identify the products of a range of nuclear reactions has allowed isomeric decays in very weakly produced nuclei to be observed. The correlation between the implantation of an identified ion in a stopper and an isomeric decay, up to a few μs later, produces low-background spectra. The selectivity of the isomer spectroscopy, combined with simple γ-ray spectra, which contain just a few transitions, means that the moderate energy of scintillator detectors is sufficient to analyse these spectra. The first experiments of this type were performed at the Lohengrin and LISE spectrometers of the ILL and GANIL, respectively, at the beginning of the century, using BaF_2 scintillators. The introduction of $LaBr_3$(Ce) detectors, with their superior energy resolution [2], has allowed the range of isomeric decays available for study to be greatly extended. The fast-timing technique can therefore be applied to

the majority of cases of μs-isomer decay at the focal point of a mass spectrometer. With this in mind the FATIMA collaboration was formed to build a large array of $LaBr_3$(Ce) detectors for fast-timing studies at the focal point of the super-FRS of FAIR, within the framework of the DESPEC collaboration. The FATIMA collaboration has members from Spain, Poland, Germany, France, Sweden, Romania, Bulgaria and the UK. Possible mechanical configurations of this array are reported in [6]. Ongoing technical developments for the FATIMA array are described in the next section.

TECHNICAL DEVELOPMENTS WITHIN NUPNET

All members of the FATIMA collaboration, with the exception of the UK universities, are involved technical developments of the fast-timing technique within the EU-funded NuPNET framework.

The use of large arrays of scintillator detectors with tens of detectors, leading to hundreds of possible detector-pair combinations makes individual time-walk calibrations of each pair very difficult. Regis and co-workers have very recently proposed the Generalized Centroid Difference Method, which relies on the symmetry properties of the detectors in an array, allowing a time-walk curve to be generated for the whole array [7]. To obtain the best results using this method requires the array to have as much spherical symmetry as possible, which has obvious consequences for the design of FATIMA and other fast-timing arrays.

The workpackages in the fast-timing NuPNET project include tests of new scintillator materials and crystal shapes, photosensors, shielding, integration, β detectors, electronics and simulations. To date $LaBr_3$(Ce) scintillator crystals have been found to have the most desirable properties for fast-timing experiments, with $CeBr_3$ a good low-background alternative, having only slightly inferior energy and time performance. Hybrid-shaped crystals, which combine a cylindrical-shaped base with a conical top section, have recently been tested by the UC Madrid group and have superior time resolution to cylindrical crystals of similar dimensions. Crystals of this shape have been simulated to give the best performance for the FATIMA array [6].

The performance of Si-APDs has been tested by the TU-Darmstadt group and currently these do not have the necessary surface area to be used with typical fast-timing crystals (1.5" diameter) and phototubes remain the current best choice for photon detection.

At present chains of analogue electronics are used to process the time signals from fast-timing detectors. With larger arrays it would be desirable to use digiziters to process simultaneously energy and time signals. To date the timing performance of digital systems does not match that of analogue systems, though results obtained by the LPSC Grenoble group show only moderately degraded performance. Aykac *et al.* [8] have shown that sampling rates of $\sim$5 GHz are required to match the analogue-electronic setups for slower scintillating crystals, such as LSO. The energy resolution of analogue and digital electronics is identical for $LaBr_3$ crystals.

Together, these ongoing developments offer hope for improved performance of fast-timing arrays and furthermore theoretical chemists have recently predicted crystals with scintillation properties superior to $LaBr_3$(Ce), with around 100000 photons emitted per

MeV and 30 ns decay times. An updated FATIMA array, with superior performance, can therefore be implemented at EURISOL.

CONCLUSION

Fast-timing is a direct timing method able to measure lifetimes of the excited states of nuclei in the ps-ns region. As measurements can be performed with low statistics, then it is particularly suitable for the study of weakly produced exotic nuclei produced at EURISOL. The fast-timing technique has been used with β-decay, in-beam reactions and isomer-decay to obtain the lifetimes of excited states. The FATIMA collaboration, consisting of members for 8 countries has been formed to build a 4π array of fast-timing detectors. Ongoing developments within the NuPNET framework have already lead to, and will lead to improved instrumentation performance.

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The Advanced Nuclear Instrumentation of NUSTAR

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NUSTAR comprises the current nuclear structure, astrophysics and reactions programme at GSI and its proposed continuation and extension at FAIR. NUSTAR relies on the availability of exotic rare isotope beams produced by fragmentation reactions and fission of relativistic heavy ions. The fragment separator FRS and a versatile set of instruments, including gamma arrays, particle spectrometers and a storage ring enable unique experiments at GSI. The Super-FRS at the FAIR facility will provide several orders of magnitude stronger beams, providing access to the extremes of nuclear stability. To exploit these opportunities novel experimental set-ups are in preparation. R&D efforts result already now in improved detectors and enables the NUSTAR collaboration to steadily enhance the sensitivity and selectivity limit of their experiments. Current NUSTAR instrumentation highlights as well as development projects and activities will be discussed.

Introduction

The physics of exotic nuclei is the most important frontier in contemporary Subatomic Physics. Established entities such as magic numbers cease to be valid when going towards the drip-lines, exotic shapes appear as well as unforeseen decay modes and new collective phenomena. Furthermore, there is an obvious connection to astrophysical processes and the elemental abundances in the Universe, in particular through the r-process, which takes place across very neutron-rich nuclei. The objective of the NUSTAR collaboration is to study the structure of exotic atomic nuclei, to investigate reactions of these nuclei, and to apply the results for answering astrophysical questions. Key fundamental questions to be addressed are

- What are the limits for existence of nuclei?
- How does the nuclear force depend on varying proton-to-neutron ratios?
- How to explain collective phenomena from individual motion?
- How are complex nuclei built from their basic constituents?
- Which are the nuclei relevant for astrophysical processes and what are their properties?

NUSTAR is planned to be operated at the FAIR facility at GSI Darmstadt, Germany. This facility will have two unique features:

- High-energy Radioactive Beams (≤1.5 GeV/u)
  - -Efficient production, separation, transmission and detection aided by Lorentz boost
  - -Access to also the heaviest nuclei without charge-state ambiguities
  - -Large range of attainable reaction mechanisms
- Storage rings
  - -Mass measurements and beam preparation/manipulation
  - -Isomeric beams
  - -Novel experimental tools.

The central instrument of NUSTAR at the FAIR facility is the Super-FRS, a super-conducting fragment separator enabling the production and in-flight separation of secondary exotic isotope beams. The Super-FRS can also be operated as a high-resolution spectrometer system for nuclear physics experiments. Dedicated experiments in three distinct areas or “branches”, namely the low-energy branch (LEB), the high-energy branch (HEB) and the ring branch (RB), provide the instrumentation to investigate ground state properties and decay properties of exotic isotopes, the structure of their excited states and their reaction mechanisms.

Only the combination of the complementary results provided by these different but related experiments will lead to consistent answers for the fundamental questions of contemporary nuclear physics and astrophysics. NUSTAR follows an evolutionary approach. The physics program of NUSTAR has already begun at GSI. The intention is to replace and enlarge those experimental set-ups, which are currently employed with components developed specifically for NUSTAR at FAIR at their earliest availability. This guarantees a steady flow of world-class physics results using continuously improving detection equipment and experimental techniques.

In addition, this approach enables a largely physics driven and smooth transition to NUSTAR at FAIR, with a fast start-up phase and thus very early physics results from the new facility.

The Low Energy Branch

A majority of the NUSTAR experiments, namely MATS, LASPEC, HISPEC and DESPEC belong to the LEB. R&D for most of the components of these experiments was successfully finished, major investments took place, and funding for all required additional components has been secured. Early implementations have proven their operation capability.

HISPEC/DESPEC

HISPEC/DESPEC addresses nuclear structure and astrophysics questions using radioactive beams delivered by the Super–FRS with energies of up to 400 A·MeV for in-beam reaction studies, or stopped and implanted beam species for decay studies. The HISPEC set-up comprises a suite of heavy-ion tracking detectors to determine for each radioactive beam particle, its energy, mass, charge and direction towards a secondary (active) target. Beam-like particles from reactions at this target are being detected by the position sensitive ΔE-E-ToF calorimeter LYCCA. For the γ-spectroscopy of nuclei excited in the reactions the AGATA spectrometer is foreseen. AGATA is shared between different European host laboratories, implying concentrated experimental campaigns for HISPEC. The implantation detector AIDA, based on highly granular Si detector stacks, forms the core of the DESPEC set-up. Depending on the physics requirements the compact high-resolution Ge-detector array DEGAS, a $LaBr_3$ fast timing array (FATIMA), or a total absorption spectrometer (DTAS) is planned for γ-spectroscopy, while the arrays BELEN and MONSTER serve for neutron measurements.

An early implementation of the HISPEC set-up is already operational and in use, as well as the DESPEC arrays FATIMA and BELEN. Characteristic for HISPEC/DESPEC detectors is their modularity, enabling experiments with reduced sensitivity already with sub-arrays at an early stage. Increasing the number of modules to eventually complete the arrays leads to the ultimate sensitivity. The project focuses on those aspects of nuclear investigations, which can be addressed uniquely with high-resolution spectroscopy set-ups. The emphasis lies on medium heavy and heavy systems with exotic proton-to-neutron ratios. The universality of the beams delivered by the Super-FRS and the high energies avoiding multiple charge states keeps a wide area of isotopes of the highest importance for spectroscopy experiments.

MATS/LASPEC

Employing the most exotic radioactive isotopes of the Super-FRS, stopped in the gas catcher, extracted and transported by a RFQ, the MATS set-up allows pushing forward the limit of Penning-trap mass spectrometry to very exotic nuclei. LaSpec on the other hand enables collinear laser spectroscopy of the rare species. MATS/LaSpec are the most advanced experiments of NUSTAR producing outstanding physics results since 2010. As soon as the Super-FRS and the LEB with its building become available unique experiments will become possible.

important issues for MATS such as the use of highly-charged ions in mass spectrometry on radioactive isotopes addressing the important r-process in nuclear astrophysics with TITAN at TRIUMF as well as the use of a multi-reflection time-of-flight mass separator (MR-ToF) for mass measurements of the extremely exotic isotope ^{54}Ca with ISOLTRAP at ISOLDE could be demonstrated both in 2012. In addition, the TRIGA-SPEC Facility, used as the MATS and LaSpec prototype apparatus, recently demonstrated the first extraction of radionuclides from the TRIGA research reactor in Mainz.

The LaSpec collaboration is similarly working at different facilities worldwide and is pushing at the frontiers of both sensitivity and accuracy. After the first successful demonstration of the usage of an RFQ cooler and buncher at Jyväskylä a decade ago, similar devices have been installed at ISOLDE (CERN) and at TRIUMF (Vancouver) and are now routinely applied for laser spectroscopy, improving the signal-to-background ratio of the collinear fast beams method by orders of magnitude. While the ions are stored in the RFQ or during extraction, they can be

addressed with pulsed lasers to selectively populate metastable states that provide preferential properties for collinear spectroscopy, e.g., more accessible transitions, known atomic hyperfine factors, higher sensitivity for hyperfine structure or charge radius changes, etc. This has been shown at Jyväskylä and will soon be applied at ISOLDE as well. There, it has been demonstrated that β-asymmetry detection can also be used to determine isotope shifts. By modeling the optical pumping and the transition into the strong field, the lineshape of the spectra could be sufficiently well described to extract the isotope shift. With this technique it was possible to study the charge radii of the Mg isotopes along the complete *sd*-shell and observe the transition into the island of inversion. Moreover, the sensitivity of the collinear-anticollinear frequency-comb-based approach for high-accuracy measurements on light isotopes was further increased using a photon-ion coincidence technique. This allowed the determination of the charge radius of ^{12}Be. Just recently, the Collinear Resonance Ionization Spectroscopy setup CRIS at ISOLDE has demonstrated its potential in the spectroscopy on francium isotopes. Such a technique combines the high resolution nature of collinear spectroscopy with the high sensitivity of in-source spectroscopy and can be used in combination with decay spectroscopic techniques.

The High Energy Branch

The High Energy Branch of the Super-FRS will house only one experiment, namely R^{3}B.

R3B

The R^{3}B experiment is designed to measure reactions with radioactive beams with magnetic rigidities of up to 20 Tm corresponding to beam energies of about 1 A·GeV. This is perfectly matched to the RIB production in the Super-FRS and gives access to a large range of reactions as spectroscopic tools. The experimental set-up encompasses systems achieving highest efficiency and resolution for detection of all messengers in complete kinematics following a break-up reaction; neutrons, gamma rays, protons, light ions and heavy fragments.

This requires a large-gap dipole magnet with large bending power to allow neutrons being detected in coincidence in the forward direction. A superconducting iron-free magnet has been designed, and is already under construction (GLAD). In order to achieve the resolution of better than 1 MeV required by nuclear structure and astrophysics experiments, special detectors have been designed for neutron detection (NeuLAND) and photon and particle detection around the target (CALIFA and target-recoil detector). In order to ensure fragment identification even for the heaviest beams around mass A=200, very thin large-area heavy-ion tracking detectors are needed. Finally, the DAQ and readout systems for all detectors have been designed including a high-resolution time-distribution system allowing for free-running sub-systems. The project is well on track and a first version of the setup with 20% detectors will be ready for commissioning runs in 2014.

The R^{3}B experiment is unique in several aspects, the most important are:

- Capability of measuring reactions in full kinematics with high resolution at high beam energies up to 1 A·GeV, tracking and identification capabilities even for heavy beams with mass around A=200
- Large-acceptance measurement corresponding to a 4π acceptance in the CM system for a wide energy range, versatility of the design allowing the study of many reaction types
- High-efficiency calorimeter enabling invariant-mass measurements up to high excitation energies

The large-acceptance superconducting dipole magnet (GLAD) has been built under the leadership of CEA Saclay. The cold mass including the superconducting coils has been assembled and is presently inserted into a test cryostat for commissioning. The final cryostat has been ordered.

The design of the NeuLAND neutron detector has been finalized. Prototype tests and simulations have shown that the solution of a fully active detector meets the performance criteria on resolution and in particular on multi-neutron recognition power. The TDR has been submitted

to FAIR in November 2011 and is in the review process. 200 sub-modules of the detector in the final design have been purchased including 400 PM tubes, HV supply channels, and an ASIC (TAQUILA)-based frontend readout system. These modules have been configured in a special structure for a characterization experiment with mono-energetic neutrons. A call for tender for the first round of construction with so far secured funds from BMBF is in preparation.
The CALIFA calorimeter for γ rays and light ions consists of two parts, a barrel covering angles up to about 45° in forward direction and a front-cap covering the forward angles. The design of the barrel, consisting of 1952 individual CsI crystals, has been finalized. A TDR has been submitted and is being reviewed. A 20% detector consisting of barrel-type sub-modules will be constructed until 2014, allowing commissioning and first physics runs in conjunction with the new dipole GLAD and 20% NeuLAND. The design of the front-cap is in progress, foreseeing a phoswich design of $LaBr_3$ and $LaCl_3$ crystals. The design of the tracker for light charged particles has been finalized, having a three-layer structure of Si micro-strip detectors in a lamp-shade form and a dedicated ASIC frontend. The call for tender has been issued and a first segment has been delivered. The detector is fully funded and a partial detector will be available for beam tests in 2014; the full detector will be implemented in 2016.

The Ring Branch
The NUSTAR experiments of the ring branch generally rely on the availability of the New Experimental storage Ring (NESR) which is not part of the initial phase of FAIR. Only the ILIMA programme can to some extent be performed at the initial Collector Ring (CR). EXL and ELISe concentrate on ambitious R&D work while performing early implementation experiments at the ESR at GSI. This approach intends to keep the collaborations active until the ring complex of FAIR can be realized. Obviously the opportunity of using the High-Energy Storage Ring (HESR) and the CRYRING as intermediate instruments for the NUSTAR ring experiments has triggered on-going, thorough studies.

ILIMA
The ILIMA scientific program pursues three main goals, investigating Isomeric beams, Lifetimes and Masses. Most of the mass measurements program envisioned in the original ILIMA proposal for FAIR can be completed already at the CR, which is one of the main facilities for the ILIMA scientific program. The CR is being specifically designed for operating in the isochronous ion-optical mode, which is the prerequisite for isochronous mass spectrometry (IMS) of short-lived nuclides produced at the Super-FRS. IMS in CR will employ two time-of-flight detectors placed in one of the straight sections of the ring. IMS can be applied to stable nuclei as well as to nuclides with half-lives as short as a few tens of microseconds. Since a single stored ion is often sufficient to determine its mass, nuclides produced with tiny rates like one ion per day or even one per week can be addressed. This ultimate sensitivity and efficiency of the IMS technique will allow studies of the most exotic nuclear species which are at or beyond the limit of accessibility by experimental techniques anywhere else in the world.
Mass measurements with Super-FRS-CR have a huge discovery potential. Some highlights are:

- Masses of waiting point nuclei in rp- and r-process nucleosynthesis, access to exotic nuclei down to the sub-millisecond range with isochronous techniques.
- Possible quenching of N=82 and N=126 shells in neutron-rich nuclei
- Nucleon correlation energies in nuclei with extreme neutron-to-proton ratios
- Mapping of borders of nuclear existence
- Neutron-unbound high-spin isomers close to the neutron drip-line.

Operation of the HESR with heavy ions injected from the CR was also found to be feasible. It will be equipped with stochastic and electron cooling systems. Thus, the high-resolution mass measurements of cooled nuclides, which were originally foreseen in the NESR, may be possible in the HESR. The Super-FRS-CR-HESR measurements will be conducted on nuclides with half-lives longer than a few seconds. Schottky mass spectrometry (SMS) will be applied for this purpose.

A new resonant Schottky detector implemented in the ESR allows measurements of the revolution frequencies of single stored ions within a few milliseconds. This time resolution is sufficient to enable lifetime measurements in the CR tuned in the isochronous ion-optical mode. Several Schottky pick-ups will be installed to cover the entire frequency acceptance of the CR, which will allow simultaneous lifetime measurements of many different ion species. Furthermore, since the Schottky detection is non-destructive, simultaneous mass and lifetime measurements will be possible. In addition, the CR will be equipped with position-sensitive particle-detector setups. These detectors will be used to detect daughter ions after an in-ring radioactive decay.

EXL and ELISe

The EXL and ELISe collaborations have proposed measurements of reactions of light ions and electrons with radioactive ions in rings. These measurements have been planned such that they can be performed at several stages. The short-term goal of the EXL collaboration was to design detectors, which can already be placed at the existing ESR ring and used in the experiments with the present GSI facilities producing radioactive nuclei close to the valley of stability with reasonable intensities. This goal has partly been achieved. In fact, the first physics runs have been performed in October 2012. After these successful runs, the detector will be expanded to cover a larger part of the phase space for the coming years. Once the FAIR facility starts to run, one can use the present ESR and the future HESR (and also possibly the CRYRING) for these measurements. For this purpose, transfer lines should be provided to bring the beams of radioactive ions to these rings. Some modifications of the rings are also mandatory. The EXL setup can then be used for the studies with even more exotic nuclei. This would form the mid-range plan of the collaboration.

The ELISe experiment with its colliding beam setup is expected to be unique for the next decade in terms of achievable luminosity for a given radioactive ion yield and selectivity due to the simultaneous reconstruction of excitation and decay process. The need for such a facility has been demonstrated with the newly built SCRIT facility at RIBF in Japan. In view of the possible activities using the ESR ring facility, a study for operating the ELISe experiment at a modified ESR has been carried out with good success.

To achieve the best performance as proposed in the original proposals, one needs to build a dedicated ring with a large acceptance and more space for various detector systems. This ring (NESR) is, presently, not part of the initial phase of the FAIR project and should be included in the long-range plan at a later stage.

Tagging Around RITU

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Abstract. The Recoil decay tagging technique has been the workhorse for in-beam spectroscopy of neutron deficient and heavy elements for nearly 20 years. The advances in both the technique and in instrumentation have allowed the study of very exotic nuclei, down the the 10 nanobarn cross-section level. The majority of this work has been carried out at the University of Jyväskylä, Finland. Here, a review of the technique and instrumentation is given with also a view to the future.

Keywords: Recoil decay tagging, Recoil Separators, in-beam γ-ray and decay spectroscopy
PACS: 29.30.Kv, 29.30.Ep, 29.40.-n

A BRIEF HISTORY OF RDT

The first recoil decay tagging was performed using the SHIP velocity filter in conjunction with a NaI array at the target position and a Si strip detector at the focal plane in the mid-'80's [1]. The aim of the experiment was to use the characteristic alpha decay of ^{180}Hg (implanted into a Si detector at the focal plane of SHIP) to select prompt gamma-ray transitions at the target position. The experiment was to prove that radiative capture had really occurred after a ^{90}Zr beam impinged on a ^{90}Zr target. The experiment not only proved that the radiative capture of ^{90}Zr + ^{90}Zr has occurred, but also proved that it was possible to use the charged particle decays of recoiling nuclei as a form of channel selection ("tag") following compound nucleus formation and decay. The name recoil decay tagging (RDT) was first coined by E.S. Paul *et. al* in the mid-'90's when the same procedure was applied to the island of alpha and proton decaying nuclei above ^{100}Sn at Daresbury Laboratory [2].

After an initial flurry of experiments in the late '90's and early this millenium there has been a steady advancement and refinement of the technique and instrumentation. The University of Jyväskylä, Finland (JYFL)and Argonne National Laboratory, IL, US (ANL), are the main laboratories active in RDT studies. The following report concentrates on the instrumentation developments at the University of Jyväskylä, that have led to this technique successfully identifying nuclei from ^{66}As [3] to ^{256}Rf [4] and down to cross sections of 10 nanobarns (^{180}Pb) [5].

INSTRUMENTATION

The separator used for RDT studies at JYFL is the gas-filled separator RITU [6]. It has a QDQQ configuration and the distance from target position to focal plane is 4.8m, yielding a flight time of 0.5-1us for nuclei recoiling from fusion evaporation reactions. This allows the study of isomeric states at the focal plane, which decay via γ-ray

emission with half-lives down to the 100 ns level and charged-particle decays with half-lives as short as 5-10 μs. The latter limit is set by the electronic readout time unless trace data from digital electronics is taken. Since, its commissioning in 1992 RITU has had two upgrades. The dipole chamber was increased in size so the beam stop was further away from the main trajectory through to the focal plane. The other was the installation of a differential pumping system before the target chamber. These two modifications significantly reduced the scattered particle components at the focal plane and opened up new possibilities for the study of lighter nuclei.

Positioned at the focal plane of RITU is the the GREAT spectrometer [7, 8]. It is unique in the fact that it houses a planar Ge detector within the vacuum chamber, situated $\sim$5 mm from the rearside (w.r.t the beam direction) of the double-sided Si strip detectors (DSSDs). Therefore, the planar detector is highly efficient at detecting, not only low energy X-rays and γ rays, but also beta-decays.

Another unique development, which arrived along with GREAT in 2002, was the new, triggerless, total data readout (TDR), data acquisition system [9]. Rather than requiring a hardware trigger, the TDR system reads all input channels separately and events are time stamped them using a 100MHz metronome. The data are then collated and merged in to a single stream of data, time-stamped to a precision of 10 ns. The GRAIN analysis package is then used to analyse the data both on and off-line [10].

Over the years the Ge arrays at the target position have steadily increased in efficiency from Jurosphere in 1997 with an efficiency of $\sim 1.5\%$ at 1.3 MeV to the current JUROGAM II array with an efficiency of $\sim 6\%$ at 1.3 MeV. Other devices used at the target position of RITU are: the SAGE spectrometer for the simultaneous detection of γ rays and conversion electrons[11], The DPUNs plunger device [12] for lifetime measurements of excited states, the LISA spectrometer for the study of fast charged-particle emission and the UoYtube array [13] for vetoing charged-particle exit channels and in the future for charged-particle identification.

EXTENSIONS OF RDT

Recoil isomer tagging (RIT) [14, 15] and recoil beta tagging (RBT) [16, 13] are extensions of RDT along with what is known as the calorimeter technique for the study of super-heavy elements [17, 18].

RIT relies in the nucleus having an isomeric state, which lives long enough for it to be identified at the focal plane of RITU. The decay is then used to tag γ rays from excited states feeding the isomeric state at the target position. The technique also works in reverse if the transitions feeding the isomer have been observed before the isomeric decay.

RBT is a very challenging technique, but is possible for N$\sim$Z nuclei, which beta-decay via Fermi super-allowed transitions. These decays are orders of magnitude faster and their beta-decay endpoints are several MeV higher than the majority of nuclei in their vicinity. Hence, setting a short correlation time window and a high energy gate on the beta-decay enables the identification of excited state in these exotic nuclei [19, 20, 3].

The calorimeter technique utilises the sum energy of all conversion electrons emitted in a cascade following the de-excitation of an isomeric state, in very-heavy nuclei. This

sum energy is detected in the same pixel in the DSSDs as the recoil implantation and therefore can be used to select the γ rays feeding the isomeric state, which were detected at the target position [17, 18]. This is particularly useful and efficient for heavy nuclei, which have large internal conversion coefficients and isomeric states with applicable life-times.

Another interesting extension of RDT is the possibility of using deep inelastic reactions to form neutron-rich nuclei. The heavy, target-like fragment, is kinematically forward focussed and passes through RITU, finally implanting into the DSSDs at the focal plane, where it may subsequently alpha decay. The alpha decay is then used to tag γ-ray transitions at the target position from the light, neutron rich fragment [21].

All these techniques combined have lead the first observations of excited states in over 60 nuclei.

FUTURE OUTLOOK

Developments are under way at both JYFL and ANL and also, in the future, RDT will be carried out at GANIL when AGATA is coupled to the VAMOS separator used in gas-filed mode. In the near future MARA, a new vacuum mode separator will be commissioned at JYFL and ANL has been granted funds to build AGVA, a new gas-filled separator. Advances in digitising Ge detectors outputs and also developments of "tracking" Ge arrays means that studies using the RDT technique will allow the studies of more exotic nuclei in the heavy masses and also reach further beyond the proton dripline. In summary, though RDT has been around for nearly 30 years its use is far from exhausted.

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Detection of high-energy protons and γ-rays using a $LaBr_3$(Ce)-$LaCl_3$(Ce) phoswich array

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Abstract. CEPA4 is a new phoswich array for the detection of high-energy protons and gamma-rays from nuclear reactions and spectroscopy of beta-delayed particles and gamma-rays. This new detector consists of four individual closely-packed scintillator detectors, each of them made of 4 cm of $LaBr_3$(Ce) and 6 cm of $LaCl_3$(Ce) in phoswich configuration (optically coupled and with a common readout). In this contribution we report on the results of a beam test performed at the Bronowice Cyclotron Centre (CCB) in Krakow, showing the response of this versatile instrument to high energy protons (70 - 230 MeV). Furthermore, we show that we can reconstruct the original energy of fast protons (E $>$ 200 MeV) which pass through the total length of the crystal while still retaining a good energy resolution.

Keywords: phoswich, $LaBr_3$(Ce), $LaCl_3$(Ce), pulse-shape analysis, spectroscopy, proton detector
PACS: 29.40.Mc, 29.30.Ep, 29.30.Kv

INTRODUCTION: EXPERIMENTAL MOTIVATION

The $(p,2p)$ reaction experiments have long been used to study the single-particle properties of bound nucleons inside the nucleus. These experiments are based on the detection of the two outgoing protons in coincidence with an angle of 90^o between them in the laboratory system (less than 90^o in inverse kinematics experiments). The angular and energy distributions of the outgoing protons, in combination with those of the gamma-rays from the de-excitation of the recoil nucleus, reveal the structure (energy and angular momentum) of the hole-states left by the knocked-out proton as long as the detection system is sufficiently good.

The R^3B Collaboration has proposed and designed an experimental set-up to perform measurements, in complete kinematics, of reactions with radioactive beams at relativistic energies. These beams will be produced and selected using the in-flight production method at the Super-FRS device of the future FAIR facility. One of the sub-detector systems in the R^3B setup will be a gamma-ray and proton calorimeter surrounding the reaction target position: CALIFA [1].

Fast scintillator materials and properly segmented detectors for Doppler correction are needed to study reactions at relativistic energies. However, the simultaneous detection of high-energy gamma-rays and protons with a reasonably good energy resolution is far from trivial. One possible solution, based on a phoswich configuration, was already presented in [2] . In that work we tested, for the first time, a small stack of two scintillators optically coupled, for the simultaneous detection of gamma-rays and protons. We could

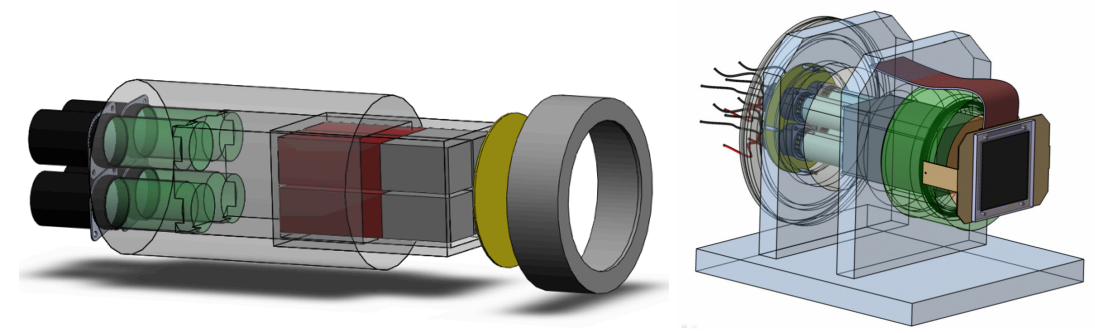

FIGURE 1. Detailed scheme of the CEPA4 detector. Left panel: in red there are the four photomultiplier tubes, in red/grey one can see the squared prisms representing the phoswich units, in yellow a thin Al window and, finally, the ISO160 coupling ring to the reaction/decay chamber. Right panel: suport for CEPA4 and DSSSD detector coupled to the entrance face, as was mounted for the beam test described in the text.

demonstrate that, using pulse-shape analysis techniques, one can separate the energy deposited in both scintillator crystals. This small cylinder was the first prototype along the way to the final design of the detector units that will comprise the forward endcap of the CALIFA calorimeter, namely the CEPA detector.

THE PHOSWICH ARRAY CEPA4 AND ITS RESPONSE TO HIGH-ENERGY PROTONS

Encouraged by our results and the Monte Carlo simulations in [2], we designed a second prototype: CEPA4, an array of 4 individual optically separated scintillator units, each of them consisting of 4 cm of LaBr3(Ce) coupled to 6 cm of LaCl3(Ce) in phoswich configuration and packed together in a can of Al of 0.5 mm thickness with a total entrance surface of 60×60 mm^2 and a readout glass window of 4 mm thickness. A scheme of the detector can be seen in Fig. 1. In the left panel it is shown the special ISO160 port to allow for the possibility of adding a Silicon detector to work in vacuum (in a reaction or decay chamber) keeping the phoswich array in air. In the right panel one can see the support and the Silicon DSSSD detector coupled to the phoswich array as used in the beam test described below.

The response of CEPA4 to high-energy protons was measured using proton beams from the cyclotron at the CCB facility in Krakow [3]. The CCB accelerator is designed for medical treatment and provides mono-energetic proton beams ranging from 70 to 230 MeV with a resolution $\Delta Ep < 1\%$. The maximum energy was just enough to test the punch-through of protons in the total of 10 cm phoswich, which happens around 200 MeV. The two-layer detector can be used as a ΔE_{LaBr3} vs E_{Tot} telescope in order to determine the initial energy, see Fig. 2. Pulse shape analysis detailed in [2] was performed to reconstruct the primary energy of the protons. An example of such a measurement and representation is shown in Fig. 2. It represents a two-dimensional plot of type ΔE *vs* E, typical of a telescope configuration. This type of plot has been traditionally used for particle identification, and we can actually use it for this purpose

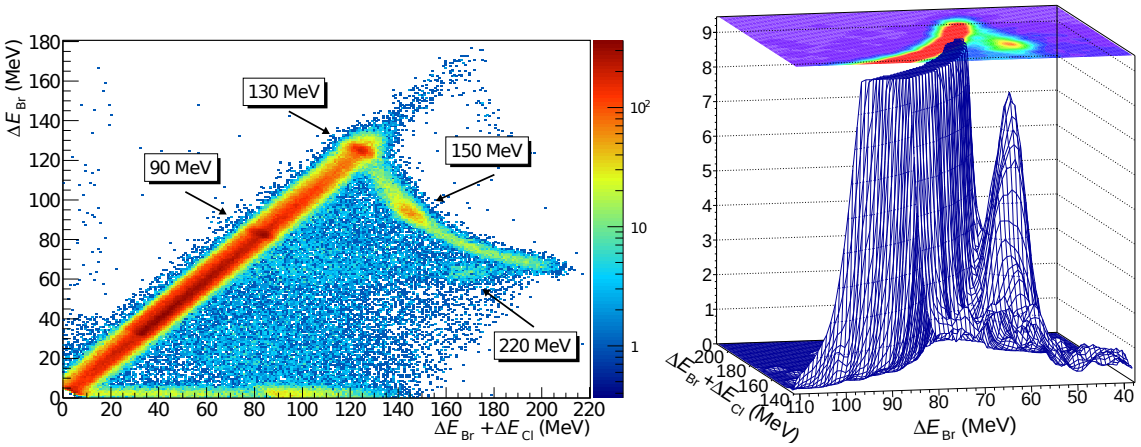

FIGURE 2. Left: Two-dimensional $\Delta E - E$ plot for the sum of 4 different runs with proton energies: 90, 130, 150 and 220 MeV. The vertical axis represents the energy deposited in the $LaBr_3$ crystal and the horizontal axis the total energy deposited in the phoswich. Right panel: same as left panel but in a three-dimensional representation and with a zoom in the area around the peak at 220 MeV.

as well. However, in our case, the aim of such a representation is to reconstruct the energy of the incident protons even if they have passed through the total length of the phoswich unit. Fig. 2 displays the energy deposited in the $LaBr_3$ versus the total energy deposited in the phoswich unit. An add-back procedure has been used on an event by event basis so that we have added the energy deposited in all four crystals. In the left panel of the figure we can clearly see the spot corresponding to 90 MeV protons, fully absorbed in the first crystal of the phoswich, namely the $LaBr_3$. Continuing along the diagonal we find the spot of the 130 MeV protons. These are at the limit of absorption in the first crystal, all energies above will pass through the $LaBr_3$ and enter the $LaCl_3$ crystal. One of such examples are the 150 MeV protons that we can see as a spot in the banana corresponding to all the protons stopped in the second crystal. Finally, it is more difficult to visualize, but we have also included the spot which corresponds to the 220 MeV protons that pass through the entire length of the phoswich unit. We can zoom in pointing at the 220 MeV spot and change to the three-dimensional representation of the right panel. In this way we can have an impression of the ability of the CEPA4 detector combined with the pulse-shape analysis to separate the 220 MeV protons that have passed through the detector from the continuum at lower energies. This implies that, with the appropriate unfolding algorithm, one can reconstruct the original energy of the protons even at the energies that push the Bragg peak out of the volume of the detector. By performing the appropriate projections and energy calibration for a whole set of energies from 70 to 235 MeV one can study the energy resolution of the CEPA4 device as a function of the proton energy, defining energy resolution as ΔE/E, with ΔE the full width at half maximum of the gaussian fit to the full absorption peak and E the centroid of the peak. This is represented in Fig. 3. One can clearly distinguish between the three different regions depending on the position of the Bragg peak in the detector. For energies below 130 MeV the energy resolution improves with the proton energy and reaches as low as 3% . In the intermediate region, which includes energies ranging

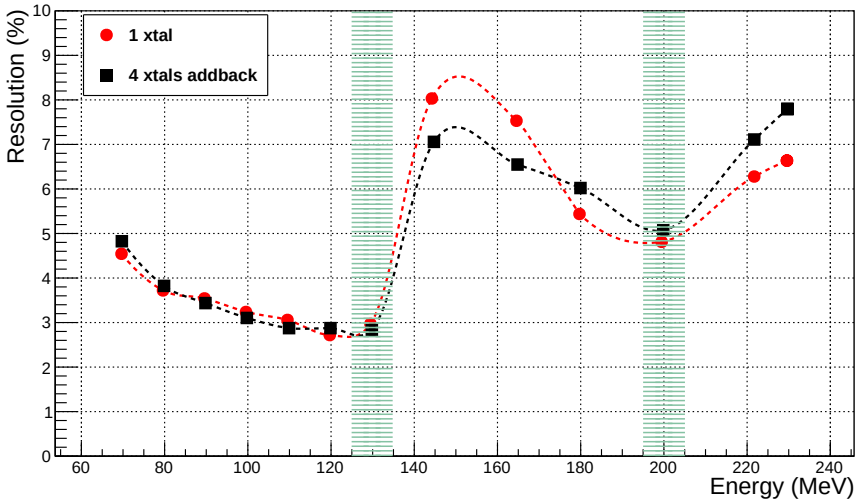

FIGURE 3. Energy resolution as a function of the proton energy. The first vertical shaded region is at the energy in which the Bragg peak lies on the limit between the two crystals. The second vertical shaded region is at the energy in which the Bragg peak lies on the edge of the second crystal. Beyond this point the protons pass through the entire length of the phoswich unit.

from 130 to 200 MeV, the resolution starts at 8% for the worst case: 145 MeV, right after the first punch-through, and then improves with increasing energy again until it reaches 5%, right before the second punch-through at 200 MeV. Finally, in the last energy region, above 200 MeV one can still project and fit the peaks, obtaining the last two points shown in the resolution curve of Fig. 3. In this high-energy region the energy resolution becomes worse with increasing energy as predicted by Monte Carlo simulations [2] However, we can still separate the peaks and reconstruct the energy of the incident protons with a resolution of 7% at 230 MeV, and expect a resolution around 10 to 15% at 280-300 MeV. One could improve the energy resolution at these energies by increasing the length of the second crystal and therefore increasing the total punch-through energy.

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ELISe: electron scattering off RIBs - status and perspectives

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Abstract. In this paper the opportunities and prerequisites for carrying out electron scattering experiments off unstable beams for the first time will be outlined. A colliding beam experiment with intersecting electron and RIBs will be described which allows to make best uses of the precious unstable nuclei for elastic and inelastic scattering using a pure electromagnetic probe. The experiment could be already realized within the modularized start version of the FAIR facility which is currently being constructed.

Keywords: electron scattering, unstable nuclei, collider experiment
PACS: 25.60.-t, 29.20.db, 29.38.Db, 25.30.Bf, 25.30.Dh, 25.30.Fj

ELECTRON SCATTERING OFF UNSTABLE ISOTOPE BEAMS

TABLE 1. Luminosities L for 0.74 GeV/nucleon ion beams of several reference nuclei. Here, $T_{1/2}$ is the half-life of the nucleus at rest, τ its total life time, and N the total number of ions stored in the NESR storage ring.

Element	$T_{1/2}$, s	τ, s	N	L, $\mathrm{cm^{-2}s^{-1}}$
^{11}Be	13.8	35.6	$2.1 \cdot 10^{10}$	$2.4 \cdot 10^{29}$
^{35}Ar	1.75	4.5	$8.5 \cdot 10^{7}$	$1.7 \cdot 10^{27}$
^{55}Ni	0.21	0.5	$2.0 \cdot 10^{7}$	$4.0 \cdot 10^{27}$
^{71}Ni	2.56	6.5	$4.3 \cdot 10^{7}$	$1.1 \cdot 10^{27}$
^{132}Sn	39.7	68.2	$1.2 \cdot 10^{9}$	$1.9 \cdot 10^{28}$
^{133}Sn	1.4	3.5	$7.3 \cdot 10^{6}$	$2.0 \cdot 10^{26}$
^{238}U	10^{17}	60	$6.0 \cdot 10^{10}$	$1.0 \cdot 10^{28}$

Electron scattering has shown to be a powerful tool in the realm of stable nuclei for several decades. The leptonic probe is in particular sensitive to charge distributions and transition densities and allows for extracting their features in elastic and inelastic scattering, respectively. This gives access to a direct determination of charge radii (and potentially surface diffusenesses, and higher moments) from the form factors on an absolute scale, providing e.g. anchor points for relative measurements of charge radii using laser spectroscopic methods throughout isotopic chains. In inelastic scattering processes, the transferred momentum dependence of the transition form factors, results in the possibility to separate different transferred angular momenta in the excitation process. Furthermore, electric and magnetic form factors can be distinguished, again by their particular scattering angle dependence. Using this information yields precise information on the excitation process through a measurement of the scattered off electrons.

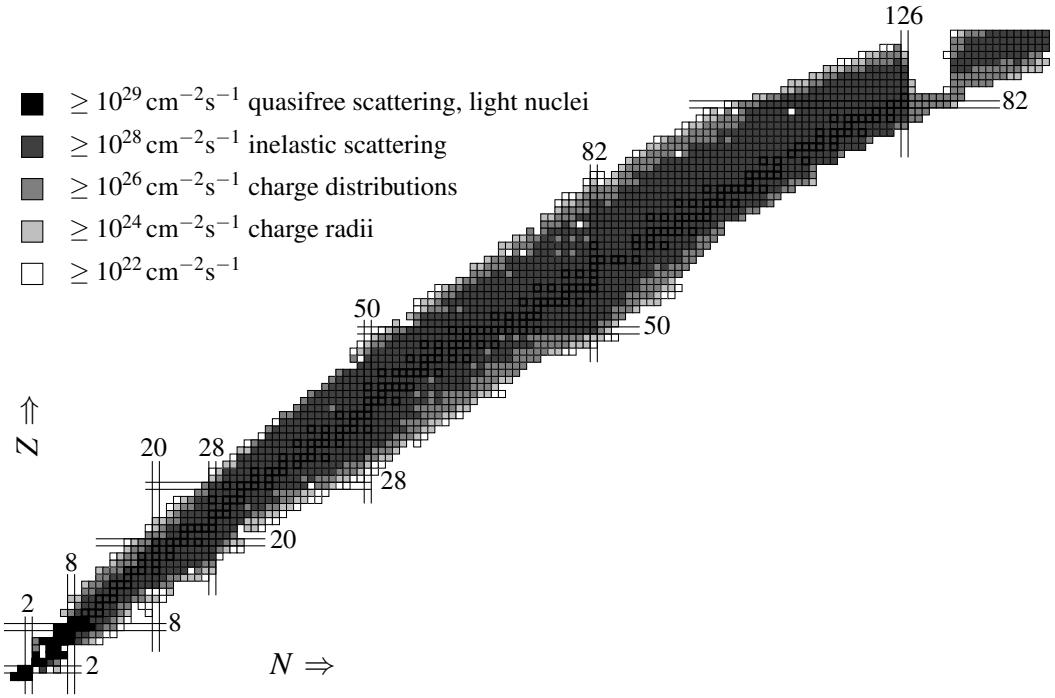

FIGURE 1. Maximum achievable luminosities for individual 0.74 GeV/nucleon ion beams at the interaction zone. Shown is a nuclear landscape where the luminosity is plotted as function of the charge Z and the neutron number N according to the grey scale code shown in the upper left corner. Stable isotopes and magic numbers are labeled and distinguished by extended lines. A central plateau is visible, that drops rapidly at the edges where the most unstable and short-lived nuclei that can be studied with ELISe are situated. These luminosities comfortably suit to the requirements given in Table 1 for a wide range of isotopes far from the valley of beta-stability. The simulation calculation takes fully into account, (i) production and separation process, (ii) transport through separator and beam lines, (iii) cooling and storage in the storage rings, and (iv) decay losses.

The ELISe experiment at FAIR [1] aims in its full design version for elastic, inelastic, and quasielastic electron scattering studies off secondary beams [2], provided by the SuperFRS, being stored in the new experimental storage ring (NESR) and intersecting with an electron (antiproton) storage ring (EAR), for the first time.

The worldwide only other project SCRIT, addressing electron scattering off unstable nuclei produced by electrofission at rest, by means of storing them in the trapping potential of the electron storage ring, is discussed elsewhere in these proceedings.

The achievable luminosities determine the physics programme (recently, e.g. [3]) for the facility. In figure 1 and table 1 the design values for the ELISe experiment at the NESR storage ring for FAIR are shown, and the corresponding physics opportunities are sketched. The total life time τ results from (i) half life of the isotopes and (ii) atomic life time in the rest gas of the UHV in the ring. The total number N of stored ions in the ring is limited by intra beam scattering. This means in turn, that even at lower production yields, the plateau values for the luminosities, as shown in figure 1 can be still reached, but the drop at the outskirts of the nuclear lasndscape will commence earlier.

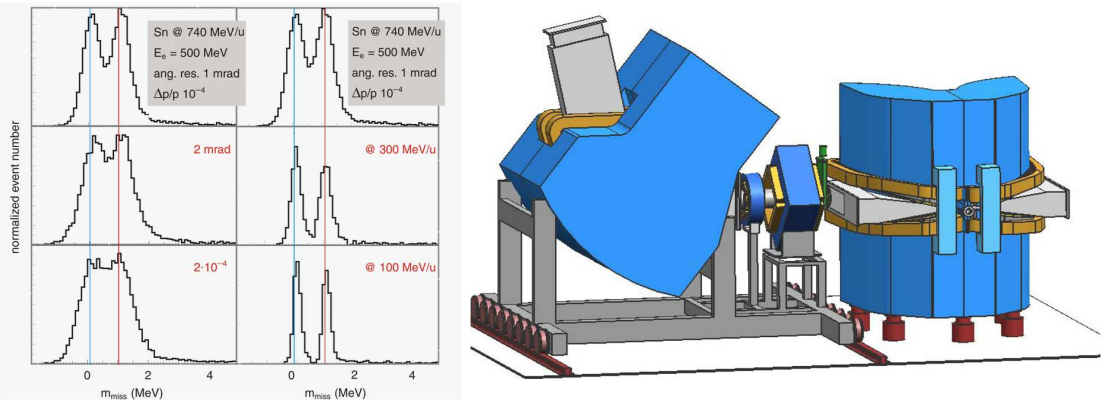

FIGURE 2. Left panel: obtainable resolution utilizing a large acceptance high resolution spectrometer with 1 mrad and 10^{-4} relative momentum resolution for the electron. Modeled was a fictive ^{132}Sn isotope with an excited state at 1 MeV. The mostleft panels show the degradation of the energy resolution with twice worse spectrometer parameters, respectively. The spectra to the right show how energy resolution improves once the target gets gradually to rest. Right panel: Spectrometer arrangement of QHD type coupled to the in-ring superconducting pre-deflector magnet. The design provides the properties assumed in the simulation calculation.

TECHNICAL REALISATION

The achievable CM energy with 740 MeV/u secondary beams and 500 MeV electrons, the design values for ELISe, will be up to 1.5 GeV in colliding beam kinematics, and a sufficiently good resolution for nuclear structure studies puts rigid constraints on the electron spectrometer to be used : (i) a momentum resolution of $\delta p/p = 10^{-4}$, and (ii) an angular resolution of $\delta\theta = 1$ mrad, while covering the largest technologically achievable solid angle.

Figure 2 shows the resulting spectrometer design [4, 5], and outlines the impact of worse resolution in angle and relative momentum for the electron measurement. As can be seen, lowering the ion energy in the storage ring leads to an improved achievable resolution. This becomes intuitively clear as the observed degradation compared to the pure spectrometer resolution initiates in the colliding beam kinematics. The maximum number of ions stored in the storage ring, however, favours strongly the larger energies, as the undesired effects of intra beam scattering will be less apparent in that case. Higher enrgies also turn out to be advantageous, in view of the Mott cross section with strong angle dependence. A particular momentum transfer can be realized at smaller angles at higher CM energies, thus, with enhanced cross sections, higher rates can be achieved with the same amount of precious secondary beam particles. In this way, gain factors of several orders of magnitude can be obtained, compared to conventional electron scattering with solid targets.

A particular advantage of colliding beam kinematics is, that unlike conventional electron scattering with (solid) targets at rest, here target-like ions emerging from the interaction zone can be studied with high efficiency in the magnetic spectrograph, being represented by the first dipole magnet following the interaction zone, see figure 3, which will be equipped with suitable detection equipment for charged particles. This will allow

FIGURE 3. Revised scheme enabling setting up the ELISe experiment at the current location of the already existing ESR. The setup suggests modifying its design to comprise enlarged straight sections.

for a precise study of the deexcitation process of secondary beam particles, e.g. by using the invariant mass method, and in general enhanced coincidence measurements, where e.g. the number of neutrons can be determined with ease by measuring the mass of the target-like fragment with practically 4π solid angle coverage and high efficiency.

By introducing the modularized start version (MSV [1]) for FAIR the construction of the NESR storage ring has been delayed. The existing ESR at GSI, the current workhorse for ring experiments, is meanwhile seen as its precursor. A potential pathway to an early realization of the ELISe is depicted in figure 3. By modest modifications to the ring, all within the existing building boundaries, the ELISe experiment can be realized already now. The main differences would be a slightly lower beam energy (340 MeV/u) and a restricted accessible range for the most exotic secondary species (see discussion above). Both would nevertheless allow for a very viable experimental start programme.

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The SCRIT Electron Scattering Facility at the RIKEN RI Beam Factory

M. Wakasugi and SCRIT collabolations

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Abstract. The SCRIT Electron Scattering Facility, aiming at electron scattering off short-lived unstable nuclei, has been constructed at the RIKEN RI Beam Factory. This facility consists of a race-track microtron (RTM), an electron storage ring (SR2) equipped with the SCRIT system, and a low-energy RI separator (ERIS). SCRIT (self-confining radioactive isotope ion targeting) is a novel technique to form internal targets in an electron storage ring. Experiments for evaluating performance of the SCRIT system have been carried out using the stable $^{133}Cs^{1+}$ beam and the $^{132}Xe^{1+}$ beam supplied from ERIS. Target ions were successfully trapped in the SCRIT system with 90 % efficiency at a 250 mA electron beam current, and luminosity exceeding 10^{26} /(cm^{2}s) was maintained for more than 1 s. Electrons elastically scattered from the target ions were successfully measured. We are now preparing new electron detectors, which consists of a high-resolution magnetic spectrometer WiSES, drift chambers, and trigger plastic scintillators.

Keywords: Nuclear charge distribution, Elastic electron scateering
PACS: 21.10.Ft, 25.30.Bf

INTRODUCTION

Much of our knowledge on fundamental nuclear properties is from electron scattering off atomic nuclei[1, 2]. Electrons are structureless particles, and their interaction with nuclei is well described by only electromagnetic interaction. Because of the weakness of this interaction, electrons deeply probe the structure of nuclei without disturbance. Electron scattering is, therefore, one of the best ways to accurately understand the internal structure of atomic nuclei. This has never been applied to short-lived unstable nuclei because there has been no method to provide a radioactive isotope (RI) target, though such an electron scattering technique would be of great utility for nuclear physicists researching unstable nuclear structures.

Collider schemes were for a time the only candidate for such experiments, but the situation changed with our success in the development of the SCRIT (Self-Confining Radioactive isotope Ion Target) technique[3, 4]. This technique is based on well-known ion-trapping phenomena in an electron storage ring. Ions are transversely confined to the immediate vicinity of the electron beam under its periodic focusing force. They are also longitudinally confined within a certain distance defined by the electrostatic potential formed in the SCRIT device. Ion cloud trapped in the SCRIT works as targets for electron scattering.

We have already demonstrated the feasibility of SCRIT as a target in our study at the KSR[4], achieving luminosity of 1.02×10^{26} /(cm^{2}s) at a 75 mA electron beam current[5, 6]. We also predicted that SCRIT performance can be much improved by

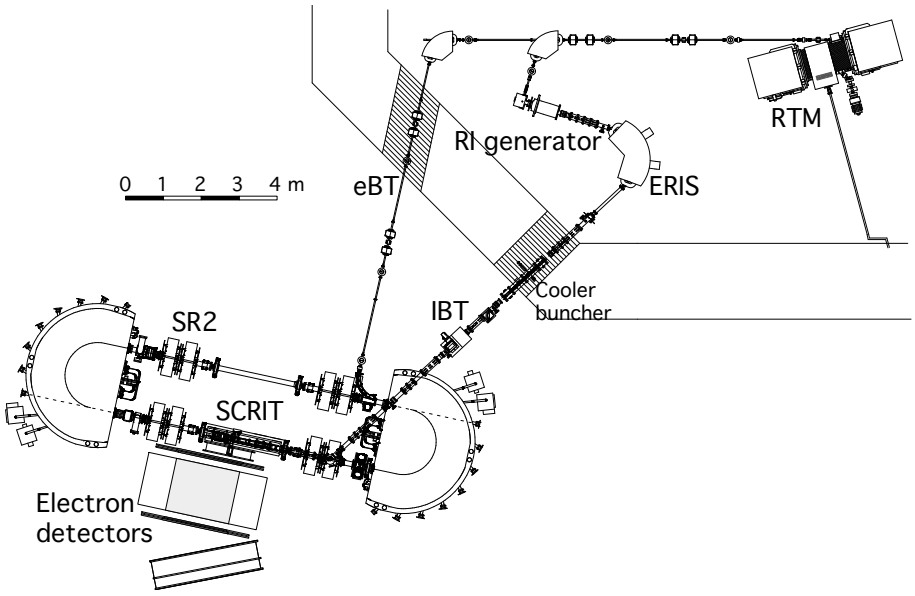

FIGURE 1. Layout of the SCRIT electron scattering facility.

increasing the electron beam current. This success led to construction of a facility dedicated to electron scattering off short-lived unstable nuclei at RIKEN-RIBF in 2009. New electron accelerators, the injector microtron RTM (Racetrack Microtron) and the electron storage ring SR2 (SCRIT-equipped Riken Storage Ring), were commissioned in 2010, and the SCRIT system was installed into the SR2 in the same year. An ISOL system equipped with an RI generator, called ERIS (Electron beam–driven RI separator for SCRIT), was also constructed. RI beam production at ERIS was started in 2013 and the extraction efficiency is now under improvement. Construction of the core facility instrumentation is nearly complete, though some components are still under construction.

THE SCRIT ELECTRON SCATTERING FACILITY

Overview of the facility

Fig. 1 shows an overview of the SCRIT electron scattering facility. The facility consists of the RTM electron accelerator, the SR2 electron storage ring, and the ISOL system ERIS. The SCRIT system is inserted in a straight section of the SR2. Electron beams accelerated by the RTM to 150 MeV are injected into the SR2. During electron-beam accumulation in the SR2, the RTM drives RI production. Bremsstrahlung gamma rays converted from the electron beams irradiate a UC_x target in the ERIS target ion source. RIs produced by photo-fission reaction are extracted from the ion source and mass-separated with the analyzing magnet. Continuous RI ion beams with energy less than 50 keV are transported to the cooler buncher, which is based on a radio-frequency quadrupole. Ions are stacked for an appropriate time in the cooler buncher, and pulsed RI ion beams are supplied for injection to the SCRIT. RI ions trapped in the SCRIT form a

dense ion cloud around the electron beam orbit. Electrons scattered from the target ions exit the vacuum chamber, and are detected by an electron detector system that consists of a magnetic spectrometer (WiSES), drift chambers, and trigger scintillators.

SCRIT system

Although the SR2 can accelerate the beam up to 700 MeV, electron beam energies less than 300 MeV are required in electron scattering experiments. Currently, the accumulation current and lifetime are typically 300 mA and 1 AH, respectively. The electron beam size and current are equally important properties for SCRIT experiments. At the current operation point, the beam size at the SCRIT device is $\sigma_x = 0.8$ mm horizontally and $\sigma_y = 0.4$ mm vertically. Large beam currents, small beam sizes, and stable beam circulation are favorable properties for SCRIT electron scattering experiments. Details about accelerators are described in our previous paper[7]. The RI ion beams from ERIS are transported to the cooler buncher, which stacks continuously injected RI ions for an appropriate time. Since the cooler buncher is now under development, details will be described elsewhere. Pulsed RI ion beams from the cooler buncher are transported to the SCRIT system through a 7.0 m ion beam transport line (IBT).

Fig. 2 is a schematic of the SCRIT system. The SCRIT device, scraper-type beam position monitors, the switching deflector, and two sets of button-type electron beam position monitors (BPM) are precisely aligned on the movable platform. The SCRIT device is an assembly of three racetrack-shaped cylindrical electrodes. The SCRIT device produces electrostatic potential for longitudinal ion trapping, as shown in Fig. 2. Potential applied to the central electrode, called the SCRIT potential, is set so that the

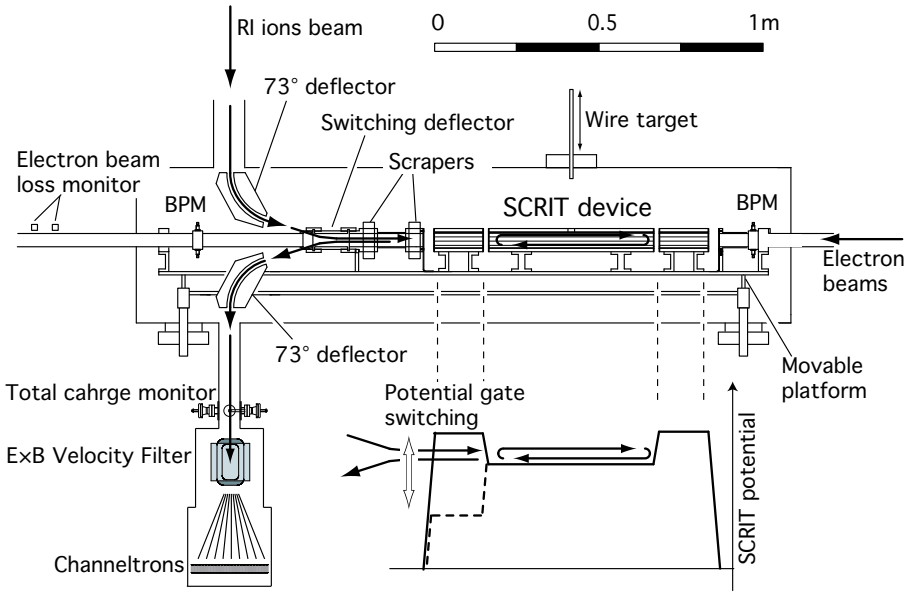

FIGURE 2. Schematic view of the SCRIT system and potential structure in the SCRIT device.

kinetic energy of the injected ion beam is reduced to less than a few eV. Two short electrodes at each end produce the barrier potentials. Ion beam injection and extraction are controlled by fast switching of the barrier potential (Fig. 2). The ion beam is next merged with the electron beam at the exit of the switching deflector, transversely captured, and guided to the SCRIT device by the electron beam. The switching deflector is also used as the extractor by changing its polarity, directing extracted ions to the analyzer. The charge of extracted ions is measured by the total charge monitor acting as slits at the entrance of the analyzer. A small number of ions passing through the total charge monitor enter the $E \times B$ velocity filter. Mass and charge-state analyzed ions are detected. The electron beam loss monitor is placed near the electron beam axis, 2 m downstream from the SCRIT device. The loss monitor is two plastic scintillators that partially count shower components produced by electron beam loss. We found that the difference in the counting rate with and without target ion trapping in the SCRIT is proportional to the luminosity. The loss monitor was therefore used as an online indicator of luminosity.

Isotope separator ERIS

The ERIS is an ISOL-type low-energy RI-ion beam separator. The 150 MeV electron beam from the RTM irradiates the UC_x target, which contains about 30 g of ^{238}U. A total fission rate of 2.2×10^{11} fissions/s is estimated at a 1 kW electron beam power. In this case, the production rate of ^{132}Sn, our first planned target in the day one experiment, is expected to be 2×10^9 particles/s. The ion source is a forced electron beam-induced arc discharge (FEBIAD)[8, 9]. Fission products are mass-separated by the 120° analyzing magnet, which has a bending radius of 0.8 m and a maximum magnetic rigidity of 0.96 Tm. ERIS was successfully commissioned using stable Xe isotopes in 2012. Mass resolution and overall efficiency, including ionization, extraction, and transmission efficiencies, were evaluated at a 20 keV acceleration energy. The mass resolution $M/\Delta M$ for Xe^{1+} was 1660, and overall efficiency of 21% was measure for ^{129}Xe ion beam. Ref. [10] gives details of the ERIS system and its commissioning. We have started RI beam production in 2013, and succeeded in extraction of the $^{128-132}$Sn and $^{137-140}$Xe isotopes from the ERIS.

SCRIT SYSTEM PERFORMANCE

Experimental setup

Experiments for evaluating performance of the SCRIT system were carried out using a stable ^{133}Cs ion beam generated with a test ion source and a ^{132}Xe ion beam supplied from ERIS. In these experiments, we studied ion-trapping properties in the SCRIT; namely, trapping efficiency, overlap efficiency, the time evolution of trapped ions, achievable luminosity, and the electron-beam current dependence of these observables. We also measured the elastically scattered electrons from the target ions. The electron beam current and energy in the SR2 was typically 200 mA and 150 MeV. The

current was changed from 50 mA to 250 mA in a study of the current dependence. The number of injected ions were typically 4×10^8 ions/pulse for a $^{133}Cs^{1+}$ beam and 1×10^8 ions/pulse for a $^{132}Xe^{1+}$ beam.

During ion trapping, not only the number of trapped ions but also the charge state distribution is perceptively changed by the electron beam impact ionization process. The SCRIT ion cloud is unsteady and constantly changes over time. The number of trapped ions N_{trap} is obtained from measurements of the total charge, or by the charge state distribution in cases of a short trapping time. The trapping efficiency is estimated by $\varepsilon_{trap} = N_{trap}/N_{inj}$, where N_{inj} is the number of injected ions measured at the scraper-type beam position monitors. Since luminosity measurements using the loss monitor allow us to estimate the effective number of ions, N_{coll}, that participate in collisions with the electron beams, the overlap efficiency is obtained by $\varepsilon_{over} = N_{coll}/N_{trap}$. Time evolutions of those values were observed by repeating measurements with varying trapping times.

Scattered electrons from the target ions were measured by an electron detector system. Combinations of a drift chamber, plastic scintillators and two calorimeters were used in these experiments. The drift chamber projects the electron trajectory to the horizontal plane. Two calorimeters, pure CsI and BaF_2 scintillators were placed behind the drift chamber, and a scattering angle range from 25 to 50 degrees was covered. The solid angles were 6 msr and 10 msr for the pure CsI and BaF_2 scintillators, respectively.

An operation sequence of injection, trapping, and extraction with and without the target ions was alternately repeated during the measurement. Data from every detector was tagged by these occasions. Electron beam information, such as the DCCT-measured current and the transverse beam size given by the synchrotron radiation interferometer system, was acquired along with the other data.

Properties of trapped target ions and achieved luminosity

In measurements with short (less than 50 ms) trapping time, we confirmed collisions of the electron beam with the target ions. The electron-ion collisions increased the count rate of the electron beam loss monitor and reduced the electron beam accumulation

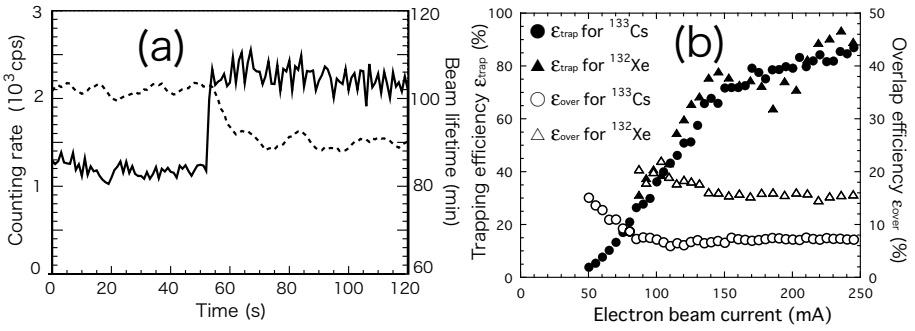

FIGURE 3. Change in the counting rate of the loss monitor (solid line in (a)) and in the beam lifetime (dashed line in (a)) at the moment of starting the measurement sequence. The trapping efficiency and the overlap efficiency (b) measured for the case of short trapping time.

lifetime. Figure 3(a) shows time trends for these at the moment of starting the ion trapping sequence. Increment in the counting rate of the loss monitor was about 1 kcps, corresponding to a luminosity of about 8×10^{26} /(cm^{2}s). From the lifetime reduction the luminosity is simply estimated to be about 1×10^{27} /(cm^{2}s). These estimations are consistent with each other.

Efficiency measurements were also performed for the short trapping time sequence. Figure 3(b) shows the current dependence of the trapping efficiency ε_{trap} and the overlap efficiency ε_{over}. The trapping efficiency almost linearly increased with current from 50 mA to 150 mA, above which it was gradually saturated. Most injected target ions were trapped at a current of more than 200 mA. We found that roughly 10% of trapped ions participated in collisions with the electron beam, although there were some differences in the overlap efficiencies for the Cs and the Xe cases due to differences in conditions of the injected beam. From this, we believe that the transverse spatial distribution of the trapped ions is three times larger in radius than the electron beam size.

We could study the time evolution of the ion trapping properties by changing the trapping time. Figure 4(a) shows typical decay curves of the relative luminosity values at a 200 mA electron beam current. A variety of decay constants were measured with the electron beam current. This experiment indicates that there is a significant factor that strongly affects the trapping properties. We studied this strange phenomenon in detail. A detailed description of that study and its interesting results are described in Ref. [11]. The trapping property is deeply affected by electron beam instabilities such as coherent synchrotron oscillation (CSO). Such instabilities are inevitable in an electron storage ring with large current accumulation. The decay constant became smaller with increasing CSO amplitude, which could be controlled by tuning the RF cavity condition because the CSO is activated mainly due to HOMs excited in the cavity. It is, therefore, possible to control the decay constant to some extent. Consequently, it was easy to extend the decay constant more than 1 s.

The luminosity achieved in the short trapping time measurement (45 ms) is shown in Fig. 4(b) as a function of the electron beam current. In case of Cs, the luminosity reached 10^{27} /(cm^{2}s) at a 250 mA current. On the other hand, luminosity for the Xe case was

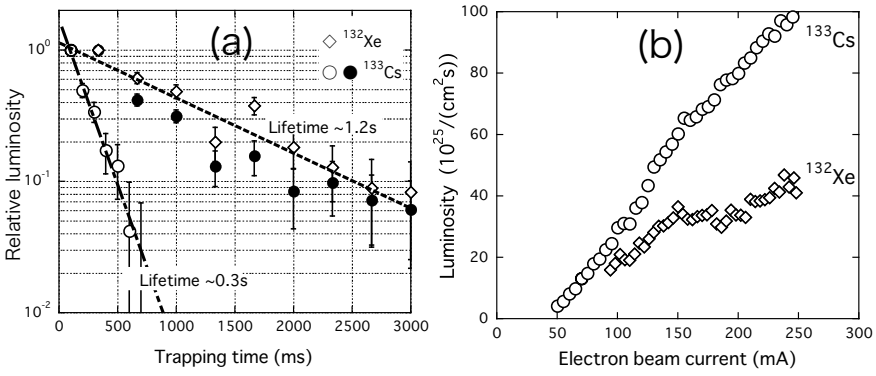

FIGURE 4. Time evolution of the relative luminosities (a) and the current dependence of the achieved luminosity (b) at a 45 ms trapping time. Data at the smallest time in (a) are normalized to 1.

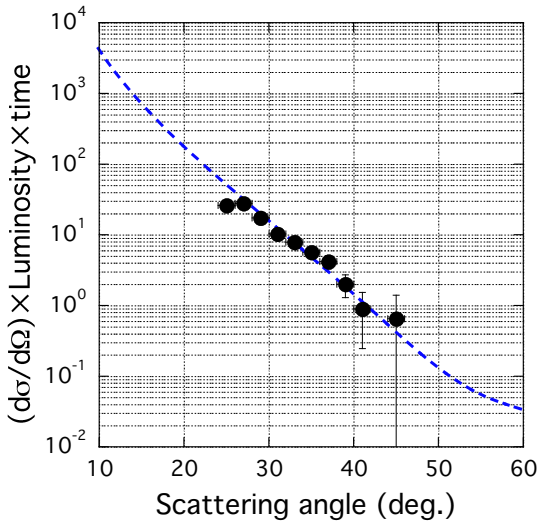

FIGURE 5. Angular distribution of elastically scattered electrons from trapped ^{132}Xe ions.

4×10^{26} /(cm^{2}s), while the number of injected ions was four times smaller than that of the Cs case. This difference in the overlap efficiency is thought to be due to injected ion beam qualities such as emittance, and to differences in the beam tuning. Low-emittance ion beams are favorable for efficient collision. In any case, therefore, luminosity over 10^{26} /(cm^{2}s) could be maintained for more than 1 s, and the target SCRIT performance set as a goal in our development has been achieved.

Measurements of elastically scattered electrons

Figures 5 shows the angular distribution of electrons scattered from trapped ^{132}Xe ions. The elastic scattering cross section for ^{132}Xe was calculated using the DREPHA program[12, 13], and it is indicated with dashed line in the figure. The experimental data are well agree with the estimations.

CONCLUSIONS

The SCRIT electron scattering facility has been constructed at RIKEN RIBF. The SCRIT system has already been installed in the SR2. ERIS has also been constructed, and the RI production has already been started. Experiments for evaluating performance of the SCRIT system have been successfully curried out using Cs and Xe ion beams. We have clarified the properties of target ion trapping in SCRIT, and confirmed that luminosity over 10^{26} (/cm^{2}s) can be maintained for more than 1 s. We have succeeded in measuring elastic electron scattering from the target ions. These experiments have established the applicability of the SCRIT system in the new facility for electron scattering with unstable nuclei. Further instrumentation such as a new electron detection system and

cooler buncher are now under development, and will be installed within a year. Electron scattering experiment for unstable nuclei is planed to start in next year.

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Advanced techniques for measuring nuclear moments, spin and charge radii

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Abstract. The future EURISOL facility will have production yields that exceed any existing (or currently under construction) ISOL facility by more than a factor of 100. Such a large increase in beam intensity will help extend measurements far from the line of stability. At the same time it will also provide an opportunity to develop new high resolution experiments that require intense beams to realize. Over the last 40 years laser spectroscopy has become one of the main methods to measure the nuclear moments and charge radii of ground and isomeric states in unstable nuclei. State-of-the-art laser spectroscopy techniques can now measure isotopes produced at rates of less than 0.1 atoms/second and will form the basis of future techniques that will be instrumental in extending our knowledge to the most exotic nuclei. Ultra-high resolution radioactive beam measurement have been reserved (in general) for light elements such as ^{11}Li and ^{11}Be . Recent measurements have shown that it is possible with trapping and laser-microwave methods to measure the hyperfine structure with an uncertainty of 72 Hz. With such high precision it may become possible to measure the magnetic octupole moment of unstable nuclei. This report will review the state-of-the-art and consider the opportunities and challenges at the future EURISOL facility with respect to moment and charge radii measurements.

Keywords: Nuclear Moments, Laser Spectroscopy, EURISOL
PACS: 21.10.Ky, 21.10.Hw,21.10.Ft

INTRODUCTION

Modern nuclear theory expects approximately 7000 bound nuclei between $2 < Z < 120$ of which over 3000 nuclei have been experimentally observed at existing facilities. The future EURISOL facility will allow a wide range of novel experiments to be performed on exotic nuclei far from stability that will extend our knowledge. Charge radii and moment measurements are especially powerful since in general these observables are measured without introducing any assumptions associated with a particular nuclear model. Moments are sensitive to single particle configurations and collective properties such as deformation and core polarization [1]. Considerable insight to the composition of nuclear wave function is possible when the magnetic and quadrupole moments are combined with a firm spin measurement. The recent confirmation of the inversion between the $\pi p_{3/2}$ and $\pi f_{5/2}$ states in ^{75}Cu and the ground-state spin of ^{72}Cu by laser spectroscopy highlight the merits of this approach [2, 3]. By comparing measurements with state-of-the-art shell-model calculations it is possible to assess the composition of the wave function and study the phenomenon of shell breaking associated with particle-hole excitations [4]. By measuring the isotope shift in the the atomic system it is possible to extract the mean-square charge radius, which is sensitive to effects such as volume changes, deformation, surface diffuseness [5]. Halo nuclei have been studied through

a comparison of the mean-square charge radius with the matter radius [6]. The future EURISOL facility will offer a unique opportunity to extend charge radii and moment measurement to the limits of stability. Since the most compelling isotopes will often be at the achievable limits of production, techniques that have single atom sensitivity and high background suppression will be essential. At the same time the facility will also produce unprecedented yields closer to stability that open the possibility of ultra-high precision techniques allowing observables such as the distribution of magnetization (Bohr Weisskopf effect) and the magnetic octupole moment to be measured. These two experimental regimes require two different but still complementary moment measurement programs. This report will focus on the application of laser spectroscopy for future moment measurements.

EXPERIMENTAL CONSIDERATIONS

The lifetime of the state (ground or excited) not only determines the production method but also the technique for moment measurements. Thus transient field, recoil in vacuum, TDPAD and laser spectroscopy/β-NMR all provide complementary information for specific lifetime ranges. Laser spectroscopy measurements can be performed on nuclear states with lifetimes down to 1 μs [7], making it the moment measuremnt technique with the widest applicable lifetime range.

When all laser spectroscopy measurements are plotted on the nuclear chart, large gaps in our knowledge are apparent. In some cases entire chains of isotopes have yet to be studied. This is due to production difficulties at existing facilities and atomic structures that have no suitable transitions for laser spectroscopy. It should also be noted that with the exception of the lightest elements laser spectroscopy rarely pushes to the limits of nuclear existence. Recently several significant advances have helped extend the range of laser spectroscopy of exotic nuclei. A major development has been that of in-source laser spectroscopy, which has demonstrated the capacity to study isotopes produced with rates below 0.1 atoms/s [8, 9, 10]. A significant improvement in collinear laser spectroscopy was the introduction of ion trapping in 2002 to reduce the background associated with scattered laser light [12, 13]. The ability to trap ions and produce a bunched beam with a repetition rate that matches high power Nd:YAG lasers has also made the technique of collinear resonance ionization spectroscopy (CRIS) possible [14, 15, 16]. This technique has demonstrated a factor of 100 increase in sensitivity compared to state-of-the-art bunched laser spectroscopy [17] and has allowed measurements to be made with yields of less than 100 atoms/second. In principle the CRIS method has the ability to study exotic nuclei produced at rates below 1 atom/s. A novel high resolution trapping technique has recently been developed to study ^{11}Be allowing the hfs A-factor to be determined with a precision of 1 part in 4×10^7 [11]. It should also be noted that this technique has the ability to study cases produced at rates below 100 atoms/second.

The opportunities afforded by the future EURISOL facility should motivate the development of novel techniques that will utilize this facility to its full capacity. There will be two distinct regimes that require two different approaches and can be grouped under exotic nuclei and near stability nuclei. At the limits of nuclear existence where

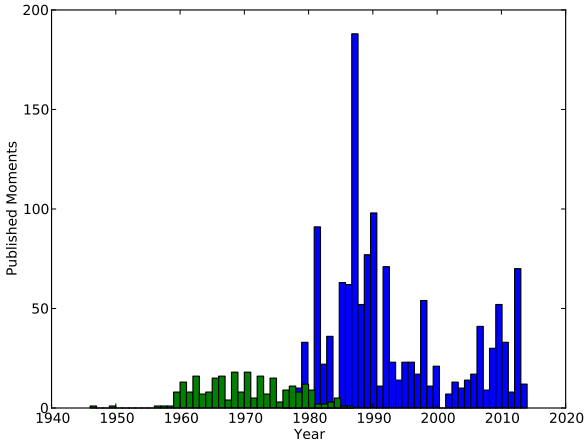

FIGURE 1. Published nuclear moment measurements per year. ABMR measurements are shown in green and laser spectroscopy measurements are show in blue. Data were taken from [18]

the lifetime drops below 1 second and the yields will drop to less than 1 atom/second. Furthermore these exotic nuclei will be typically produced with larger isobaric contamination. The key requirements for laser spectroscopy of exotic nuclei are sensitivity and selectivity, which may require the resolution to be compromised. Since very little structural information exists at drip lines, measuring only the magnetic moment or charge radius will still have a large impact. Near stability nuclei on the other hand will be produced with yields in excess of 1×10^{10} atoms/second. These nuclei will represent the precision frontier where new physics will require ultra-high resolution and accuracy as well as precision. In contrast to exotic nuclei the techniques employed will not require as high sensitivity or need to be as fast. This division already exists in modern facilities between nuclear structure and weak interactions experiments where the latter dedicate their efforts on a few key isotopes. In addition to experiments that look for physics beyond the standard model, additional nuclear observables such as the distribution of nuclear magnetism and the magnetic octupole moment are possible at the EURISOL facility.

FUTURE CONSIDERATIONS

It is tempting to use the experiments at current facilities as a template for the future. However within the time frame of the EURISOL project there will likely be dramatic changes within the field. The field has previously witnessed such effects and perhaps the greatest is associated with the introduction of laser technology in the 1970s. Between 1950 and 1970 the most popular methods for moment measurements were NMR (nuclear magnetic resonance) and ABMR (atomic beam magnetic resonance) while optical techniques were considered as old technology with little future promise. The abrupt shift in the direction of moment measurements is highlighted in Figure 1. The development of a narrow bandwidth tunable laser represented a paradigm change for the field and was very rapidly adopted at the expense of ABMR. Trapping and cooling techniques are

far from a mature field and many new and exciting developments are currently being reported.

Consideration for multiple measurements of the same isotope either at different facilities or the same facility should be made. Typically remeasurement only happens in the process of studying new more exotic isotopes when references are required. Due to the complexity and time required to run experiments there is little motivation to remeasure cases where only one previous measurement exists. This risks constraining nuclear models with a few false results. It is therefore essential that more than one group are encouraged to measure (ideally with different techniques) the same chain of isotopes at the same time.

SUMMARY

The future EURISOL facility will offer the laser spectroscopy community unprecedented access to exotic nuclei. Over the last 40 years the community has developed sensitive and precise tools that are employed at facilities around the world. Current methods will naturally improve and new concepts will emerge. The limits of nuclear existence will require the most sensitive techniques. The high yields available closer to stability open the possibility of developing new techniques to measure observables such as the distribution of nuclear magnetism and the magnetic octupole moment.

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Precision measurements with ion traps for next-generation beams

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Keywords: radioactive ion beams, high-precision measurements, Penning trap, multi-reflection time-of-flight device, beam purification and analysis, resolving power
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INTRODUCTION

Investigating nuclear properties reveals details of the nuclear interaction giving insight into a variety of physics topics. High-precision measurements of ground and excited state properties advance our understanding of the limits of nuclear stability, element formation in the Universe or fundamental symmetries and put constraints on nuclear models. Knowledge of different properties of a large range of especially short-lived nuclides is thus indispensable. A recent example is the mass measurement of ^{54}Ca ($t_{1/2} = 90(6)$ ms) performed at ISOLDE/CERN with which the question of how nuclear structure changes far away from the valley of beta stability could be addressed. Having a neutron-to-proton ratio larger than 1.7, this nucleus belongs to the most exotic systems to investigate the evolution of nuclear magic numbers. The neutron magic number at $N = 32$ was confirmed with a two-neutron shell gap of almost 4 MeV [1]. The importance of three-body forces to correctly describe the structural evolution of the calcium isotopic chain was demonstrated. Further, the excitation energy of the first excited 2^+ state of ^{54}Ca was measured at RIKEN [2] establishing $N = 34$ as magic number.

While reaching for more and more exotic nuclides, these measurements are often hampered by a minute production rate and a short half-life of the species of interest as well as a high background of contaminating ions [3]. Therefore, modern techniques have to be fast, selective, and efficient such that in special cases even a single nucleus can be sufficient to determine its properties with high accuracy [4]. Here, an overview is given of latest developments in the field of ion traps, namely Penning traps and multi-reflection time-of-flight devices. A brief review of the technical advances can be found in [5, 6, 7, 8]. Focus is laid, on the one hand, on improved techniques for mass measurements aiming at a gain in precision or mass resolving power as well as reduction of overall measurement time. On the other hand, on advances in ion-beam yield analysis, beam purification as well as isomer selection.

TABLE 1. Penning-trap mass spectrometers installed at radioactive ion-beam facilities with different production mechanisms.

Production	ISOLTRAP CERN (Switzerland)	TITAN TRIUMF (Canada)	SHIPTRAP GSI (Germany)	MLLTRAP LMU (Germany)	JYFLTRAP (Finland)	LEBIT NSCL (USA)	CPT ANL (USA)	TRIGA-TRAP (Germany)
ISOL	X	X						
Fusion evaporation			X	X	X			
IGISOL					X			
Fragmentation	X					X		
Spontaneous fission							X	
Neutron-induced fission								X
Highly-charged ions (HCI)		X						

PENNING-TRAP MASS SPECTROMETRY (PTMS)

At present, eight Penning-trap mass spectrometers are operating at radioactive ion-beam facilities. Table 1 shows the location of each spectrometer and the beam-production mechanism. In the past, PTMS on radioactive ion beams could demonstrate mass measurements reaching half-lives as low as $t_{1/2} = 8.6\,\mathrm{ms}$ in the case of ^{11}Li [9] and mass resolving powers $R = m/\Delta m > 10^6$ in the case of ^{195}Bi, where the half-life of the ground (isomeric) state is $t_{1/2} = 183\,\mathrm{s}$ ($t_{1/2} = 87\,\mathrm{s}$) [10]. The time-of-flight ion-cyclotron-resonance technique (TOF-ICR) has been the method of choice for the precise mass measurement of radioactive nuclides for over two decades [11, 12]. It exploits the relation that the cyclotron frequency ω_c of a particle with charge q in a magnetic field B is related to its mass m via

$$\omega_c = \frac{q}{m} B\,. \tag{1}$$

Confined in a Penning trap, the manipulation of a particle's eigenfrequencies using radio-frequency excitation field determines ω_c from which the mass can be extracted. The TOF-ICR technique is based on single-ion detection, yet, to obtain a TOF resonance some few hundred ions are usually required to achieve a relative statistical uncertainty on the order of 10^{-8} within a measurement time of about one hour. Until today, relative mass uncertainties below 10^{-9} could only be demonstrated on long-lived or stable nuclides [13, 14, 15].

GAIN IN PRECISION OR MASS RESOLVING POWER

Improving the achievable uncertainty of mass measurements on short-lived nuclides first became possible by manipulating the trapped particle differently. Table 2 gives an overview of different techniques which offer gain in precision or mass resolving power for separation with respect to the conventional TOF-ICR technique. A gain in precision translates into reduced measurement time at the original uncertainty if required. Beam-preparation time, the time for a single measurement cycle as well as the time needed for a mass measurement with the desired relative uncertainty are also given. Finally the number of ions needed for the respective measurement technique is given as well as the experiment where the technique was demonstrated. For rare isotopes that are produced at extremely low rates one can use the Fourier-transform ion-cyclotron-resonance technique (FT-ICR) for which one a single ion is needed for a measurement. Further developments include, on the one hand, the phase-imaging ion-cyclotron reso-

TABLE 2. Techniques for gain in precision or mass resolving power for separation.

Mass measurement	Ramsey	Octupole	PI-ICR	FT-ICR	TOF-ICR with HCI	MR-TOF
$\Delta m/m$ or precision gain cp. to TOF-ICR	3-4	3-4	≈ 15	$\approx 10^{-6}$	$\propto q$	$< 10^{-6}$
$R_{sep} = m/\Delta m$	$\geq 10^6$	$\geq 10^7$	$\geq 10^7$			$\geq 10^5$
Additional preparation time per frequency step					≥ 10 ms	
time for 1 ICR meas.	≥ 500 ms	≥ 500 ms		≈ 100 ms	≥ 500 ms	
time for 1 TOF spectrum						≥ 10 ms
# ions	≥ 100	≥ 100	few tens	1	≥ 100	≥ 100
TOF-ICR needed	to fix ω_c	to fix ω_c	to determine the total phase	no		no
demonstrated	ISOLTRAP [16, 17]	ISOLTRAP [18] LEBIT [22] SHIPTRAP [23]	SHIPTRAP [19]	LEBIT* [20]	TITAN [21]	ISOLTRAP [1]

* simulations

nance technique (PI-ICR) using phase measurement for a mass determination instead of frequency measurements, on the other hand, charge breeding for beam preparation to achieve higher-frequency motions of the trapped particle.

PURIFICATION TECHNIQUES AND APPLICATIONS

One of the major challenges for measurements on short-lived nuclides is the fast selection of the one ion of interest from the remaining isobaric ensemble. The required mass resolving power to suppress these isobars can vary from $R \approx 10^3$ up to 10^6. It is thus crucial to know the time scale within which a method can reach a certain resolving power combined with the purification step. Table 3 compares the well-known mass-selective resonant buffer-gas centering (buffer gas) being performed in the buffer-gas environment of a Penning trap to different cleaning techniques using the high-vacuum environment of the measurement Penning trap. Alternative to the conventional dipole-cleaning technique, the SWIFT (stored wave form inverse Fourier transform) technique and the simultaneous excitation of the trapped particle's eigenmotions (SIMCO excitation) have been demonstrated. While these techniques can be applied on sufficiently long-lived radioactive nuclides for preparing a pure sample, the Ramsey and dipole-cleaning technique have also been employed to separate isomers for subsequent spectroscopic experiments. A drawback of some of these techniques is the timescale of a few hundred miliseconds which makes them inappropriate for nuclides with half-lives well below 100 ms in combination with high background contamination. A double Penning-trap for high-resolution separation at the future DESIR facility of SPIRAL 2 is being setup [24]. A new requirement constitutes the need to purify samples with more than 10^4 ions.

TABLE 3. Techniques for purification and suppression of radioactive ion beam.

Beam purification	Buffer gas	Dipole / SWIFT	Ramsey	SIMCO	MR-TOF
$R_{pur} = m/\Delta m$	$\geq 10^5$	$\geq 10^6$	$\geq 10^6$	$\geq 7 \cdot 10^5$	$\geq 10^5$
# ions (acceptance)	$\geq 10^3$	$\geq 10^2$	$\geq 10^2$	$\geq 10^2$	$\geq 10^3$
time	≥ 100 ms	≥ 1 s	≥ 200 ms		≥ 10 ms
suppression	$\geq 10^2$	$\geq 10^2$	$\geq 10^2$	$\geq 10^2$	$\geq 10^4$
transmission					≈ 50 %
demonstrated	ISOLTRAP [25]	[26] LEBIT [20]	JYFLTRAP [27, 28]	ISOLTRAP [29]	ISOLTRAP [7, 30]

MULTI-REFLECTION TIME-OF-FLIGHT DEVICES

Time-of-flight (TOF) mass spectrometry is one of the most commonly used analytical tools in all fields of science. It is based on the identification of beam components with respect to their mass-over-charge ratio by separation in flight time to an ion detector. In multi-reflection time-of-flight (MR-TOF) mass analyzers, the ions use a dedicated flight path multiple times while at the same time keeping the size of the device compact. This technique increases the mass resolving power tremendously compared to TOF mass analyzers while keeping the measurement time as short as a few milliseconds. It can thus provide fast separation of ion beams as demonstrated off- and on-line [31, 32, 33], mass purification [31] as well as high-precision mass measurements [1, 34]. At present, three MR-TOF devices are installed at radioactive ion-beam facilities: GSI Darmstadt (Germany) [32], RIKEN (Japan) [33] and ISOLDE/CERN (Switzerland) [7]. An overview of the different design concepts can be found in [32]. Resolving powers comparable to that of Penning-trap techniques and subsequent suppression of contaminants can be achieved on time scales an order of magnitude smaller, see Table 2. This is true for the requirements usually present for experiments with short-lived nuclides, otherwise different conditions apply, see for example [8]. The specific appeal of MR-TOF MS lies in the fact that high-precision mass measurement with single-ion sensitivity routinely become possible for nuclides with minute production rates, strong contamination, and half-lives below 100 ms. This was demonstrated at RIKEN reaching a relative uncertainty of $6.6 \cdot 10^{-7}$ for a mass measurement of $^{8}Li^{+}$ [34] as well as at ISOLTRAP with the mass measurement of $^{54}Ca^{+}$ exhibiting a relative statistical uncertainty of $9 \cdot 10^{-7}$ [1]. Wide-band mass measurements have also been demonstrated [35].

APPLICATIONS FOR MR-TOF DEVICES

As a tool for fast beam purification, MR-TOF devices can support existing mass-measurement setups. Using multiple MR-TOF separation cycles to purify the ion of interest from contaminating ions offers a factor of 20 decrease in measurement time at a transmission coefficient of roughly 50 % [30], see Table 3. The pure samples can then be accumulated and provided for different spectroscopic experiments. In general, a MR-TOF device situated behind a radio-frequency quadrupole cooler and buncher like ISCOOL at ISOLDE and designed to its emittance would provide purified samples to

a whole range of experiments. MR-TOF devices can likewise be employed as diagnostic tool for ion-beam yield analysis. The optimization of specific parameters relevant for ion production is an integral part of the Target-and-Ion-Source Development (TISD) program for example at ISOLDE [36]. This includes the investigation of production cross section, effusion and diffusion behavior, as well as ionization efficiency. The overall production rate during proton irradiation as a function of target temperature, for example, is currently monitored using Faraday cups, while the identification of the ions of interest is performed by β and γ spectroscopy. The applicability is limited by the measurable ion count, the branching ratio of the respective decays, the half-life of the ion of interest as well as background and detection efficiency. An MR-TOF spectrum can be used to analyze the qualitative as well as quantitative composition of an unknown ion beam as a function of the different production and ionization parameters [6]. The advantages of ion-beam yield analysis using an MR-TOF device constitute the measurement time on the order of 10 ms, direct ion detection, non-scanning operation, resolving powers on the order of 10^5 and no dependence on decay properties. Once the isobaric composition of the beam is identified, each peak in the MR-TOF spectrum can be monitored individually and respective yield changes can be observed relative to ISOLDE ion-production and separation parameters, such as target and transfer line temperatures, delay from proton impact to the opening of the ISOLDE beam gate, or position of the separator slits. Also the chemical release properties can be probed with an MR-TOF device.

If the energy difference between a nuclear ground state and isomer is large, the purification techniques describe above may have sufficient resolving power to separate these states. A different approach is to attempt isomer selection at the ionization stage of beam production. The Resonance Ionization Laser Ion Source (RILIS) can probe the large hyperfine splittings of atomic transitions that occur for some elements. Tuning of the wavelength can result in preferential ionization of a nuclear ground state or isomer. The MR-TOF device can assist with the optimization of this wavelength tuning by TOF separation of the surface and laser-ionized components of the ion beam. It provides a background-free means of detecting the photo-ions whilst the laser is scanned across the hyperfine structure of the atomic transition. This method can offer the necessary information for providing isomerically pure beams, which in turn can be made available for different precision spectrometry or decay spectroscopy experiments.

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Silicon and Gas Detectors in Nuclear Physics Experiment

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Abstract: *In this presentation a limited overview of the instrumentation and techniques based on Silicon and Gaseous detectors for charged particle detection, is presented. Attempts are made to single out areas which stands to be challenges towards building instrumentation of discovery in the domain.*

Measurements with beams far from stability often have low luminosity. So, over the last two decades the Nuclear Physics, NP community has devoted a strong drive towards developing instruments having an extensive solid angle cover. ("4π" in publications, is recurring in many of the titles on nuclear instrumentation.) Targets have also seen "renewal" via "active-targets" and cryogenic approaches. The sizable solid angle, efficiencies and "effectively thick" targets allowed pioneering work to be done with low beam intensities with published multi-particle (see HIRA/NSCL) and particle-gamma coincidences measurements (see MUST2, TIARA, T-REX etc.). Further, with the projectiles being the nuclei of prime spectroscopy interest has resulted in the requirement for fine granularity of the detectors; in inverse-kinematics reactions studies we are now capable to obtain position, energy, time and particle-identification per pixel or voxel to trace out the kinematics and extract cross-sections. Thus we now often talk of highly segmented arrays. With beams far from stability we have adverse effects. 'Contaminated' beams with large emittance have resulted in developments in beam tracking/identification and particle trajectory reconstruction in magnetic spectrometers. A corollary of such developments in the segmented sensors necessitates high performance multi-channel electronic systems with high dynamic ranges and specific signal processing.

Weather it be a silicon or gas detection media and the accompanying electronics, NP does not hold a leading role in their major development, today. Most of the source of progress is reported from Particle Physics where the surfaces to be covered by such devices are many order of magnitude larger than in NP. Thus in Particle Physics, we observe a huge technical effort with "armies" of specialized engineering, technical staff and physicist to carry such developments. Big players are also laboratories (Astro Physics) developing satellite carried instruments where "perfection" is the underlying motto and where resources are infinite by NP standards. It is obvious we

cannot afford such luxuries today. Thus over the last 10-15 years Nuclear Physics has been borrowing techniques from Particle/Astro Physics. Not to belittle our field, exception exists, of course. Some of the NP techniques have infiltrated or deployed in Particle Physics. Ge arrays for high gamma resolution spectroscopy are a pinnacle example (AGATA, GRETINA, SeGA…) mastering pulse shape for position and energy resolution. Another akin example is particle identification, PID, through pulse shape analysis (FAZIA work at Florence University, Ref. 1). Also the use of DSSSDs in ultra-high vacuum is another interesting example when doing physics with storage rings (see at this workshop Phil Woods). The NP needs to reach extreme dynamic ranges has and NP engineers are busy doing work in this area which will no doubt be deployed, eventually in particle physics. Transverse innovation from Particle Physics is observed in other area, like medical imagery. Having NP groups resident in large national laboratories and universities which having strong interests in Cryogenics, Solid State, Astro, Particle Physics, Micro-electronics, etc often enhances such crosscutting technical and scientific developments and methodologies. Therefore such groups should be encouraged to participate in transverse developments .

Silicon sensor for physics have profited enormously from the microelectronics industry. Most of the manufacturing techniques used for detectors stem from there. Companies that make our detectors have a significant investment to make in methodology, equipment, control and clean room environments. The result being that our purchasing source is very limited, leaving less then a hand full of companies to choose from. In the case of NP the choice is two or three at very most. The reasons for this are because the numbers of detectors we purchase are very petty and when we want a detector it has to fit our specifications (mostly geometry because of our very close compact geometries, solid angle needs and number of channel "economies"). Given the production costs and return on investment very few industries can survive. This is indeed of significant concern in Europe and worldwide. Solutions do exist, but not without significant EU financial support. To note a repercussion of all this is that a number of NP projects are unable to afford the development costs of an instrument, thus we see next-to-no "nouvelle" ideas emerging from within our field (e.g. edge-less devices or applications of 3-D techniques, radiation hardened devices, …). Not to leave this paragraph with a requiem note, I will refer you to work done principally at from Firenze University (ref) for high mass ($Z>4$) which was mimicked by work at IPNO ($Z<4$) (see Marléne Assie at this workshop for the nouvelle algorithms and results) on PID employing neutron transmuted Si and crystal oriented silicon devices. The results are spectacular for ($Z>4$) and most encouraging for ($Z<4$). Challenge exist: How stable is the good PID resolution to radiation damage, for example. Can we afford a constant quality production of detectors? PID and ToF measures are they compatible at low impact energies (<2MeV.A)? Once we need highly segmented devices (spectroscopy in invers kinematics) what is the PID efficiency and dynamic ranges? Is orientation critical and if yes is there an affordable solution? For high mass there is a significant threshold – what are the solutions, if any? Can we put our act together and build a high bandwidth DAQ that permits PID and dynamic range? Nevertheless the results are encouraging and detector arrays like GASPARD, HYDE and TRACE will be eventually built and place in gamma arrays like PARIS or

AGATA. I would like to add that at forward angles the PID technique for heavy masses could be employed for heavy ions (Z<45) at lowish bombarding energies or for quasi-projectile spectrometer. For EoS physics (FAZIA) it is particularly positive if the physics is supported ever to supported Europe. The 4π cover weather it is EoS or particle spectroscopy is costly in terms of development, realization and maintenance. The only way, it seems to me, that we can ever get an instrument in Europe is if we get together, forget ourselves and promote a single project (today we have TRACE, GASPARD and HYDE for spectroscopy) for the community. We have not yet done this. It is challenging.

The latter paragraph underlines the inhibitive costs in developing new (or revive old) techniques with silicon. An example of this is thick (>2mm) large area (>50cm^2) Si(Li) devices. MUST2 (Ref. 5) in employing Si(Li) was indeed a trial by fire. The attempt to develop large area devices proved very expensive and not necessarily satisfactory. Consequently, today, to cover a reasonable dynamic range with a retained energy resolution (and no holes in the spectra) we thus need several 2mm Silicon. Going to $LaBr_3$ need not be the acceptable final solutions. A challenge would be to invest in reaching larger thicknesses with large area with "standard" Si. Less of a challenge is the understanding DSSSD. Namely, effects associated with inter-strip have been elucidated very nicely (Ref MUSETTE) however not necessarily all fully understood. It will be of import to have a published freeware, easy to use study of "CAD" driven simulation that can fully represent the effects – including pulse shape effects of course. This is a mini-challenge to our domain but wanted to make explicit decision making when "mounting" specifications for big (TRACE, GASPARD like) to less-big projects (T-REX or SHARK size).

Diamond as a charged particle detector is well known - excellent timing, idem for its radiation harness. Thus it is an excellent medium for tracking if one has enough energy in the beam. Works on silicon where prices are not so excessive as for "translucent carbon" have yielded what are known as 3-D devices (Ref. 3) which have comparative specifications. From W[3], the NP community have not tried such devices. The challenge is not huge but not small either – already one has to locate funds and modify Si sensors and the electronics. Now, to provide a solid-state to gas transition I will mention the works done by the group at CEA/SEDI some time back, to track, at a very high rates with diabolic position resolution (70μm, 0.5ns, 100% efficiency, 10^7Hz)– KABES/NA48. It employs of gas media coupled to MICROMEGAS gas amplifier. Applications to high incident energies beams (GSI & RIKEN) are obvious. Challenge will be - can the results be reproduced for heavy ions? Can the method be fully deployed at low gas pressure for slow ions? Can one use the gas medium to have Z resolution for low masses? The KABES idea is not estrange since we are all dabbling with gas media. So I guess we will see this soon. A point to add here which is particularly important when considering intense exotic beams, be it FAIR, SPAS, RIKEN, SPIRA2 or the far future EURISOL – we are more and more aware of the needs associated with tracking of the beam as close to the source as possible. Besides limiting detectors today we have no electronics toy system that allows close to the

source beam tracking. The latter is an additional challenge, seemingly hard to fund for NP.

Again, over the last decade, we have assisted to change in the orientation in charge particle detection: Namely to move away from DSSSD based medium (MUST2, T-REX, HIRA, HELIOS, SHARK …) to the use of gas medium as a detector and in particular as detector where the gas as a target. The latter is presented at this workshop (See talk by Thomas Roger), where we now talk of an Active-Target (AT#TPC). To understand what brought about this change it is worth saying a few words about the history of things as seen from the French community, in particular. When building the focal plane detectors for VAMOS (eventually in MAGNEX (LNS, Catania) and SHIRAQ (RIKEN)) at IRFU we implemented, for the "first" time in this domain, a Particle Physics ASIC called GASSIPLEX. That development was a seed for the AT#TPC, MAYA, because we needed "many" channels and there was no way we could afford a conventional electronics for this. So Particle Physics was instrumental in launching MAYA (Ref. 4). The device has been used to do physics at GANIL, TRIUMF and ISOLDE. In MUST2 (Ref. 5) we went full hog and developed all the hardware including the ASIC. Ultimately MUSETT (Recoil decay tagging device) was born from MUST2. It was also derived from our confidence to employ microelectronics based systems. Particle to Nuclear crosscutting comes also in the development MICROMEGAS (Ref. 6) and GEM (Ref. 7) gas amplifiers. These micro pattern devices have spectacular advantages over wire amplifiers and easy to integrated in TPCs/AT#TPCs. Now we see numerous applications beyond physics. The physics of these devices and manipulation are relatively well understood within Particle Physics community. When it comes to NP community this is limited to a hand few of scientists/engineers. Further, heavy ions in a gas and the accompanying effects have yet to be clarified. Some of the effects can be detrimental to an effective use of gas media. Nevertheless, we know that TPC-like instruments are now constructed, being or planed in many institutions. A few comments which are non-exhaustive constitute challenges; i) delta electrons (around the beam in the gas) and how to reduce their effects to reach precision vertices extraction and hence energy and angle measurement, ii) gas mixture/pressures systematic studies, iii) operative coupling of TPCs with solid state devices/scintillators which would avoid holes in the spectra, iv) exhaustive tests on new DAQ systems coupled to a TPC for nuclear physics. I will underline v) to set-up bench marking experiments (resolutions, dynamic ranges, ...) to constitute a solid proof-of-principle document. The projects in the making or in an advanced stage of planning/testing – for a sum count; TACTIL (York), MAYA (GANIL), SPIRIT-TPC (RIKEN), LAMPS (IBS Korea), R^3B-TPC (GSI), MINOS(IRFU/SPhN), AstroBox (IRFU & Texas A&M), AT-TPC (NSCL), ACTAR (GANIL), (Texas A&M) , CAT(Tokyo University) and others. Given that the above queries might shed a shade of gray in the community approach - I will emphasis a positive notes for a paragraph or two. But, before doing so I would like to mention a dilemma facing at least the French community and which is possibly already contaminated the Americas. We observe a number of research physics programs addressing particle spectroscopy (at low energy) in invers kinematics where one hand we adhere to 4πSi + Gamma array (TRACE(Legnaro, IT), GASPARD,

HYDE(Huelva, SP etc.). On the other hand the gaseous AT-TPC, ACTAR, … are understood to be "claiming" equivalent performance. Funds are not easy to come by, so we cannot assault the problem by saying we build several working copy of each and then we will decide. So the challenge (or crises) here is to decide to devote time to perform comparative benchmarking. NP cannot afford a belated "flop" in our domain. Seen from far, reliable yardstick will inevitably draw overlapping domains of interest which will help to deflate the crises. I consider that "extra-push" for gas instruments has had adverse effects in deciding on a "Si ball".

AstroBox attempts to measure energy spectra in a gas medium for light ions (p and α) in β delay proton emission (Ref. 8). The β are very prolific with a wide energy spectrum. The captured data in a gas yield p spectra with thresholds below 100keV. A comparison with Solid State detectors the β^+ background for AstroBox is reduced by factors of 500 at 200keV. Apart from the background reduction the result is interesting because it gives confidence in charge deposition linearity and resolution at low p energies. In the (ref.) we also publish identification spectra of the "implanted" beam, hence a good normalization. Without going to any details, an equivalent AstroBox set-up in a focal plane detector or beam gives charge identification /position tracking. With respect to ion chambers the advantage being the high gain of the gas amplifiers giving excellent signal/noise ratios and fast response. The challenge to employ gas amplifiers in the above "full-energy" modes is being deployed at IRFU, Texas A&M, IPNO and Riken. We should have results soon, bench-marked the "full-energy" method in the gas amplifiers for charge resolution. If positive results are given we stand to see such developments in a number of accelerator labs in the future.

Today, perhaps the most ambitious program in nuclear physics with Silicon is the R^3B tracker being built by the UK nuclear physics community working at GSI/FAIR. The object being to being spectroscopy/reaction studies employing (p,2p, γ), (p,np), (p,α) … for nuclei far from stability at relativistic energies on a hydrogen/deuteron targets. To obtain excitation energy resolution from the protons the proton angular resolution has to be excellent (Ref. 9) and thus requiring a fine segmentation of the trapezoidal thin Si detectors. The residual energy of the protons will be measured in CALIFA and so will the gammas (see Haik Simon in this workshop). The electronic-mechanical efforts are akin to particle physics works. Also, the tracker will have 120kchannels thus requiring a significant innovative effort in the DAQ. The tracker is being prepared for 2016 tests. A contrasting development, with the first experiment some three months ago, is MINOS. The reactions are the same. The physics of objectives overlap widely. The method is very different. MINOS (Ref. 10) employs a thick liquid target (<200mm=$0.8\text{x}10^{24}$ atom/cm^2 for RIKEN) and extracts spectroscopy from gammas of bound nuclear ejectiles. The LH_2 target gives a huge luminosity allowing for experiments with one or less particles/second experiments. Hence nuclei far away from stability can be measured. One gains some 2 neutrons over other lower luminosity setups. To correct for the Doppler broadening a cylindrical TPC is employed to give a vertex with precisions of the order of 3mm. MINOS's TPC has 5 k channels. To track the beam DSSSDs are used. The gammas are discovered by DALI2. The tests and recent experiments confirm encouraging results. Both

instruments are of particular of impact for energies at about 300MeV.A and they integrate domains in the instrumental method for our field. They cover high energy beams, spectroscopy, reactions mechanisms, cryogenic targets, TPC, DSSSDs, tracking, ASIC technology, evolved DAQ … so of interest and thus to follow their evolution in the future. Challenges survive. Can we extract reliable physics measures particularly at higher incident energies (medium effects), can we build a TPC to perform measurements for unbound states etc, etc. Can the R^3B set-up reach the resolutions? We probably do not need to wait for a long time to see the fruit of these exploits given the efforts being placed today.

Remaining at high beam energies, I would like underline a challenge associated with DSSSDs highlighted by the initial tests of the R^3B tracker and in beam tests at HIMAC to build a "telescope" to measure Coulomb proton knock-out employing DSSSDs. In the latter case the protons in the second DSSSD are flooded by δ-electrons. In the case of the R^3B tracker the "same thing" happens. Solutions are not easy to come by. Gold/metallic foils for R^3B tracker for example. As mentioned earlier a analogous challenge is present for active-targets a low and high energies. ERC funded ACTAR-TPC, should give us a bench-mark on this issue. Will a solenoid focus the electrons? AT-TPC at MSU/NSCL will go on the air soon and will provide part of the riposte for TPCs. For solid state we will have to see. This is a timeworn challenge of course.

The last section is devoted to data acquisition. Before mentioning the many channel problematics a few words about the very front end. Today whether it be GANIL, IRFU/SEDI, RIKEN, Milano University or the project AIDA, S^3, … we see a significant thrust towards an appropriate solution to the dynamic range "crises". This predicament is an old one. This impasse is present in most of our works as nuclear physicists. It has become worse because we do not only want half a dozen channel but multiples of 256 channels (Recoil-Decay-Tagging). Thus classic techniques (eg INDRA an EoS still working device at GANIL, Ref. 12) become very expensive, and volume thirsty. Further with technology we are forced to employ "nano-sized" design leading to a restricted tensions. Hence ASICs, with the ever diminish tensions is making it a stronger challenge. Note requests for dynamic ranges of 10keV to 500MeV have been requested. Will not defend overzealous specifications on the part of physicists and point out that solutions are possibly available (AIDA – STFC Daresbury and Edinburg University). The today's challenge is to make a system readily available to the community at large with an infrastructure that can straightforwardly be put into place with modest means. It is a question of time and funds. Applications are directed towards Si and gas media and of course scintillators (Gamma, neutrons and particles). Given the labs involved in this problematic we stand to obtain a currently useable solution once we adhere to supporting the projects and make the results available to the NP community.

Will now comment, in general, about DAQs, dawn form experiences that we have had with ASIC based systems for nuclear physics. The NP experience is restricted (VAMOS, HIRA, 2p-TPC (Bordeaux), MUST2, MUSETT and possibly others) but

somewhat unique. The building of custom designs is costly engineering wise and NP have had only limited familiarity in the field, in contrast with Particle Physics. In general what one is dealing with is analogic-numeric ASIC which would have pre-amps, amps etc attached to external ADCs. All that is control are made numeric. Given our limited resources we have been forcedly but profitably, driven to "introduce" generic designs. By generic we refer to parameter driving attributes such as shaping time, gain, sampling, delays, thresholds, pulser, … thus as much as possible, use the same ASIC for different detector types (MUST2 for example, with its ASIC MATE can handle DSSSDs, PD and Si(Li)). The ideal idea is to apply this architectural methodology throughout the system without making it an inextricable or excessively expensive. This, of course is not far what industry would usually develop such things of course. To reach such objectives the system today are of distributed design employing quick numeration (ADC) followed by fast copper or optic connecting fabric to a host of FPGAs. The FPGA allow, within reason, re-programmability and hence a generic approach. This philosophy has been by and large undertaken in a project called GET (Ref) in the hardware and software but less in firmware. Insisting on developing a generic thinking and practice will economize the engineering time – A challenge still to be attained. This idea is in itself a trial, an experiment … so we will see how it will workout once we put it to several test rigs and instruments. The challenge seen here is to continue on this line of thinking. Caution - building individualized or systems for specific applications for a one-off experiment is today out of date and not acceptable. Today, Particle Physics recognize this approach and call for a generic approach as well.

A point, which is a upshot from GET, is the use of non-specialized hardware or software. Reference is being made here about the present use of VME, or NIM or even CAMAC. These standards are not what we find in industry. Hence performances and prices are not up to what one finds in the telecom industry. Will not detail here, but GET and eventually R^3B were a close precursor to the use of μ-TCA with respect to the official declared standards in the Particle Physics, for example. It gives reliability, performance, price, connectivity factors well beyond our classical numeric standards. To this we add connectors, cables software etc. So the challenge would be to review our standards, renovate and rejuvenate our hardware and software gear. A mega challenge, for most of us, that like to use a screwdriver and on the spot Lego method.

In conclusion Si and gas media have and will play an important role in instrumenting Nuclear Physics experiments. Challenges still exist over the whole spectrum of the research and development and this contribution mentions only a selection of those challenges. No mention is made of solid-state devices other than Si and liquids (cryogenic or not) are not referred to and could be, for example, a source of major breakthroughs. This and others open possibilities for a number of initiatives in the future in our laboratories and together, in synergy to promote key instrumentation for particle detection. While our domain has significant impact in the science world, we stand to improve our instruments by affording to cultivate a stronger transvers approach with other domains.

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Neutron Detector Array NEDA
Status and Perspectives

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INTRODUCTION

NEDA is a compact neutron detector array for coupling with large γ-ray spectrometers such as AGATA [1]. NEDA is currently being developed and will be used in experiments with stable and radioactive beams at SPIRAL2/GANIL, SPES/LNL, NUSTAR/FAIR and at other accelerator facilities. The full version of NEDA will consist of 355 identical detector units placed at a distance of 1 m from the target position and covering a solid angle of about 2π sr. The NEDA detector units have a hexagonal shape and they will be filled with 3 litres of a liquid scintillator with good neutron-γ discrimination properties. The design of the NEDA detector units allow also for other geometries, for example a planar wall of neutron detectors at closer or further distances from the target.

The key parameters of NEDA are a large neutron detection efficiency, excellent neutron-γ and neutron cross-talk discrimination and high count-rate capability. The primary use of NEDA is for reaction-channel identification by detection of two or more neutrons in studies of exotic proton-rich nuclei produced in fusion-evaporation reactions.

The first implementation of NEDA will consist of a limited number of detectors combined with the Neutron Wall array [2, 3]. This setup is planned to be used during the AGATA campaign at GANIL in 2016-2017, in which both the NEDA and the Neutron

Wall detectors will use the new digital electronics developed for NEDA.

The NEDA collaboration consists of research groups from 12 institutes in Bulgaria, France, Italy, Poland, Spain, Sweden, Turkey, and the UK.

NEDA DETECTOR UNIT

Extensive GEANT4 [4] simulations were performed to find the optimal size of the NEDA detector units [5]. Two different scintillator materials were used in the simulations: the hydrogen-based liquid BC501A (C_8H_{10}) and the deuterated liquid BC537 (C_6D_6). Based on the simulations, it was concluded that a 20 cm deep detector is sufficient for detection of neutrons emitted in fusion-evaporation reactions with energies up to about 10 MeV. The diameter of the detector units should be as large as practically possible. A diameter of 5 inch was chosen, which is the size of the largest photomultiplier tubes (PMTs) commonly available. The simulations did not indicate any advantage of using the deuterated scintillator, which was chosen by the newly developed DESCANT array [6], instead of the standard ^{1}H-based one. In order to make it easy to pack the NEDA detector units close to each other in various geometries, the units will have the shape of uniform hexagonal prisms. Each unit will contain about 3 litres of BC501A or similar scintillator liquid. The first prototypes of the NEDA detector units have been produced and are presently being tested at INFN-LNL.

CONCEPTUAL DESIGN OF THE ARRAY

The geometry of the NEDA array has been optimized in terms of efficiency and cross-talk performance using GEANT4 [4] and LILITA_N97 [7] Monte Carlo simulations [8]. The simulations were validated by comparing to experimental data obtained in the fusion-evaporation reaction ^{58}Ni + ^{56}Fe using the Neutron Wall array. Good agreement between simulated and measured neutron time-of-flight spectra were obtained when adequate absorbing material between target and detectors (beam dump etc.) were included in the simulations and when the center-of-mass neutron energies were increased by 800 keV in LILITA_N97. At present, the reason for this increase it is not understood.

The full NEDA array will consist of 355 detector units which can be placed in a spherical geometry covering a solid angle of about 2π sr. With this setup, the gain in efficiency compared to the Neutron Wall for detecting 1, 2 and 3 neutrons are estimated to be a factor of 1.4, 8 and 10, respectively.

ELECTRONICS

The front-end electronics of NEDA will be based on the NUMEXO2 digitiser board. NUMEXO2 is a 16 channel NIM unit, consisting of a motherboard and 4 mezzanine cards, each containing four 200 Ms/s, 14 bit flash ADCs [9, 10]. The board is fully compatible with AGATA regarding triggering, synchronization, timestamping and readout. Prototypes of the motherboard and mezzanine cards have been produced and tested. The production of the final NUMEXO2 units is ongoing and will be ready by the end of 2014.

TESTS

A large number of tests of detectors, PMTs and front-end electronics have been performed during the last few years.

Neutron-γ discrimination in BC501A and BC537

A comparison of the two liquid scintillators BC501A and BC537 regarding their performance in pulse-shape discrimination of neutrons and γ rays has been carried out [11]. Special emphasis was put on the performance of artificial neural networks to take full advantage of the digital electronics. The results obtained show a better performance for the BC501A scintillator, which can be explained by the larger light yield compared to BC537.

Digital Pulse-Timing

A new digital pulse-timing algorithm, to be used by NEDA, was developed and tested [12]. The time resolutions of four 5 inch diameter PMTs (ET9390kb, R11833-100, XP4512, R4144), coupled to a cylindrical 5 inch by 5 inch BC501A-based liquid scintillator detector, were measured by employing digital sampling electronics and a constant fraction discriminator (CFD) algorithm. The zero crossing of the CFD algorithm was obtained as a cubic spline interpolation, which was continuous up to the second derivative. The performance of the algorithm was studied at the sampling rates 500 MS/s and 200 MS/s. The time resolutions obtained with the digital electronics were compared to values obtained with a standard analog CFD. The results of the comparison showed that the analog and the digital measurements at 500 MS/s and at 200 MS/s all give similar time resolutions for each of the PMTs.

Neutron-Gamma Discrimination and Optimal Photomultiplier Tubes

A comparative study of the neutron-γ discrimination performance of a liquid scintillator detector BC501A coupled to four different 5 inch PMTs (ET9390kb, R11833-100, XP4512 and R4144) was carried out [13]. Both the charge comparison (CC) method and the integrated rise-time (IRT) method were implemented digitally to discriminate between neutrons and γ rays emitted by a ^{252}Cf source. In both methods, the neutron-γ discrimination capabilities of the four PMTs were quantitatively compared by evaluating their figure-of-merit (FOM) values at different energy regions between 50 keVee and 1000 keVee. Additionally, the results were further verified qualitatively using time-of-flight to distinguish γ rays and neutrons. The results consistently show that the PMTs R11833-100 and ET9390kb generally perform best regarding neutron-γ discrimination with only slight differences in FOM values. This superiority can be explained by their relatively higher photo-electron yield, which indicates that a scintillator detector coupled to a PMT with higher photo-electron yield tends to result in better neutron-γ discrimination performance.

New Detector Materials

Recently a new solid organic scintillator with good neutron-γ discrimination properties has been developed [14] and become available on the market. The neutron-γ discrimination capabilities of a cylindrical 3 inch diameter detector of type EJ299-33 was investigated with the aim of finding out if this material would be a possible future upgrade for NEDA [15]. Two different PMTs, a 3 inch diameter ET9821 and a 5 inch diameter ET9390kb tube, were used in the tests. The photo-electron yields of the detector were measured with both PMTs. The yields were somewhat smaller than what is expected for a detector of the same size filled with a liquid scintillator of type BC501A. The decay times of the scintillator light components for both neutrons and γ rays were measured using the ET9390kb PMT and a Pu-Be source. The preliminary results show two delayed components, with decay times of 300 ns and 2.2 μs. The fractional intensities (in percent) for these two light components were 10:5 and 30:10, respectively (neutron:γ). The surprisingly strong 2.2 μs light component was observed for the first time in this type of scintillator. The FOM values for neutron-γ discrimination were measured with the ET9390kb PMT as a function of signal amplitude using the analog zero crossover (ZCO), digital CC and digital IRT pulse-shape discrimination techniques. At 200 keVee the obtained FOM values were similar to the ones obtained with the same type of PMT and a cylindrical 5 inch diameter BC501A detector, while at 1000 keVee the values were about 30 % smaller.

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Conversion-Electron Spectroscopy at EURISOL

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Abstract.
Conversion-electron spectroscopy allows low-energy transitions in heavy nuclei to be observed and is also a useful method to determine multipolarities with low statistics. Descriptions of instrumentation used for β-decay, in-beam and isomer conversion-electron spectroscopy of nuclei far from stability, and their possible implementation at EURISOL are described. Ideas for improved setups are also discussed.

Keywords: Conversion-electron spectroscopy, mutlipolarity

INTRODUCTION

Conversion-electron spectroscopy is an important method to determine the multipolarities of transitions. It is also often the only method able to detect low-energy, or high multipolarity, transitions in heavy nuclei. This is especially true for odd-A or odd-odd heavy nuclei. Methods which determine the multipolarities of γ rays, such as angular correlations or angular distributions need typically 10^4 detected counts, or more. Transfer and Coulomb excitation experiments also allow the determinations of a limited set of states in reaction products, but cannot always be performed on the most exotic nuclei due to the weak beam intensities. Although the determination of $\log ft$ values from β-feeding intensities can be used to assign spins of states in nuclei far from stability, this can be unreliable due to large Q_β values, leading to a pandemonium effect. Conversion-electron spectroscopy can be used to determine the multipolarities of transitions between states close in energy ($\sim$20–400 keV, depending on Z), in heavy nuclei. Furthermore the measurement of low-energy transitions is necessary to ensure that all members of a decay cascade have been observed.

It is possible to construct experimental setups with high efficiency ($>$10 %) and similar energy resolution to Ge detectors ($\sim$2.5 keV) [1]. As conversion coefficients change by typically a factor of 2, or more, between different multipolarities then they can be experimentally determined with just a few tens of detected counts [1, 2]. The low statistics required means that this technique can be applied to the study of weakly produced exotic nuclei. A brief description of some of the instrumentation used for in-beam, isomer and β-decay conversion-electron spectroscopy of exotic nuclei will be provided, along with ideas for future instrumentation developments.

β DECAY

Conversion-electron spectroscopy has been performed at several ISOL facilities using a liquid-nitrogen cooled Si detector placed close to a tape station where radioactive ions are implanted, as for example in [3]. The tape is used to move the radioactivity away from the measurement station, in the case of short-lived activities. The small solid angles of these detectors can however be increased, in order to study rare decays.

The development of arrays of cooled, thin, high-granularity arrays of Si detectors allows detection systems with higher efficiency to be implemented. In addition, the thin nature of such systems will allow Ge detectors to be placed behind them, giving high γ-detection efficiency. Currently these systems are often cooled using peltier devices, or alcohol, though cooling to lower temperatures could improve their resolution and noise levels, especially if high-quality Si, or even Ge, diodes are used.

An alternative setup would use an improved version of the segmented, liquid-nitrogen cooled Si(Li) detector implemented in β and isomer studies at the Lohengrin spectrometer of the ILL [1]. This detector has an energy resolution similar to that of a Ge detector ($\sim$2.5 keV), which is important as decay by electron conversion produces multiple peaks in the spectrum for each transition (K_e, $K(X)$, L_e, M_e, γ).

IN-BEAM

A variety of detection systems have been used for in-beam conversion-electron spectroscopy. So-called "Orange" spectrometers have fixed magnetic fields, whose strength must be varied to focus electrons of a particular energy on to the detector element. As time-consuming field scans are necessary to discover new transitions then such devices are not particularly applicable to study of weakly produced exotic nuclei.

The SPEDE spectrometer [4] is designed to be used in Coulomb-excitation experiments with with radioactive ion beams produced at ISOLDE and re-accelerated by HIE-ISOLDE to a few MeV/A. The spectrometer consists of a highly segmented CD detector placed upstream of a secondary target, used for Coulomb excitation, in conjunction with the Miniball Ge array. The CD detector is placed upstream to minimize the background generated by δ electrons hitting the target. The spectrometer is able to detect conversion electrons emitted by recoiling ions and such a device would be ideal for in-beam spectroscopy at EURISOL. The CD detector of the SPEDE spectrometer also forms part of the SAGE spectrometer [5], used at Jyväskyla, in conjunction with the JUROGAM-II Ge array. An 0.8 T solenoid is used to transport electrons almost 1 m to the CD detector, greatly reducing the background. The transport efficiency of the magnetic field is $\sim$7 %, in the energy range 200–400 keV. High-voltage barriers can be applied to reduce the number of δ electrons hitting the CD detector. Again, such a device would be useful for in-beam conversion-electron spectroscopy at EURISOL. A further improvement could be the use of a superconducting coil to generate the magnetic field, giving much smaller electron orbit radii, thus making the electron detection more efficient and practically energy independent. Superconducting coils were already used some time ago for in-beam conversion-electron spectroscopy [6]. The system in [6] was able to measure conversion-electrons down to 50 keV in energy.

ISOMERIC DECAY

Observations of the decays of isomeric states is a sensitive way to study the excited states in nuclei far from stability. The correlation between the detection of a mass-selected ion and the subsequent decay of an isomeric technique a few 100-ns, or μs, after the arrival of the ion permits the study of very weakly produced nuclei. To date the majority of experiments of this type have studied γ decays, though a few have looked at the conversion electrons, or $E0$ transitions, emitted.

Conversion-electron spectroscopy has been performed on neutron-rich fission fragments at the Lohengrin in-flight spectrometer of the ILL for more than 10 years. In this setup an ionization chamber is used to identify ions, and also slow them down to a desired velocity. This velocity is chosen so that the fragments stop in the last 1 μm of a 6-μm thick Mylar foil placed at the end of the ionization chamber. A cooled, two-fold segmented, windowless Si(Li) conversion-electron detector is placed behind the Mylar foil, in a separate vacuum. As the ions stop close to the end of the Mylar foil then any conversion electrons emitted from isomeric decay cascades lose little energy when traversing the foil and can be detected down to low energy $\sim$15 keV [1, 2]. The close geometry of the setup, and large active area of the Si(Li) detector (12 cm^2) also gives high efficiency $\sim$20 %. Conversion coefficients of isomeric decays far from stability have been determined with this setup with low statistics, for example in ^{136}Sb [7].

The Si(Li) detector from the Lohengrin setup has also been used in similar experiments at the LISE spectrometer of GANIL. The ions selected from fragmentation reactions are stopped in a 25-μm thick Kapton foil, inclined at $\sim$30° to the beam. The Si(Li) detector was placed perpendicular to the beam, facing the inclined Kapton foil [8].

A setup to detect isomeric conversion-electron decays, following Coulomb-excitation, was recently implemented at the LISE spectrometer [9]. Ions produced in a fragmentation reaction impinged on a thin secondary Pb target and some fraction of these were Coulomb excited and then implanted in a plastic scintillator downstream. Alcohol-cooled Si detectors were placed around the plastic scintillator allowed the detection of conversion electrons with energies upwards of $\sim$150 keV.

Highly pixelated double-sided silicon strip detectors (DSSSDs) are used as implantation detectors in fragmentation and in-flight fission experiments. The use of such detectors means that both isomer spectroscopy and β decay experiments can be performed in parallel for weakly produced nuclei. The correlation between the implantantion an identified ion and its subsequent β-decay, detected in the same pixel, allows β-decay spectroscopy to be performed. The use of DSSSD detectors for conversion-electron spectroscopy has also been tested [10]. The lower observation limit was found to be $\sim$150 keV making their use for the observation of high-multipolarity decays in very exotic nuclei possible.

The construction of a new conversion-electron detector for low-energy decays from isomeric states should be considered. Several methods are possible to accomplish this, including the implantation directly into a cooled Si(Li) detector, or stopping the ions in Kapton foil, with a Si(Li) detector situated nearby. The possibility of transporting the conversion electrons from a foil to the detector, using a (superconducting) solenoid, would increase the effective solid angle of the detector.

CONCLUSION

Instrumentation currently in use to perform conversion-electron spectroscopy of low-energy transitions in nuclei far from stability, populated following β-decay, in-beam reactions, and isomer decay has been described. These are useful tools to study the structure of nuclei far from stability. Possibilities for improving these setups have been mentioned.

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Future prospects with scintillator arrays

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Abstract. Scintillator detectors have been key to nuclear physics from its earliest days. While many scintillator materials are extremely well established, new materials are coming to prominence which offer performance in between that of traditional scintillators and high-purity germanium detectors. In addition, silicon photomultipliers are beginning to be competitive with the traditional photomultiplier technology. This short article reviews some of the developments in this technology.

INTRODUCTION

Advances in nuclear physics are driven by advances in detector technology. In order to profit from future facilities such as EURISOL, new detector systems will be needed that can exploit the available beam intensities to their best advantage. In terms of gamma-ray detection, there are two settled technologies: scintillator detectors and high-purity germanium detectors. In general, the former offer high efficiency but have limited energy resolution. By contrast, germanium detectors offer high energy resolution but have much lower detection efficiency. Detection efficiency for germanium arrays has been improved in recent years through the implementation of gamma-ray tracking which also allows the reconstruction of peaks with high energy resolution even from fast-moving sources. The very high cost of such gamma-ray tracking detectors means that it is very unlikely that a full 4-pi array will exist in the near future.

Scintillator crystals are a well-established technology. The hygroscopic material, NaI(Tl), is the workhorse of this type of material and is exploited widely in nuclear physics and in societal applications such as oil and gas exploration. A typical energy resolution is around 7 % at 667 keV. A second common material is CsI(Tl) which has a less linear response than NaI(Tl) which makes it less suitable for gamma-ray detection but its differing response to charged particles such as protons and alpha particles allows for particle identification. A third material commonly used in nuclear physics is BaF_2. This crystal has a fast and a slow component to its scintillation light output. The fast component is often exploited for fast timing measurements.

NEW SCINTILLATOR MATERIALS

There is much activity worldwide in developing new scintillator materials. Of interest are crystals with high light output, fast time response, and linearity. In practical terms, nuclear physics commonly requires large crystals especially in terms of building large arrays. The cost of the individual elements must, of course, also be feasible but with longer timescales such as that associated with EURISOL, it is relevant to take a snapshot of the present state-

of-the-art, since something which is presently a small crystal in the lab may become a mature technology over the next decade. The most established of the "novel scintillators" is $LaBr_3$(Ce). This material is very linear and has an energy resolution of around 3% for 667 keV. Importantly, it can be grown to large sizes facilitating the construction of detectors relevant to nuclear physics (although the main driver of all such technology is homeland security). The drawback of $LaBr_3$(Ce) is that St Gobain Crystals own the patent on the cerium doping. Since they are effectively the monopoly supplier, the cost of this material remains high. Nevertheless, $LaBr_3$(Ce) has already begun to find wide application in nuclear physics from fast timing arrays to large calorimeters such as PARIS. PARIS uses a phoswich design of $LaBr_3$(Ce) coupled to NaI(Tl) to reduce cost while still exploiting the main advantages of the novel scintillator.

Other materials with properties better than NaI(Tl) and approaching $LaBr_3$(Ce) are becoming available in larger sizes. For example, $CeBr_3$ can achieve energy resolution better than 5% [1]. It has the advantage over $LaBr_3$(Ce) of not having internal radioactivity. SrI_2 is also available with resolution approaching that of $LaBr_3$(Ce) but is a much slower scintillator with a decay time of ~1.5 us and is currently much more expensive. At the present time, investigations are proceeding on co-doping of crystals such as $CeBr_3$ and $LaBr_3$(Ce) with e.g. Sr. This appears to lead to improved proportionality and energy resolution [2] but this is yet to translate into commercially available crystals. Polycrystalline ceramic materials such as GYGAG are available in small quantities and are attractive in terms of their high density and effective Z. They also offer energy resolution better than 5% at 667 keV and good timing resolution.

Elpasolite scintillators such as CLYC [3] are commercially available in sizes useful for gamma-ray detectors. These materials have a good energy resolution but are of additional interest through their ability to detect thermal *and* fast neutron detectors. Thermal neutron detection comes about through the presence of lithium in the material which can be enhanced using enriched ^{6}Li, while the fast neutron sensitivity arises due to the content of ^{35}Cl. Pulse shape discrimination may be used to distinguish neutron events from gamma rays.

SCINTILLATION LIGHT DETECTION

Scintillation light is conventionally recorded with photomultiplier tubes. Modest improvements in this technology have taken place in the last few years, for example, the availability of ultrabright cathodes. A significant game-changer in this area is associated with the recent advances in silicon photomultiplier (SiPM) technology. SiPMs are arrays of avalanche photodiodes. With tens of thousands of individual APDs, and SiPM can provide a near-linear response when illuminated with scintillation photons of an appropriate wavelength. This technology is being driven by medical imaging particularly the desire to carry out simultaneous PET and MRI imaging which means placing a PET imager within an MRI machine [4]. Photomultiplier tubes may not operate in high magnetic field but SiPMs are insensitive to magnetic field. This property is also of high relevance in many areas of nuclear physics.

The performance of SiPMs is improving very rapidly with strong reduction in dark current which is the main impediment to wide implementation of this technology. Large individual elements such as 6-mm X 6-mm are routinely available and are readily tiled. SiPMs run off low (<100 V) voltages which is a significant advantage over conventional PMTs. SiPMs coupled to novel scintillators are providing performance close to that achievable with PMTs. Moreover, some variants such as the SensL C series [5] may also offer a route to fast timing measurements since they have separate energy and fast timing (~300 ps) outputs and can respond to individual photons.

SUMMARY AND CONCLUSIONS

While scintillator detectors are a well-established technology, there are significant technological advances in this area in recent years. Novel scintillators such as $LaBr_3$(Ce) are already routinely available in large sizes albeit at a high cost compared to standard scintillator materials. Other materials are in the R&D stage and offer better performance still. This technology is likely to mature over the next decade. Meanwhile, the silicon photomultiplier technology is rapidly coming of age, driven by the requirements of medical imaging. These prospects taken together offer important opportunities for future facilities like EURISOL.

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The GASPARD project: a four π array to study direct reactions

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Abstract. GASPARD is a 4π Silicon array designed for direct reaction measurements at the next generation of facilities. The detector is designed to be inserted into the next generation of gamma arrays such as AGATA and PARIS, so that it is very compact and as much as possible transparent to gammas. It will also integrate any type of targets. Due to the high compacity of the detector, the standard technique to identify low energy particles relying on time-of-flight versus energy can no more be used. This is why a research and development program has been started in order to check the performances of pulse shape analysis technique in order to discriminate the very light particles (Z≤2). The discrimination of Z=1 particles has been shown down to 2.5 MeV.

INTRODUCTION

The new facilities that are being built in Europe like Spiral2 or FAIR will offer a unique opportunity to explore the unknown part of the nuclear chart called the "terra incognita". The beams produced will provide for heavier mass nuclei where the density of states is high. Key experiments in this new opening area will require the coupling of efficient charged particle arrays with efficient gamma array. They will deal with shell evolution along the isospin direction, with the study of pygmy resonances and of paring and clusterisation in asymmetric matter with low-density to normal density and also with nuclear astrophysics. The development of more and more exotic beam production has to meet the development of very efficient and precise experimental techniques and associated devices.

One of the most powerful methods for obtaining spectroscopic information on the structure of nuclei is the investigation of light-ion induced direct reactions, i.e. elastic or inelastic scattering, or one- and few-nucleon transfer reactions. Transfer reactions may be used to deduce spins and parities from the characteristic angular momentum transfer of the reaction as well as energies of the excited states. Moreover since the cross-section magnitudes essentially reflect the probability of finding a nucleon in a given shell model orbit, the extracted spectroscopic factors allow one to learn directly about the configuration of nuclear states. For reactions in inverse kinematics, the information of interest can be deduced by measuring the kinematical characteristics (energy and scattering angle) of the light fragment. Large-area charged-particle arrays are a natural choice for this strategy. However, a potentially large contribution from the energy loss and small-angle straggling in the target is of concern. In order to compensate for low beam intensities thick targets are used which degrades the excitation energy resolution. Besides the improvements brought by the cryogenic targets of pure hydrogen and helium with thin windows, the windowless proton target CHyMENE [1] will be available soon but its requirements for vacuum have to be taken into account from scratch in the design of a coupled detector.

The current typical detection set-up for direct reactions measurements in inverse kinematics relies on high granularity and high resolution double-sided stripped Silicon detectors (DSSSD) for the measurement of the energy and scattering angle of the light ejectile. The heavy residues are either detected by a spectrometer or an identification device such as an ionisation chamber and plastic hodoscopes. The optimal excitation energy resolution obtained is of a few hundred keV [2]. In case the populated excited states lie closer in energy, gamma rays detectors surrounding the target will be required to supplement the experimental set-up.

With the next generation of European facilities, direct reactions will enter a new phase. The heavier nuclei that will be produced will have a high density of states that only gamma-rays detectors will be able to disentangle. The coupling of a charged particle detector to a gamma array with high efficiency

will become crucial as it will bring new information like the feeding of the different states and the gamma angular distribution. This is why the GASPARD array is designed to be coupled with the most efficient gamma-ray arrays such as AGATA [3] and PARIS [4].

DESIGN OF GASPARD

Simulations have been performed for the choice of the design of the GASPARD array. The needed granularity has been investigated as well as several configurations. The design has finally converged to

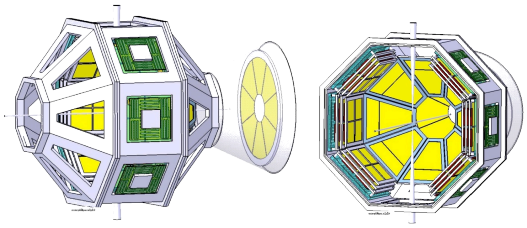

FIGURE 1: The GASPARD design

the one shown in Fig.1 where there is a ring of square detectors at 90 deg. and two rings of trapezoidal detectors in the forward and backward direction. In the very forward angles, an annular detector will be used. Each piece of detector will be composed of a thin 500µm double sided stripped Silicon detector (DSSD) and of one 1.5mm thick DSSD in the backward direction and two thick DSSD in the forward direction where the most energetic particles are emitted.

SIMULATIONS
Test case: d(132Sn,pγ)

In the region of masses greater than 100, ^{132}Sn is the only other doubly-magic nucleus with the stable ^{208}Pb. It will be the core to study the single-particle excitation and will be used as a reference

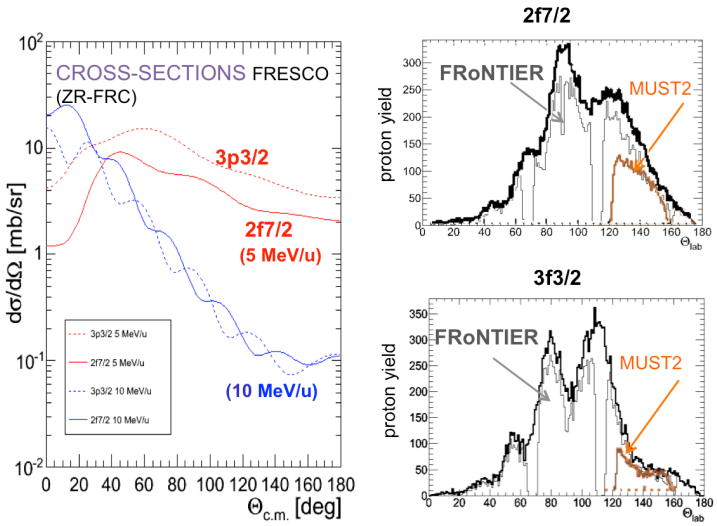

FIGURE 2: (Left) Theoretical cross-section (from FRESCO calculations) for ^{132}Sn(d,p). (Right) Total proton yield (in black) and proton yield from FRoNTIER (grey) compared to MUST2 (orange).

nucle

us to understand the behavior of the surrounding nuclei. The nuclear shell effects are revealed by the identification of the single-particle (-hole) and 2-particle (- hole) states and by the spectroscopic factors. They can be obtained by transfer reactions, for example d(^{132}Sn,pγ) measurement.
In the simulations a beam of ^{132}Sn produced at 10 MeV/u impinging on a CD_2 target of 2mg/cm^2 thickness with a beam spot size of 2 mm has been considered. The theoretical cross-sections are shown for the $3p_{3/2}$ and $2f_{7/2}$ orbitals on Fig. 2 as well as the expected proton yield.

The yield of proton is mostly in the backward direction where the MUST2 array cannot be placed in the existing MUST2-EXOGAM-VAMOS set-up. In this case, the GASPARD array increases the efficiency of the current set-up by a factor of 4 (see. Fig. 7). Moreover the efficiency of the PARIS array (50% at 1 MeV) as compared to the efficiency of the EXOGAM set-up (10% at 1 MeV) enables to gain a factor of 5. So all together an increase of the efficiency by a factor of 20 is achieved when using the GASPARD-PARIS set-up.

Gamma ray attenuation

Simulations to study the attenuation of gamma rays have been performed with the spherical configuration of PARIS. The reduction of the photopeak efficiency at 662 keV following the addition of an aluminum vacuum chamber (2 mm thick), the GASPARD silicon detectors (2.5 mm thick in total) with PCB and a layer of copper (4mm thick) for electronics cooling was investigated. Fig. 3 illustrates the different configurations used in those simulations and the associated results for the 662 keV gamma

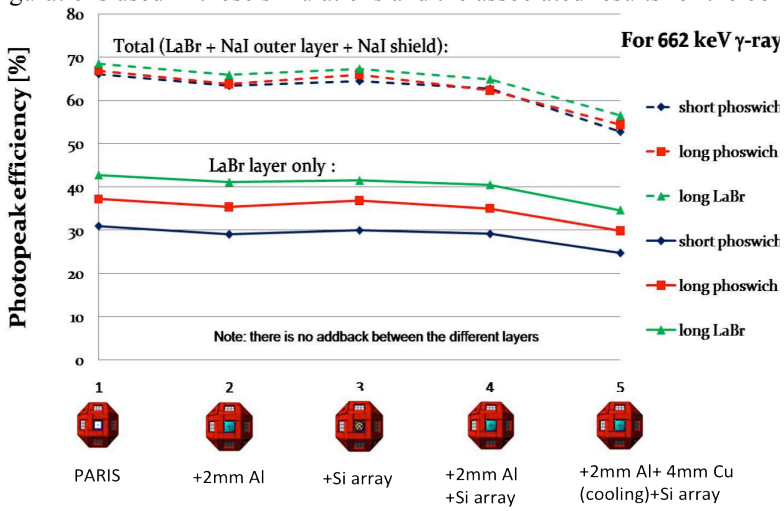

FIGURE 3: 662 keV photopeak efficiency attenuation for the 5 configurations described in the text.

ray. The drop in efficiency due to the vacuum chamber and the silicon array is relatively small. The drop becomes clearly significant when a 4 mm copper plate is added to the back of the silicon array. The contribution of the LaBr inner layer is indicated by a solid line. The contribution of all crystals (LaBr+NaI) is represented by a dashed line. This simulation show that the electronics and its cooling should be placed perpendicular to the detectors in the dead zones in order to preserve transparency.

PULSE SHAPE DISCRIMINATION STUDIES

In order to solve the issue of particle identification with the standard technique of time-of-flight, the pulse shape analysis technique for light particles has been investigated. This technique has been studied extensively for heavy nuclei by the FAZIA collaboration [5,6] with pad detectors of large area but the case of light particles has never been addressed. It relies on the digitalization of the charge and/or current signal with a frequency that should be adapted to the rise time of the registered signal. The case of light particles should be the most difficult case as the rise time of the signal is very fast and a high sampling rate may be essential to obtain a good discrimination. Several test experiments have been performed at the Orsay Tandem. The first test gave a proof of principle for the PSD of light particles using a pad detector from the FAZIA pool and using commercial electronics with a maximum sampling rate of 100 MHz [7].

In the GASPARD project, highly segmented Silicon detectors will be used so that the PSD on DSSSD had to be investigated. In this aim, a 500um thick DSSSD made of nTD wafer cut at 8 degrees and provided by Micron Semiconductors [8] was used. The nTD type guarantees a good uniformity in resistivity for the detector [5] and the cut at 8 degrees avoids channelling of the particle in the detector [6]. The strip pitch of this detector is 485um for a surface of 62mm x 62mm. The detector was designed to have 90 degrees bent kaptons (type of cables getting the signals from the detector out, made of

kaptons) with a very narrow frame. The ohmic side of the detector was facing the beam in order to increase the PSD possibilities [5]. Only four strips on each side of the detector were read by PACI

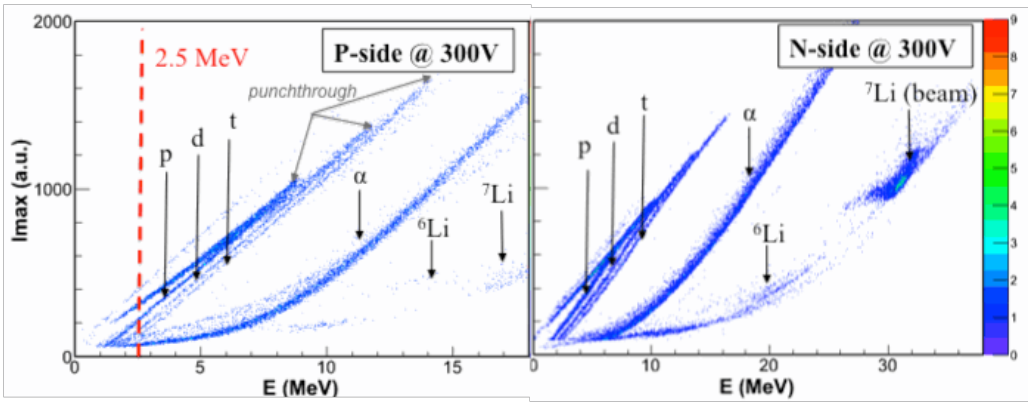

FIGURE 4: Maximum of the current signal (Imax) versus maximum of the charge signal (E) for the two sides of the DSSSD with a bias of 300V. The punch-through of protons is clearly seen on the left.

preamplifiers [9] with a gain of 32 mV/MeV. These preamplifiers give current and charge signals that were read by the MATACQ [10] digitizers at 1 GHz sampling rate with a time window of 2,048 us. A ^{7}Li beam at 35 MeV was impinging on a ^{12}C target and produced mostly Z=1 and Z=2 particles.

The identification spectra obtained using only the maximum of the current signal and the maximum of the charge are shown on Fig. 4 for the N-side and the P-side with a bias of 300V corresponding to the depletion voltage of the detector. No filtering or interpolation has been applied to the data. Only the interstrip events have been removed from the analysis. The Z=1 particles can be well discriminated (see Tab. 3) down to 2 MeV on the P-side (the threshold is higher on the N-side as it is the low-field side). The isotopic separation Z=1, Z=2 and Z=3 is also very satisfactorily achieved.

CONCLUSION

In summary, the GASPARD project has shown that the constraint on the integration into the next generation of gamma array together with the transparency and the possibility to use any type of target can be fulfilled. The PSD technique will be a challenging technique for the identification of light particles but shows nice separation of hydrogen isotopes. Furthermore the associated electronics should be studied in order to be able to sample at minimum 200 MHz and to be able to handle many channels (~15 000 for GASPARD).

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SHARC: A Versatile Silicon Array for use with Radioactive Ion Beams

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Abstract. As the boundaries of nuclear physics research are being extended further into the exotic regions of the Segrè chart, the development of highly versatile detectors optimised for in radioactive ion beams has become key. SHARC, the Silicon Highly-Segmented Array for Reactions and Coulex, is a compact silicon array which has been used for a variety of deifferent experiments. Its design is such that the configuration can be changed depending on the kinematics and detection requirements of the experiment. Its compact design allows it to be coupled to other detector systems, such as TIGRESS at TRIUMF. The technical aspects, previous experiments and future possibilities for the array will be discussed.

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INTRODUCTION

With the large variety of different beams available at laboratories worldwide, having a detector system that is truly adaptable to different experimental conditions is a considerable advantage. SHARC was designed so it can be used for many types of experiments and be able to detect charged particles from protons up to heavy ions. For inelastic scattering and transfer in inverse kinematics, a good energy resolution with particle identification is essential; fusion evaporation reactions require a large angular coverage and

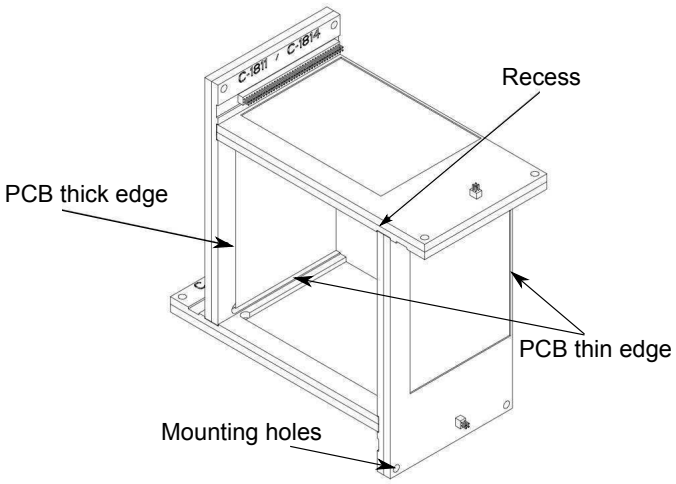

FIGURE 1. A box of ΔE-E telescopes, mounted in the 'windmill configuration'.

particle identification, and for Coulomb Excitation (Coulex), an amplification gain low enough to detect heavy ions up to 400 MeV would be required [1]. SHARC needs to be compact so that it can be used with other arrays, but also to have a changeable design depending on the kinematic requirements of the experiment. SHARC is based on the concept of TIARA [2], which is a compact double-layered octagonal barrel of resistive strip silicon detectors with a high angular coverage. SHARC, however, employs double sided silicon strip detectors (DSSSDs) of various thicknesses, depending on the experimental needs.

TECHNICAL DETAILS

In order to optimise the angular coverage, the SHARC setup is symmetric around the target position, with a box of four DSSSDs and a CD array upstream and downstream of the target. The gap between the two parts of the array allows for the target mechanism to be rotated in and out of the array. Each DSSSD box is designed to have the maximum azimuthal angle coverage possible, by offsetting the active silicon on the PCB and mounting the detectors in a 'windmill configuration' (shown in Fig. 1) [1]. The active silicon almost reaches the thin edge of the PCB, so that when it is mounted into the recess of the adjacent detector, there is unbroken coverage in ϕ. This results in a thick edge of PCB that excludes some angles in θ, but the SHARC frame allows this to lie toward or away from 90°, depending on the needs of the experiment. Figure 1 shows the mounting of ΔE-E telescopes in this configuration, but it is also used for the mounting of a single layer of DSSSDs.

The box detectors, Micron Semiconductor BB11 detectors, are segmented into 24 3-mm horizontal strips and 48 1-mm vertical strips. The active area of the silicon is 72×48 mm, mounted on a PCB measuring 104×61.1 mm. The detector thicknesses vary depending on the experiment: for transfer reactions in inverse kinematics, an example setup is an upstream box of 1000-μm detectors and ΔE-E telescopes downstream

(140 μm ΔE backed by an unsegmented MSX-35 1500-μm pad detector).

The CD arrays comprise four quadrant Micron Semiconductor QQQ2 detectors. These quadrants are segmented into 16 rings and 24 radial sectors, and each cover 81.6° in ϕ, with a radius of 9 mm to 41 mm. The CD array can also be utilised in a ΔE-E configuration, with a QQQ1 annular pad detector. The thicknesses of the QQQ2 detectors ranges from 80 to 1000 μm.

The SHARC array is designed to be compact, and without cables, measures $127.2 \times 127.2 \times 216.5$ mm to the flange. It is housed in a bespoke stainless steel chamber ($\oslash 192 \times 258$ mm), which allows it to be enclosed within a closed γ-ray array, such as TIGRESS. The signals from all cables are passed through 16 PCB feedthroughs in the chamber end, which are fixed with epoxy.

Full details regarding the performance of SHARC can be found in Ref. [1].

PAST WORK

In 2009, SHARC was used in-beam for the first time in concert with TIGRESS [3] and the TRIFOIL detector downstream [4]. States in ^{26}Na were populated directly using the ^{25}Na(d,p) reaction in inverse kinematics, employing a 3×10^7pps beam of ^{25}Na at 5 MeV/u from ISAC-II at TRIUMF. Eight TIGRESS clovers, four at 90° and four at 135°, were mounted around the SHARC chamber, 14.5 cm from the target, flanked by BGO shields. Gamma rays emitted from the recoiling ^{26}Na nuclei (with $\beta = 0.091\%c$) were subject to addback and Doppler corrections offline. The FWHM resolution of the 1805-keV γ ray is 18(23) keV at 135°(90°) after Doppler correction. An in-beam scintillator detector, the TRIFOIL, was mounted at zero degrees. A 10-μm thick scintillation foil, framed in a plexiglass light guide, was mounted 40 cm downstream of the target behind a 30 μm aluminium stopper foil, which was chosen to stop slow and heavy products from fusion evaporation reactions, whilst still allowing the ^{26}Na recoil nuclei and unreacted beam to reach the TRIFOIL. The TRIFOIL has three photomultiplier tubes, and a coincidence in two provides a trigger, which was used for the effective reduction of unwanted fusion-evaporation reactions, both in proton and γ-ray spectra. These three arrays were employed with success; proton angular distributions for states in ^{26}Na were measured in SHARC, cleanly extracted by gating on γ-ray transitions detected in TIGRESS. A level scheme of the states populated in ^{26}Na was attained using proton excitation energies from SHARC, γ-ray data from TIGRESS and using the TRIFOIL to remove unwanted background. This analysis is being prepared for publication. Another successful experiment with SHARC and TIGRESS, the two-neutron transfer ^{12}C(^{6}He,^{4}He)^{14}C* reaction, will not be detailed here, but the reader is referred to Ref. [5].

FUTURE WORK

SHARC will also be compatible with future arrays, at TRIUMF and further afield. An exciting development is the ElectroMagnetic Mass Analyser, EMMA, for ISAC-II at TRIUMF [6]. The cases of interest for studies with SHARC, EMMA and TIGRESS

combined are ^{132}Sn(d,p) in inverse kinematics, with proton angular distributions measured in SHARC, (d,p) reactions in the ^{78}Ni region, and (t,d) and (t,p) studies using neutron-rich beams from ARIEL and the Charge State Booster (CSB). Having EMMA at zero degrees will also allow the opportunity to use beams that have significant contaminants, since the final reaction channel can be gated on the focal plane.

Another furture prospect for SHARC is in concert with DESCANT, the DEuterated SCintillator Array for Neutron Tagging. It will comprise up to 70 individual scintillators in a hemisphere configuration. Discrimination between γ rays and neutrons will be provided by pulse-shape analysis, and it is designed to be used in conjuction with TIGRESS and EMMA. An example setup would see DESCANT and TIGRESS upstream and downstream of the target, respectively, and SHARC would surround the target. The cases of interest include proton transfer, (d,n) reactions, to study the proton-induced (p,γ) and (p,α) reactions. This would, however, involve a further development of SHARC, for signal retrieval and processing.

In addition to the radioactive ion-beam prospects described, installation of SHARC is also planned at stable-beam facilities. At such facilities, SHARC would be utilised for the detection of secondary decay particles in forward-kinematics experiments. In such cases, the populated states would be identified using a high-resolution spectrometer, with the charged-particle decay-channels identified at high efficiency, using the large-coverage segmented silicon array. Potential reactions for this type of experiment include (p,p'), (α,α'), (p,d), (p,t), and $(^3\mathrm{He},t)$.

SUMMARY

SHARC is a versatile, compact silicon array which boasts high angular coverage, particle identification and excellent energy resolution. It has been successfully employed with TIGRESS and the TRIFOIL at TRIUMF. It is small enough to be transported and used with other large arrays like AGATA, and has a flexible design that will accommodate different kinematics, detection requirements and beam intensities.

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