Introduction - Experiment and instrumentation

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New element synthesis

There has been significant development during the past five years or so. New on-line separators have come into play, old work horses have been or are being improved. Confirmation of a significant part of data from hot fusion reactions is there already. Exciting experiments are underway or have been scheduled.

The synthesis of even heavier elements will require development *e.g.* in the following fields:

- accelerators (maybe dedicated to SHE)
- on-line separators
- targets
- detectors and electronics (to handle shorter half-lives, for example)

The confirmation of the findings from hot fusion reactions will benefit from developments in:

- on-line separators (also those capable of dealing with multi-nucleon transfer products)
- targets

One of the main challenges is the firm determination of the product mass number (without using mother-daughter relationships).

Nuclear structure studies

During the past years, old techniques have been honed, such as alpha decay fine structure studies. There has been a real surge of in-beam studies and isomer spectroscopy with major improvement in the understanding of single-particle structure in the No region, for example.

Structure studies of what are typically called trans-fermium nuclei will benefit from developments in:

- Prompt gamma-ray and electron spectroscopy; need to be able to handle high count rates
- Prompt particle identification
- Focal plane detectors and related electronics (for on-line separators); need to be able to detect high and low energy gamma-rays, electrons; need to handle short life times
- Life time measurements

Methods from other fields for the determination of key observables (spin etc) may be beneficial.

Need for concerted action

There is a lot of development work being done in several laboratories world-wide, especially regarding spectroscopic methods, detector systems and electronics (digital, in particular) as well as on-line separators and related techniques. It is clear that major steps forward will be taken during the next 5-10 years. It seems, however, that some effort is being wasted by lack of sufficient coordination between the various projects.

Hans Feldmeier

Introduction – Definition of the Basic Questions for this Workshop

Mark A. Stoyer

Perhaps the most basic scientific question facing the superheavy element (SHE) field today that is also one of the top questions in chemistry [1], and by the way capturing the imagination of young scientists as well, is just exactly how many elements are there? Where is the end of the periodic table? Can we untangle and understand the complexity of the nuclear forces at play in a superheavy nucleus near the end of the chart of nuclides? Indeed, for this introductory talk, FUSHE2012 might be redefined as searching for a Fundamental Understanding of SHE.

Current predictions of chemical periodicity extend to element 172 [2]. The fragility and evolution of nuclear shells for lighter elements is well known [3] and thus makes prediction of the heaviest closed shells uncertain. Because current predictions with state-of-the-art models differ widely as to what the next doubly magic nucleus after ^{208}Pb should be, ranging from Z = 114, N = 184 [4] to Z=120, 124 or even 126 with N = 184 [5] and Z = 120, N = 184[6], predictions of the maximum proton number or maximum number of nucleons in a bound nucleus are even less certain. Nevertheless, some predictions of additional magic numbers within the context of certain nuclear models using certain interactions are Z = 120, 132, 138 and N = 172, 184, 198, 228, 238, 258 [7], and even up to nuclei such as ^{472}164 [8]. Predictions of dominate decay modes in the Z = 140 and N = 228 region have also been made [9]. Experimentally, nuclides as heavy as ^{294}118 have been reported by the Dubna/Livermore collaboration [10].

The questions of the limits of nuclear stability in the heaviest elements and the locations of the next closed proton and neutron nuclear shells naturally lead to many other related questions. What are the chemical properties of the heaviest elements and is chemical periodicity altered as relativistic effects become more important? Are there astrophysical scenarios in which SHEs are produced or does fission limit the production of SHEs? What are the mechanisms which determine “magic” combinations of neutrons and protons and thus the locations of the next regions of spherical SHEs? Are there preferred nuclear reactions for the production of SHEs?

The goal of this workshop is to discuss these larger scientific questions in terms of near and far term strategies, and thus the topics to be covered are numerous and interrelated. An overview of experimental and theoretical activities and important scientific questions in each area has been presented in the prior two talks before the coffee break. The workshop has been organized in sessions to discuss SHE synthesis, SHE nuclear structure studies, chemistry of the heaviest elements, and the global picture of SHE. Advances in experimental techniques, instrumentation and theory will be discussed. While a result of the workshop will not be the identification of the last chemical element, certainly development of a roadmap for future SHE research is attainable.

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[1] Science magazine, July 1, 2005, “*Top 125 Science Questions*”.

[2] P. Pyykkö, Phys. Chem. Chem. Phys. **13** (2011) 161.
[3] U.S. Nuclear Science Advisory Committee (NSAC), *The Frontiers of Nuclear Science, A Long Range Plan* (2007) p. 61.
[4] I. Muntian, Z. Patyk, and A. Sobiczewski, Phys. Atom. Nuclei **66** (2003) 1015; A. Baran, Z. Lojewski, K. Sieja, and M. Kowal, Phys. Rev. C **72** (2005) 044310.
[5] S. Cwiok, W. Nazarewicz, and P.H. Heenen, Phys Rev. Lett. **83** (1999) 1108; J.F. Berger, D. Hirata, and M. Girod, Acta Phys. Pol. B **34** (2003) 1909; S. Typel and B.A. Brown, Phys. Rev. C **67** (2003) 034313.
[6] M. Bender, Phys Rev. C **61** (2000) 031302; Y.K. Gambir, A. Bhagwat, and M. Gupta, Phys. Rev. C **71** (2005) 037301.
[7] W. Zhang, J. Meng, S.Q. Zhang, L.S. Geng, and H. Toki, Nucl. Phys. A **753** (2005) 106.
[8] M. Bender, W. Nazarewicz, and P.-G. Reinhard, Phys. Lett. B **515** (2001) 42.
[9] H. Koura, T. Tachibana, and S. Chiba, *Proceedings of the Fourth International Conference on Fission and Properties of Neutron-Rich Nuclei*, held Nov. 11-17, 2007, Sanibel Island, FL, USA.
[10] Yu. Ts. Oganessian, *et al*., Phys. Rev. Lett. **104** (2010) 142502; Phys. Rev. C **74** (2006) 044602; Phys. Rev. C **69** (2004) 054607; Phys. Rev. C **69** (2004) 021601; Phys Rev. C **63** (2001) 011301; Phys. Rev. Lett. **83** (1999) 3154.

Yuri Oganessian

Experiment: Reaction Mechanism Studies

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The cross section for producing a heavy reaction product, σ_{EVR}, can be represented by the equation

$$\sigma_{EVR}(E_{c.m.}) = \sum_{J=0}^{J_{max}} \sigma_{CN}(E_{c.m.}, J) \cdot W_{sur}(E_{c.m.}, J)$$

where σ_{CN} is the complete fusion cross section and W_{sur} is the survival probability of the completely fused system. The complete fusion cross section can be written as

$$\sigma_{CN}(E_{c.m.}) = \sum_{J=0}^{J_{max}} \sigma_{capture}(E_{c.m.}, J) P_{CN}(E_{c.m.}, J)$$

where $\sigma_{capture}(E_{cm}, J)$ is the "capture" cross section at center of mass energy $E_{c.m.}$ and spin J and P_{CN} is the probability that the projectile-target system will evolve inside the fission saddle point to form a completely fused system rather than re-separating (quasifission). The capture cross sections can be predicted using semi-empirical and model-dependent calculations within a factor of 20%, as demonstrated by comparison to data from 50-100 reactions. The survival probabilities can be calculated using well-established formalisms where the principal uncertainty is the values of the fission barrier heights. (Predictions of hot fusion reactions are particularly susceptible to these uncertainties due to the occurrence of multiple chance fission.) Fission barrier heights are, on average, known to 0.4 MeV with the largest discrepancy between experiment and prediction being about 1 MeV. This leads to uncertainties of about an order of magnitude in fission rates. Nonetheless the procedures for calculating W_{sur} are fairly well understood as is the dependence of W_{sur} upon reaction parameters. The fusion probability P_{CN} is not well known nor is its dependence on excitation energy or the reaction entrance channel. The results of a number of recent measurements of P_{CN} will be summarized and comparisons made between various formalisms for P_{CN} and measurements.

Recently there has been increased interest in alternate approaches for the synthesis of superheavy nuclei such as multi-nucleon transfer reactions involving the collision of massive nuclei. Results from recent and on-going studies of model systems will be discussed along with preliminary results for the synthesis of heavy nuclei using these reactions.

The possibilities of synthesizing new n-rich heavy nuclei using radioactive beams using FRIB, Spiral2, CARIBOU, and ReA3 are presented. Exciting new opportunities for the study of the atomic physics and chemistry of the heaviest elements exist.

There are several new developments in instrumentation which should illuminate studies of the reaction mechanisms such as plans for new separators, reaction product mass analyzers, etc. Challenges exist for the preparation of appropriate targets for these studies, particularly related to the availability of high specific activity actinides.

Theoretical models of formation dynamics of SH nuclei

V. Zagrebaev

Keywords: formation dynamics, fusion reactions, multi-nucleon transfers, neutron capture

There are three reaction mechanisms which can be used for the production of superheavy (SH) nuclei, namely,

- **fusion reactions,**
- **multi-nucleon transfer reactions in collisions of heavy ions with actinide targets,**
- **multiple neutron capture.**

Formation dynamics of SH nucleus in **fusion reactions** is usually decomposed into the three reaction stages: capture (or contact) stage, formation of more or less spherical compound nucleus (CN) in competition with quasi-fission, and cooling of excited CN by evaporation of light particles in competition with dominated fission process. The first stage is well understood and properly described within the channel coupling approach. Uncertainty factor in prediction of the capture cross sections at near-barrier energies is about 2. The last reaction stage (cooling) is described satisfactorily within the standard statistical model. However, for SH nuclei significant uncertainty in calculation of the corresponding decay widths originates from unknown values of fission barriers (defined here by shell corrections), badly determined damping factor of the shell corrections and collective enhancement factor of level density. The most uncertain and poorly understood is the second reaction stage of SH nucleus formation, evolution of two touching nuclei into the configuration of CN. Quite opposite (excluding each other by physics assumptions) theoretical models are used for description of this reaction stage. Unfortunately, experimental study of this reaction stage is currently unfeasible.

Rather appropriate theoretical model is developed for description of deep inelastic scattering and **multi-nucleon transfer reactions** in collisions of heavy ions. This model is based on stochastic (Langevin type) equations of motion. It was successfully applied for description of available experimental data. However there is only a few experimental data on multi-nucleon transfer reactions in low energy collisions of very heavy (actinide) nuclei. As a result the values of several important physical parameters (such as nuclear viscosity, proton and neutron transfer rates) remain rather uncertain. A choice of appropriate collective degrees of freedom and explicit calculation of (time dependent) potential energy surface need additional discussion and study.

A set of equations for description of a sequence **of neutron capture** and beta-minus decay processes leading to production of heavy and SH nuclei is rather simple and well defined. Strong neutron fluxes might be provided by nuclear reactors and nuclear explosions under laboratory conditions and by supernova explosions in nature. Most interesting r process (which may lead to formation of long-living SH nuclei located on the island of stability) passes through the unexplored area of neutron rich nuclei. For these nuclei one may use only theoretical estimations for neutron capture cross sections, fission and beta-decay half-lives. Unknown features of neutron fluxes generated in core-collapse supernova explosions or in the mergers of neutron stars (total fluence and time of irradiation) put additional obstacles in predictions of SHE formation in these processes and in estimations of their possible abundance in nature.

Future of SHE research.

What has to be done within the next few years?

V. Zagrebaev

Keywords: fusion reactions, pathway to the island of stability, multi-nucleon transfers, neutron enriched SH nuclei

(1) **Elements 119 and 120** may be synthesized in the Ti and/or Cr fusion reactions with the cross sections of about 0.05 pb (50Ti+249Bk), 0.04 pb (50Ti+249Cf) and 0.25 Pb (54Cr+248Cm). It is quite probably that these are the heaviest SH elements with $T_{1/2} > 1$ μs. The elements with Z>120 being synthesized in similar fusion reactions might have too short half-lives (less than 1 μs) to be detected at existing facilities.
(2) Strong shell effects define the properties of SHE. The understanding of these effects and other properties of SH nuclei is heavily impeded by the absence of experimental data on decay properties of the not-yet-synthesized isotopes of SH elements located between those produced in the “cold” fusion reactions and those produced in the “hot” fusion reactions and also by the yet missing neutron-enriched isotopes of these elements. This **gap in SH mass area** can be easily filled in fusion reactions of 48Ca with lighter isotopes of actinide elements (239Pu, 241Am, 243Cm …). Predicted cross sections for the production of new isotopes of SH nuclei were found to be quite large, and the corresponding experiments can be performed at existing facilities within rather short term beam runs.

(3) There are no combinations of stable projectiles and relatively stable targets which may allow us to synthesize neutron enriched **SH nuclei located on the island of stability** in fusion reactions. The use of radioactive ion beams cannot solve this problem due to their low intensity. Predicted cross sections of multi-nucleon transfer reactions leading to formation of SH nuclei located on the island of stability are also too small. However there is a chance to reach the middle of the island of stability due to possible beta(+) decay of neutron enriched isotopes of elements 115 and/or 113 (and their daughter products, elements 114 and 112) which can be synthesized in ordinary fusion reactions (48Ca+249Bk, 2n channel, cross section is 0.3 pb, 48Ca+250Cm, 3n channel, 0.8 pb) with the cross sections quite attainable at existing facilities.

(4) Multi-nucleon transfer reactions can be used for synthesis of **neutron enriched long-living SH** nuclei located along the beta-stability line. 48Ca and 136Xe beams are much less favorable as compared with uranium-like beams. New neutron enriched isotopes of Fm and No (up to mass number of 266) might be synthesized in the multi-nucleon transfer reactions with the cross sections greater than 1000 pb.

COLLECTIVE PROPERTIES/IN-BEAM SPECTROSCOPY

A. LOPEZ-MARTENS

From atomic beam magnetic resonance measurements, it has been known for quite some time that nuclei close to Fm are well deformed [1]. Theoretical calculations predict a quadrupole axial deformation parameter _ between 0.25 and 0.3 for nuclei in this region. These values agree well with what can be inferred from the measured spectroscopic electric quadrupole moments. The most beautiful proof of deformation came in the late nineties with the observation in ^{254}No of a sequence of -ray transitions forming a rotational band[2]. The yrast rotational band in ^{254}No has since been observed down to very low spin [3] and extended from spin 14 to 24~ [4] providing evidence that transfermium nuclei are quite stable against fission and opening the field of in-beam spectroscopy to very heavy nuclei. By studying the properties of rotational bands at the top end of the nuclear chart, we can learn about the dynamical properties of nuclei, in particular how and when alignments occur, changing the content of the nuclear wavefunction and modifying the response to rotation. One of the key observables here is the moment of inertia, which is very sensitive to the amount of nucleon-nucleon correlations and can therefore give a handle on the behaviour of pairing, the location of gaps in the single-particle spectra and on the presence of other collective degrees of freedom. The details of the electromagnetic properties within rotational bands depend on the underlying single and mutli-particle configurations. The ratio of M1 over E2 transition intensities can therefore be a powerful tool to pin down the nature of rotational structures and help determine the proper sequence of single-particle states in a given nucleus. Finally, the stability of such heavy nuclei as a function of spin can also be accessed through in-beam spectroscopy. This is quite a crucial point since heavy nuclei are produced at high spin.

The outline of the presentation is the following: I will briefly go over the 2 experimental techniques currently used to perform spectroscopy around the target position: i) Coulex, transfer and inelastic reactions and ii) fusion-evaporation with recoil-(decay) tagging. The behaviour of the moments of inertia and 2^+ energies extracted from groundstate bands in even-even nuclei will be presented and discussed taking into consideration the most recent additions and extensions: ^{256}Rf [5], ^{250}Cm, ^{250}Cf [6]. This will naturally bring me to talk about the stability of heavy nuclei at high angular momentum. The recent study of bands built on high-K structures in ^{250}Fm [7] and ^{252}No [8] will be the object of the next part of the talk followed by the study of strongly coupled bands in odd nuclei with the heaviest example of ^{255}Lr [9]. The problematic case of ^{253}No will be discussed in the light of combined photon and electron data [10, 11, 12]. This will then lead me to talk about the new array for prompt electron and -ray spectroscopy (Silcon And GErmanium array) and show preliminary data on ^{251}Md taken this winter. In the last part of the talk, I will consider the issues we face to pursue this type of study further and give some conclusions and perspectives.

References

[1] L.S. Goodman et al., Phys. Rev. A 11 (1975) 499
[2] P. Reiter et al., Phys. Rev. Lett. 82 (1999) 509
[3] P. Butler et al., Phys. Rev. Lett. 89 (2002) 202501
[4] S. Eeckhaudt et al., Eur. Phys. J. A 26 (2005) 227
[5] P.T. Greenlees et al., to be published
[6] S.S. Hota, PhD thesis (2012)
[7] P.T. Greenlees et al., Phys. Rev. C 78 (2008) 021303(R)
[8] B. Sulignano et al., to be published
[9] S. Ketelhut et al., Phys. Rev. Lett. 102 (2009) 212501
[10] P. Reiter et al., Phys. Rev. Lett. 95 (2005) 032501
[11] S. Eeckhaudt, PhD thesis (2006)
[12] R.-D. Herzberg et al., Eur. Phys. J. A42 (2009) 333

Structure of low-lying states of transactinides

P.-H. Heenen

Very promising tools to describe the spectroscopy of super-heavy nuclei are the models based on the introduction of a microscopic self-consistent mean-field. There are many variants of these models: they are based on an energy density functional of the Skyrme type, on a finite range functional like the Gogny force or on a relativistic Lagrangian. They can also be divided in two categories corresponding to two different ways of considering correlations. The first case corresponds to the spirit of the energy density functional method: the modeling of the strong interaction include the effect of these correlations in its parameterization. In the second case, beyond mean-field correlations have to be included explicitly.

Irrespective of these conceptual differences, all these models perform in a rather similar way. Global properties are qualitatively similar and in agreement with the data. In particular, experimental alpha transition energies are reproduced satisfactorily, deformations properties differ only marginally. The main differences concern the position and the magnitude of the shell gaps. None of these models predict a significant shell gap at Z=114, but gaps at 120 or 126. Moments of inertia of even isotopes are also in agreement with the available data.

The situation is different for spectroscopic properties, i.e. for spectra of odd isotopes. The states of these nuclei are calculated by microscopic models by performing self-consistently a one-quasiparticle excitation, which takes into account the blocking of the qp and the polarization of the nucleus. Some models also take into account the new terms generated by the breaking of time-reversal invariance due to the qp excitation. The excitation energies of some states show some strong disagreement with the data, for all the available parameterizations of the EDF. Even if the qp are not directly related to single-particle orbitals in these models, the magnitude of the error (of the order of 1 MeV) is so large that it points to a wrong position of some orbitals. It has not been possible up to now to find a way to cure these problems. The problem is not trivial in particular because the EDF are adjusted on general properties of nuclei and of nuclear matter and cannot be adjusted locally without losing the generality (and the interest) of the models.

A study of the influence of two factors on the spectra shows that these spectra are very sensitive to details of the EDF. The introduction of a tensor term induces changes of a few hundred keV that are sufficient to modify the order of the levels in the spectrum of an odd nucleus, without however curing the main drawbacks of the parameterizations. Theoretical arguments indicate that the spreading in energy of a theoretical spectrum is related to the value of the effective mass used in the EDF: the lower the effective mass , the more spread the spectrum. A calculation using equivalent EDF's but with different values for the effective mass shows that this is not always true: other changes in the single particle spectra due to the change of the effective mass may invalidate this property. Since an effective mass lower than the nucleon mass is justified by the absence of some correlations in a mean-field calculation, the most appropriate way to treat this problem is probably to introduce explicitly the missing correlations.

A question that has to be asked is which kind experimental data should help to improve the theory. It is clear that the origin of the actual disagreements has first to be understood, which is not an obvious task. To correct this deficiency will probably require the introduction of new terms in the EDF and probably the most effective way to proceed is first to study spectra of lighter odd nuclei for which many data are already available: in the rare earth region and in isotopes around U. At this stage, the most useful experimental developments are probably to make more accurate the spectroscopy of transactinides for which data already exist by a more solid determination of spin and parity of the low lying states. Another useful development would be also to extend the knowledge of the spectra of even (and if possible odd) nuclei by measuring transition probabilities.

Quasiparticle Trends Towards the Next Shell Gap

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The most pressing question concerning the nuclear structure of the heaviest elements is the location and magnitude of the next major spherical shell gaps beyond doubly-magic ^{208}Pb. This will determine the location and extent of the suggested “super-heavy island” of relative stability and ultimately may help us define the end of the periodic table, and mass and charge limits of the chart of the nuclides. To address these issues we can attempt to probe the relevant nuclei directly, illustrated by the new results on elements up to Z=118, or to indirectly investigate the details of the quasi-particle structure of lighter nuclei with Z>100. In the latter case, we are attempting to provide detailed tests of various theoretical models, the very same models that have different predictions for the next doubly-magic spherical super-heavy nucleus. The experimental goal is to extend the studies of quasi-particle structure to the nuclei with the highest Z and N that can be reached.

I describe the experimental status. A great deal of detailed structure information exists for nuclei up to Z~100. I use the example of recent studies on ^{249}Bk to illustrate the point. Additionally, there is a lot of recent activity in the trans-fermium region up to Z=104. A variety of techniques, including alpha spectroscopy, isomer spectroscopy, and prompt gamma-ray spectroscopy, provide a wealth of complementary information and our understanding of these systems is steadily improving. I illustrate this by using the examples of recent studies of ^{255}Lr. Finally, we are beginning to see the first traces of structural information from experiments aimed at nuclei with Z>105. I show examples of such work in Sg, Hs, and Ds.

It is clear that theory and experiment must advance together if we are to fully address our key questions. Broadly, theoretical investigations can be categorized in two families: macroscopic-microscopic (MM) and microscopic self-consistent density functional theories (DFT). I compare the extant experimental data with both MM and DFT models. MM models can reproduce most one-quasiparticle states in the region from Z=89-100 with reasonable accuracy (I find that typically ~85% of 1qp states are within 200 keV of MM model predictions). However, these models often involve tuning the potential parameters to achieve a good fit and, while local predictions seem rather reliable, the question remains as to how well they can be extrapolated to the super-heavy systems near Z=114, N=184. On the other hand, I show that DFT models generally have less accurate reproduction of experiment (only ~35% 1qp states are reproduced to within 200 keV and there is a broad distribution indicating that in some cases the deviation for specific orbitals can exceed 1 MeV). I point to recent progress in improving DFT methods, such as including particle-vibration coupling, which might steadily improve the spectroscopic quality of these theories.

I describe how the study of the rotational response of nuclei can help us characterize particular quasi-particle structures. In particular, the moments of inertia, presence or absence of signature splitting, and the relative alignments of rotational sequences can all provide keys to understanding the structure of states upon which the rotational bands are built. I illustrate this, using examples of ^{241}Am and ^{255}Lr. In addition, the electromagnetic decay properties, such as branching ratios, can also provide a key to unlocking quasi-particle assignments and I use results on ^{251}Md as an example. One must also bear in mind that the rotational response of bands in even-even nuclei can also provide information on quasi-particle structure. The example I use is the alignment properties, visible in the behavior of the moments of inertia, for bands in ^{252}No and ^{254}No. The combination of deformation and rotation can lower key orbitals originating near the spherical shell and bring them close to the Fermi surface of lighter deformed trans-fermium nuclei. Indeed, studies such as this may be the only way to find traces of specific states, such as the $k_{17/2}$ neutron orbital, involved in the shell structure of super-heavy systems.

Finally, I turn to future experimental opportunities both in the short- and longer-term. There are several accelerator upgrade projects in the works, which will result in several different facilities around the world providing intense beams of ^{48}Ca, ^{50}Ti, and the like ($1\text{p}\mu\text{A} < I_{BEAM} < 10\text{p}\mu\text{A}$). In addition, there are many efforts to upgrade focal-plane detector systems. I describe our efforts at the 88-Inch Cyclotron. The combination of more efficient focal-plane detectors and increased beam intensities offer unique opportunities in decay spectroscopy (for example, alpha-gamma and isomer-decay experiments). I believe we shall be able to push these studies into the Hs (Z=108) region. For prompt spectroscopy, we cannot use the most intense beams available since our detector systems are unable to cope with the instantaneous count rate. However, new advanced detector systems such as GRETINA /GRETA and AGATA, which are essentially shells of high-efficiency, high-resolution, segmented Ge detectors, offer new opportunities and we may soon be able to perform prompt spectroscopy on nuclei up to Sg (Z=106).

Decay Properties of SHE

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The existence of Superheavy Nuclei is a phenomenon of nuclear structure, as the macroscopic fission barriers drop below the ground-state motion oscillation (≈0.5 MeV) at around $Z = 104$. So the stability of heavier nuclei is strongly dependent on details of the arrangement of the nucleons in the nuclear potential, finally determined by the nuclear interactions.

In this sense nuclear structure investigations are the key for understanding the existence of superheavy nuclei and the (possible) termination of the charts of nuclei with respect to the quests of the maximum number of protons a 'stable' nucleus can bear and the survival probability of heavy compound nuclei against prompt disruption during the deexcitation process. Information on nuclear structure is obtained a) from studying the 'basic' radioactive decay modes, related to a change of the mass and/or atomic number of the nucleus, from ground-state or metastable excited states (isomers) and b) from internal transitions, e.g. γ-decay or internal conversion. Among a) the most important decay modes, detectible with high sensitivity using presently available experimental set-ups, are spontaneous fission and α-decay. Spontaneous fission is a collective process delivering only limited information on nuclear structure. An interesting phenomenon in this sense, however, is the modification of the fission barrier due to the unpaired nucleon in nuclei with odd proton and/or odd neutron numbers. Angular momentum conservation leads in these nuclei to an enhancement of the fission barrier and vice versa to an extension of the fission half-life compared to neighbouring even-even nuclei, usually denoted as 'fission hindrance'. The hindrance factor is dependent on the development of the single particle level(s) occupied by the unpaired nucleon(s) at deformation. The enhancement of the fission barrier compared to neighbouring even-even nuclei is denoted as 'specialization' energy.

α-decay is 'easy' to measure and already from few observed events basic properties of a nucleus, as the half-life or (with some restrictions) the Q_α – value can be extracted. Comparing measured half-lives with results from empirical relations between Q_α –value, Z, A and half-life 'hindrance factors' for α-decay can be extracted, allowing to draw some conclusions on spins and parities of the decaying and populated states. However, only in combination with γ- and/or CE (conversion electron) spectroscopy α-decay becomes a real powerful method for investigation of nuclear structure in detail. Still, it has to be considered, that levels may remain undetected as they are not populated by the α-decay or the following transitions towards the ground-state. As α-decay represents the mass difference of mother and daughter nuclei it is further a sensitive probe for localizing nuclear shells.

In the region of 'light' transactinides investigation of the various types of β-decay (β^-, β^+, EC) has been in the past a powerful method of nuclear structure investigations. In the transfermium region this technique is only little developed so far, as it requires 'clean' (A and Z separated) samples, which is hardly to access using the implantation of complete fusion products in silicon detectors as applied widely in SHE research. So, X-ray – γ – coincidence measurements have to be applied to identify the nuclei, which require, however, high production rates and thus can be employed only for a few cases. In interesting technical development is trap-assisted spectroscopy, providing ‘clean’ samples by using ion traps.

Decay studies of two- or multi-quasiparticle states (‘K – isomers’) have become in recent years a powerful method to investigate ‘high’ lying excited levels (typically E* > 500 keV) in transfermium nuclei. Importance of these studies, however, is not only evident with respect to excited nuclear levels, but also with respect to the stability of two- or multiquasiparticle states against ‘basis’ nuclear decay modes as α-, β- decay and spontaneous fission, expressed figuratively as a ‘stability on a higher level’.

Theory: ground state properties and the limits of the regionof superheavy elements

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It is well known that the stability of superheavy elements is determined exclusively by quantum (shell correction) effects. Thus, the details of shell structure are important in the definition of both the properties of these elements and the location of the island of increased stability of superheavy nuclei. Unfortunately, different classes of theoretical models predict different centers of this island. The following combinations (Z = 114,N = 184), (Z = 126,N = 184) and (Z = 120,N = 172) of proton Z and neutron N numbers define the centers of the island of stability in the macroscopic+microscopic (MM) approach and non-relativistic (Skyrme) [SDFT] and relativistic (covariant) [CDFT] density functional theories [1], respectively. Historically, this is not exclusive list since some old parametrizations of the MM approach gave Z = 126 and some parametrizations of the SDFT and CDFT gave Z = 114 as a large proton shell gap. However, detailed analysis of the single-particle properties ruled out these alternatives.

Self-consistency effects (related, for example, to central density depression [3]) are quite likely responsible for the differences in the predictions of the MM and SDFT/CDFT approaches. The differences in the description of both the energies of the centroids of different spin-orbit doublets [which depend on orbital angular momentum] and spin-orbit splittings contribute into the differences between SDFT and CDFT. It is important to remember that when these quantities are compared with experimental data in spherical nuclei, particle-vibration coupling and polarization effects have to be taken into account [4]. The accuracy of the description of the single-particle states is lower in the DFT approaches; this was recently illustrated in the systematic studies of deformed one-quasiparticle states in the CDFT [5]. However, due to low effective mass of the nucleon the relevant gaps in the CDFT calculations are larger than the ones in the MM approach so these inaccuracies should not affect substantially the Z = 120 shell gap in CDFT. In addition, this gap retains its status even in particle-vibration coupling calculations [4]. However, the Z = 172 shell gap is smaller and thus less robust with respect to the inaccuracies of the model description of single-particle energies and correlation effects beyond mean field [4].

Spherical shell gaps in superheavy nuclei are not sufficiently large to generate the effects similar to the ones produced by the shell gaps in lighter doubly magic nuclei, so their notation as “magic” may be misleading. The impact of these gaps on two-neutron separation energies is only marginally (by ~ 50%) larger than the impact of deformed Z = 100 and N = 152 shell gaps in heaviest actinides. Shell correction energies are also significantly less localized in the vicinity of spherical shell gaps as compared with the ones in lighter nuclei [2]. As a consequence, the predictions of the MM, SDFT and CDFT approaches in the part of the triangle defined by (Z = 114,N = 184), (Z = 126,N = 184) and (Z = 120,N = 172), where experimental data is available, are similar. So this data cannot be used to eliminate either of model predictions about the center of island of stability.

Considerable progress has also been made recently in the investigation of fission barriers in actinides and superheavy nuclei both in the MM and DFT approaches (see overview in Refs. [6]). Fission barriers are important since they define the stability of superheavy elements. The effects of triaxiality and octupole deformation are taken now into account in these approaches. MM and DFT approaches provide comparable description of inner and outer fission barriers in actinides and indicate similar particle number dependencies of the heights of inner fission barriers [6]. It turns out that the accuracy of the description of inner fission barrier heights is not very sensitive to the accuracy of the description of single-particle energies in normal deformed minima and the effective mass of nucleon. However, despite these successes in actinides the predictions for fission barriers in superheavy nuclei differ substantially: the differences between the different classes of the models or even within one class of models [dependence on the parametrization] still exists and its is appreciable [7, 6].

References

[1] M. Bender, K. Rutz, P.-G. Reinhard, J. A. Maruhn, and W. Greiner, Phys. Rev. C58, 2126 (1998).
[2] M. Bender, W. Nazarewicz, P.-G. Reinhard, Phys. Lett. B515, 42 (2001).
[3] A. V. Afanasjev and S. Frauendorf, Phys. Rev. C 71, 024308 (2005).
[4] E. V. Litvinova and A. V. Afanasjev, Phys. Rev. C84, 014305 (2011).
[5] A. V. Afanasjev, S. Shawaqfeh, Phys. Lett. B706, 177 (2011).
[6] H. Abusara, A. V. Afanasjev, and P. Ring, Phys. Rev. C 82, 044303 (2010), ibid C85, 024314 (2012),
[7] M. Kowal, P. Jachimowicz, and A. Sobiczewski, Phys. Rev. C82, 014303 (2010).

Precision Measurements of Ground State Properties of the Heaviest Elements

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Ground state properties of rare isotopes such as masses, nuclear spins, nuclear moments, and charge radii are indicators of their nuclear structure. High-precision mass measurements directly provide binding energies and thus allow the study of shell effects, for example via differential quantities such as the two-neutron separation energy. Masses also provide anchor points for alpha-decay chains reaching out to even heavier nuclides that are not accessible directly yet. Laser spectroscopy of the heaviest elements probes the influence of relativistic effects on their atomic structure and, in addition, provides experimental data on nuclear properties such as spins, moments, and charge radii independent of a particular nuclear model.

In recent years sensitive methods have been developed to deal with the very low production rates for the nuclides of interest. In addition, the preparation of low energy radioactive beams, a prerequisite for most precision experiments, is nowadays accomplished employing buffer gas stopping cells and radiofrequency quadrupole (RFQ) beam cooler and buncher devices. In this combination the nuclides of interest are slowed down in argon or helium gas at pressures of about 100 mbar, then cooled, bunched, and purified removing unwanted components. Such low-emittance bunched beams can serve mass spectrometers, for example.

Penning traps provide masses of rare isotopes with uncertainties of $\delta m/m \approx 10^{-8}$ based on cyclotron frequency measurements. They can presently access nuclides with half-lives down to about 10 ms and with production rates as low as one particle per minute. This gives access to the region around Z=102, N=152 as demonstrated with SHIPTRAP. While traditional on-line methods require about 30 ions to be detected for a cyclotron frequency measurement with a Penning trap, non-destructive electronic detection systems, routinely used for stable ions, reach single-ion sensitivity. Applying such techniques for on-line mass measurements will extend the reach of traps to nuclides with yields of one particle per hour and below.

Time-of-flight mass measurements have usually a reach far from stability and can access shorter-lived nuclides than traps, however with lower precision. More recently multi-reflection time-of-flight mass spectrometers are being developed for on-line experiments. Compared to traditional ToF devices they extend the flight path by multiple reflections of ions between electrostatic mirrors resulting in a compact device. They reach mass resolving powers up to 200,000 and can access nuclides with about 1 ms half-life and mass measurements with uncertainties of 10^{-6}-10^{-7} will be possible.

Both devices can be operated as high-resolution mass separators to provide purified, even nuclear state-selected samples. For example, one can use a MR-ToF as pre-separator for a Penning trap. In addition, either one can be used to prepare clean samples for trap-assisted decay spectroscopy experiments.

For the mass or m/q identification of a new element a low mass resolving power of about 300 is sufficient, which can be achieved with standard electromagnetic separators of various designs. In combination with the element-selective laser resonance ionization (broadband) mass spectrometers can also be used to map the isotopic yields in reaction studies, for example in multinuclear transfer reactions.

For laser spectroscopy of rare isotopes, in particular when no atomic levels are known, laser resonance ionization inside a stopping gas cell is the method of choice. This sensitive method has already been successfully applied to nuclides produced with rates of a few particles per second. It allows discovering atomic levels, as demonstrated for Fm, and to determine ionization potentials. Once some levels are known hyperfine spectroscopy will provide spins and moments, while isotope shift measurements can be performed to provide charge radii.

Liquid-Phase Chemistry of Superheavy Elements

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Chemical characterization of superheavy elements (SHE) is an extremely fascinating subject. A very important and interesting aspect is to clarify chemical properties of these elements, such as ionic charge and radius, redox potential, complex formation and so on, and to elucidate the influence of relativistic effects on valence electrons of SHE.

Liquid-phase experiments with SHE have been conducted on the basis of the following steps: i) synthesis of superheavy nuclides, ii) rapid transport of synthesized nuclides to chemical separation devices by a gas-jet technique, iii) fast chemical characterization of a desired nuclide that includes dissolution in an aqueous solution containing inorganic/organic ligands for complex formation, iv) preparation of a sample suitable for nuclear-spectroscopy: evaporation of aqueous solution to dryness, and v) detection of nuclides through their characteristic decay properties for unambiguous identification of nuclides. The chemical characterization is performed by a partition method with single atoms, e.g., liquid-liquid extraction, ion-exchange chromatography, and reversed-phase extraction chromatography. In the processes, the behavior of SHE is compared with that of its lighter homologues under strictly identical conditions. The ultimate goal of the partition experiments is to determine the so-called distribution coefficient (K_d) as a function of ligand concentration [1].

Several investigations have been carried out with automated rapid chemical separation apparatuses to measure K_d vs. ligand concentration, and innovative information about the chemistry of SHE has been obtained [2]. There are, however, still ambiguities to unequivocally understand chemical properties of SHE. Reaction kinetics in complex formation and ion-exchange/solvent-extraction processes of SHE should be carefully considered to determine K_d. We have to take into account chemical equilibrium and to determine chemical species in liquid phases, in order to compare the behavior of SHE with that by theoretical predictions.

Development of a new apparatus based on flow electrolytic column chromatography combined with cation-exchange separation has been recently carried out. Oxidation of element 102, nobelium, has been successfully conducted [3]. This approach will lead to new frontiers of liquid-phase chemistry of SHE; information on valence electronic structure of SHE through redox potentials will be obtained. The electrochemistry apparatus coupled with a rapid extraction system, such as SISAK, will be a potential candidate for further studies of redox properties of SHE. The system consists of the above chemical devices and a physical recoil separator that is used for a pre-separator to purify a desired superheavy nuclide before chemistry.

[1] J.V. Kratz, Liquid-phase chemistry, in *The Chemistry of Superheavy Elements*, M. Schädel (ed.), pp. 159-203, Kluwer Academic Publishers, Dorcrecht, 2003.
[2] J.V. Kratz, Radiochim. Acta, **99**, 477 (2011).
[3] A. Toyoshima *et al*., J. Am. Chem. Soc. **131**, 9180 (2009).

The strategy of the Chemical Research on the SHEs

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Chemical studies on the SHEs have been very successful in last several years. Performed in a close link between the theory and experiment, they allowed for determining properties of the SHEs in comparison with their homologs and helped placing them in the right positions of the Periodic Table.

Experimentally, chemical properties were studied for elements 104 through 108, as well for 112 and 114. Theoretically, predictions of various properties, trends and experimental behaviour were made for these elements and even heavier with the use of the most advanced fully relativistic methods.

The future aspects on the chemical research on SHEs can comprise the following points.

- Since the half-life and production rates of the SHES become smaller and smaller, the last element that can be chemically studied is obviously Z=116. To reach this aim, vacuum chromatography should be developed and applied for the 7p elements up to Z=116.

- Another important direction is new classes of compounds of already chemically identified SHEs, like, e.g., metallorganics of the elements of the midst of the 6d series (Rf through Hs). This will broaden the fundamental knowledge about these SHEs.

- Not less important is a detailed study of chemical behaviour of the types of compounds and chemical species that were studied earlier. This can presently be done at a higher experimental level than before due to developments in the chemical separation techniques, as well as physical pre-separators.

- A combination of physical and chemical separation will also allow for studying physical properties of isotopes of the SHEs in the chemistry experiments. This was already demonstrated by discovery of new isotopes of element 108, Hs, while studying its adsorption behaviour by gas-phase chromatography experiments.

- Spectacular recent developments in the relativistic quantum chemistry will allow for bringing the theoretical research at a higher level than before. Thus, not only old predictions could be reconsidered and more accurate values of various properties be provided, but also new types of properties and experimental behaviour can be predicted at the *ab initio* theory level, i.e., without using models.

- A new direction in the atomic electronic structure theory needed both for physical and chemical experiments can also be assessed in future.

Piet van Duppen

Hervé Savajols

Understanding SHE: relevant model developments

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The presentation will be a personal view on successes, open problems and paths to be taken. It will concentrate on nuclear structure, but also briefly address reactions and decay of SHE insofar as they can be described with extensions of the models used to describe their structure. I will concentrate on nuclear theory; hence, I will not address clever phenomenology-guided parametrization of data that allows for the guidance of experiment in the absence of theory of sufficient predictive power.

State of the art (recent major successes and breakthroughs):

- **Theory**: towards universal microscopic models of nuclear structure of high predictive power
- **Computation**: massive systematic calculations
- **Structure**: description of binding energies, bandheads, rotational bands, fission barriers, … in a unified microscopic approach (either self-consistent or microccopic-macroscopic)
- **Reactions**: microscopic “classical” description of fusion with nuclear structure models (TDHF)
- **Decay**: detailed multi-dimensional almost symmetry-unrestricted deformation energy surfaces ; towards a microscopic description of fission dynamics

Almost every aspect of theory for SHE is also relevant for the description of nuclear phenomena and processes elsewhere in the chart of nuclei. However, the relative importance of specific ingredients of the models changes with N and/or Z. SHE amplify the role of the Coulomb interaction, level density, …

Major scientific issues:

- Limitations in predictive power (Of the many-body methods? Of the parametrizations? Of both?)
- Disagreement among models in predictions for the spherical shell closures (if there are any …)
- None of the parametrisations of the available self-consistent mean-field methods (Gogny, Skyrme, RMF) does reproduce the *deformed* shell closures N=152, Z=100 indicated by many observables (S_{2n}, S_{2p}, $Q_{á}$, bandheads in odd-A nuclei, K-isomers in even-even nuclei, …)

Open questions for topical studies:

Understanding theory for SHE:

- Quantify theoretical error bars of models, methods, and parametrizations thereof
- Understand the role, impact, and importance of self-consistency (surface diffusion, central depletion of the density, higher-order deformations, …). Why do microscopic-macroscopic models work so well?
- Understand the role of correlations “beyond the mean field” (particle-vibration coupling *or* projection on angular momentum/parity/particle number, ..., + fluctuations in deformation, *or* ...) for the structure and decay of SHE. Do the correlations have to be treated explicitly for a satisfactory description of the relevant physics of SHE? If not, which terms in the interaction can/do effectively incorporate them? If yes, how do they influence structure and interfere with the adjustment of parametrizations?

- How to construct effective interactions that are predictive for SHE? (Higher-order terms ? Different kinds of terms? Modified and/or specific fit protocols? …)
- How microscopic can models for SHE become for the (super)computers of 2032?

Novel features of nuclear structure of SHE:

- The nuclear landscape at its extremes: are there (new?) exotic phenomena to be encountered that are relevant for the detection of SHE and/or the correct interpretation of data? (K or shape isomers as longest-living states, exotic shapes, ...)

Modelling reactions leading to SHE:

- How to efficiently and reliably describe the relevant physics of reactions at the Coulomb barrier in a unified model of nuclear structure+dynamics+decay?

Modelling decay of SHE:

- Can one set up a microscopic model of á decay (based on a nuclear structure model)?
- Are exotic decay modes relevant for SHE? (and compromise the detection of events via á decay?)