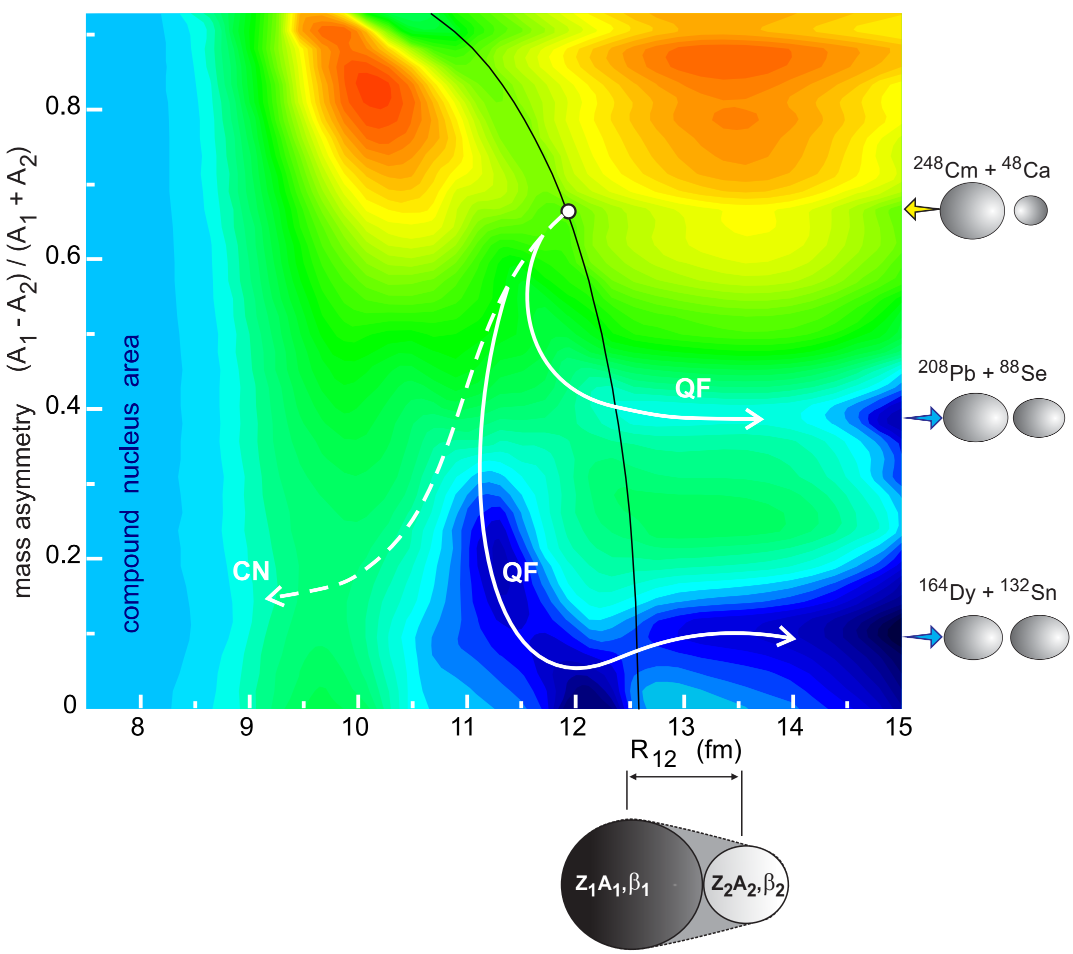
Super Heavy Nuclei 2015



Texas A&M University

College Station • Texas • March 31 - April 02, 2015

Super Heavy Nuclei International Symposium

Texas A&M University, College Station Texas, USA

March 31 - April 02, 2015

In the past forty years, twelve new elements have been synthesized and more than a hundred new nuclides have been produced. We have advanced by forty atomic mass units in a search for the limits of nuclear matter, but we have not reached these limits yet. Nevertheless, we have obtained new knowledge on the properties of the heaviest nuclei and in many cases we have confirmed the theoretical predictions.

New powerful accelerators, neutron-rich actinide targets and radioactive isotope beams together with high-efficiency experimental facilities will give us a unique opportunity to make significant progress in exploring the nature and properties of the heavy and super-heavy nuclei at the borders of nuclear masses.

Topics

- At the Border of the Island of the Super-Heavy Nuclei
- Decay Properties and Nuclear Structure of the Heaviest Nuclei
- Reactions of Synthesis of New Elements and Isotopes
- Super-Heavy Atoms. Chemistry of the Super-Heavy Elements
- Production and Fabrication of Actinide Targets
- Accelerator Facilities and Setups

The program will include 30 – 20 – 15 minute talks and short 5 minute oral contributions during the discussions, as well as poster presentations. It is expected that during the Symposium will be enough time for informal meetings where future research prospects and possible collaborations will be discussed.

Abstracts

An abstract should not exceed a single page and must be submitted as a camera-ready PDF file. Formatting guidelines: US Letter page size (21.6 cm x 27.9 cm) with text margins 0.75" (2 cm) on all sides.

Please submit abstracts by email to *she2015@comp.tamu.edu* before March 01, 2015.

Webpage *http://cyclotron.tamu.edu/she2015*

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International Symposium Super Heavy Nuclei 2015

Texas A&M University, College Station, Texas, USA March 31 - April 02, 2015

March 31, 2015

8:45	**9:00**	0:15	**Opening**	
			Introduction	
			Chair: Robert Tribble BNL, USA	
9:00	9:40	0:40	Witold Nazarewicz FRIB/NSCL MSU, USA	Superheavy Nuclei: Theoretical Challenges
9:40	10:20	0:40	Yuri Oganessian FLNR-JINR, Dubna/TAMU Russia/USA	Symposium on Super Heavy Nuclei: Our Expectations
10:20	**10:30**	0:10	**Discussion**	
10:30	**10:50**	**0:20**	**Coffee Beak**	
			At the Border of the Island of the Super Heavy Nuclei	
10:50	11:20	0:30	Sigurd Hofmann GSI Helmholtzzentrum, Germany	Super-Heavy Nuclei: Current Status And Futur Developments
11:20	11:40	0:20	Vladimir Utyonkov FLNR-JINR, Dubna, Russia	Synthesis of Superheavy Nuclei at Limits of Stability: 239,240Pu + 48Ca and 249-251Cf + 48Ca Reactions
11:40	12:00	0:20	Kosuke Morita RIKEN Nishina Center, Japan	SHE research at RIKEN/GARIS
12:00	12:20	0:20	Anatoli Afanasjev Mississippi State University, USA	Recent progress in the study of the heaviest nuclei in covariant density functional theory
12:20	12:25	0:05	William H. Bassichis Texas A&M University, USA	Ancient Map: Island of Stability
12:25	**12:45**	0:20	**Discussion**	
12:45	**14:00**	**1:15**	**Lunch**	
			Decay Properties and Nuclear Structure of the Heaviest Nuclei	
			Chair: Teng Lek Khoo ANL, USA	
14:00	14:20	0:20	Jacklyn Marie Gates LBNL, USA	Decay Spectroscopy of Element 115 Daughters
14:20	14:40	0:20	Michael Itkis FLNR-JINR Dubna Russia	Production of new neutron rich heavy and superheavy nuclei
14:40	15:00	0:20	Adam Sobiczewski NCNR, Poland	Theoretical Description of Decay Properties of Superheavy Nuclei
15:00	15:20	0:20	Mark Stoyer LLNL, USA	Approaching the Island of Stability: Synthesizing the Heaviest Elements
15:20	15:40	0:20	Alexander Yeremin FLNR-JINR, Dubna, Russia	Spectroscopy Of Transfermium Isotopes At Dubna: Results And Plans
15:40	**16:00**	0:20	**Discussion**	
16:00	**16:20**	**0:20**	**Coffee Beak**	
16:20	16:35	0:15	Zhongzhou Ren Nanjing University, China	Nuclear Charge Radii of Superheavy Nuclei and Exotic Nuclei From the Experimental Decay Data
16:35	16:55	0:20	Michael Kowal NCNR, Poland	Candidates for Long Lived High-K Ground States in Superheavy Nuclei
16:55	17:15	0:20	Dieter Ackermann GSI Helmholtzzentrum, Germany	Paving the Way to the Island of Stability – Superheavy Element Research at GSI and Beyond
17:15	17:35	0:20	Rolf Herzberg University of Liverpool, UK	Combined Electron and Gamma Spectroscopy of Heavy Nuclei – Optimising the SAGE Spectrometer
17:35	17:55	0:20	Peter MÖller LANL, USA	Comments on Superheavy-Element Stability and Production
17:55	18:05	0:10	George Souliotis National University of Athens, Greece	Microscopic Calculations of Low Energy Fission within the CoMD (Constrained Molecular Dynamics) Model
18:05	**18:25**	0:20	**Discussion**	

April 1, 2015

Reactions of Synthesis of New Elements and Isotopes

Chair: Joseph Natowitz
Texas A&M University, USA

8:30	9:00	0:30	Walter Loveland Oregon State University, USA	Heavy Element Synthesis Reaction Mechanisms
9:00	9:20	0:20	Gurgen Adamian BLTP-JINR, Dubna, Russia	Isotopic Trends in Production of Superheavy Nuclei
9:20	9:40	0:20	Cody Folden Texas A&M University, USA	Production of Near-Spherical Nuclei in Hot Fusion Reactions
9:40	10:00	0:20	Galina Knyazheva FLNR-JINR, Dubna, Russia	Fusion probabilities in heavy ion induced reactions
10:00	10:10	0:10	Alexander Karpov FLNR-JINR, Dubna, Russia	Superheavy nuclei: which regions of nuclear map are accessible in the nearest future
10:10	**10:30**	0:20	**Discussion**	
10:30	**10:50**	**0:20**	**Coffee Beak**	
10:50	11:10	0:20	Dariusz Seweryniak ANL, USA	Recent Spectroscopic Results Near the Z=100, N=152 Closed Shells
11:10	11:30	0:20	Gottfried Muenzenberg GSI Helmholtzzentrum, Germany	SHE Research with Rare-Isotope Beams – Challenges and Perspectives
11:30	11:45	0:15	Sophia Heinz GSI Helmholtzzentrum, Germany	Probing the Stability of Superheavy Nuclei with Radioactive Ion Beams
11:45	12:00	0:15	Sait Umar Vanderbilt University, USA	Dynamics of Quasifission and Fission
12:00	12:15	0:15	Andzei Wieloch SIP, Jagiellonian University, Poland	New Experimental Approach to the Super and Hyper Nuclei Search
12:15	12:30	0:15	Katsuhisa Nishio ASRC, JAEA, Japan	In-beam fission study at JAEA
12:30	**12:50**	0:20	**Discussion**	
12:50	**14:05**	**1:15**	**Lunch**	

Super Heavy Atoms. Chemistry of the Super Heavy Elements

Chair: Joseph Hamilton
Vanderbilt University, USA

14:05	14:35	0:30	Hartmut Backe Universität Mainz, Germany	Prospects for Laser Spectroscopy at Superheavy Elements
14:35	15:05	0:30	Christoph Düllmann GSI Helmholtzzentrum, Germany	Chemical studies of the heaviest elements
15:05	15:25	0:20	Valeria Pershina GSI Helmholtzzentrum, Germany	Advanced Theoretical Studies for Chemical Identification of the Superheavy Elements
15:25	**15:45**	0:20	**Discussion**	
15:45	**16:05**	**0:20**	**Coffee Beak**	
16:05	16:25	0:20	Robert Eichler Heavy Elements group PSI-University of Bern, Switzerland	Superheavy Element Chemistry from Switzerland
16:25	16:45	0:20	Yuichiro Nagame ASRC, JAEA, Japan	Chemical Studies of the Heaviest Elements at JAEA
16:45	**16:55**	0:10	**Discussion**	

Production and Fabrication of Actinide Targets

16:55	17:20	0:25	James Roberto ORNL, USA	Production and fabrication of actinide targets for super-heavy element research
17:20	17:35	0:15	Michail Onegin NPI, St. Petersburg, Russia	Investigation of the Possibilities of Heavy Actinide Isotopes Production in High-flux Reactor PIK
17:35	17:50	0:15	Klaus Eberhardt Universität Mainz, Germany	Fabrication and characterization of actinide targets for super-heavy element studies
17:50	18:00	0:10	Rose A. Boll ORNL, USA	Actinide Materials at Oak Ridge National Laboratory
18:00	**18:15**	0:15	**Discussion**	
19:15			**Dinner**	

April 2, 2015

Accelerator Facilities and Setups

Chair: Sydney Gales

INPN Orcay/CNRS, France

8:30	8:50	0:20	Sherry Yennello Texas A&M University, USA	Rare Isotope Beams at TAMU Cyclotron Institute
8:50	9:15	0:25	Sergey Dmitriev FLNR-JINR, Dubna, Russia	FLNR SHE Factory
9:15	9:40	0:25	Christelle Stodel GANIL, France	Study of very heavy nuclei at GANIL-SPIRAL2 facilities
9:40	10:05	0:25	Michael Thoennessen NSCL, MSU, USA	The Facility for Rare Isotope Beams
10:05	**10:25**	0:20	**Discussion**	
10:25	**10:45**	**0:20**	**Coffee Beak**	
10:45	11:05	0:20	Winfried Barth GSI Helmholtzzentrum, Germany	R&D Activities Towards a Future CW LINAC at GSI
11:05	11:25	0:20	Michael Block GSI Helmholtzzentrum, Germany	Nuclear Structure Revealed by High-Precision Mass Measurements
11:25	11:45	0:20	Greg Chubarian Texas A&M University, USA	High efficiency recoil spectrometer for Superheavy Element Factory
11:45	12:00	0:15	Zach Kohley NSCL, MSU, USA	Opportunities to study the SHE production mechanism with rare isotopes at the ReA3 facility
12:00	12:15	0:15	Aditya Wakhle NSCL, MSU, USA	Isospin Dependence of Quasifission and Heavy-ion Fusion with Neutron Rich RIBs
12:15	**12:35**	0:20	**Discussion**	
12:35	**13:35**	**1:00**	**Lunch**	
13:35	13:55	0:20	Andrey Popeko FLNR-JINR, Dubna, Russia	On-line Separators for the Dubna Superheavy Element Factory
13:55	14:15	0:20	Oleg Tarasov NSCL, MSU, USA	Using LISE++ for heavy ion reactions at low energies
14:15	14:30	0:15	Nathan Brewer ORNL, USA	Microsecond Activity from α-emitters observed at the DGFRS with Digital Electronics
14:30	14:45	0:15	**Discussion**	
14:45	**14:55**	0:10	**Closing**	
15:15			**Cyclotron Tour**	

Superheavy nuclei: theoretical challenges

Witold Nazarewicz

Department of Physics and Astronomy and FRIB/NSCL,
Michigan State University, East Lansing, MI, USA
Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

What are the heaviest nuclei and atoms that can exist? Are superheavy atoms and nuclei different from lighter species? Is there an island of very long-lived nuclei? Are superheavy nuclei produced in stellar explosions? Questions such as these provide formidable challenges for both experiment and theory.

In this talk, theoretical advances in superheavy nuclei research will be reviewed.

Symposium on SUPER HEAVY NUCLEI: Our Expectations

Yuri Oganessian*

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** Texas A&M University*
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My talk, in fact, is an expanded introduction to the two and a half-day symposium, which is going to include presentations and discussions on the current state and future development of research in the field of heaviest atomic nuclei. Symposium SHN covers various areas of atomic and nuclear physics, nuclear chemistry, and partly astrophysics.

The program mainly focuses on discussing the most problematic issues, makes attempts to find answers with various approaches, assessing new opportunities associated with a construction of large accelerator facilities and new, more sophisticated experimental devices.

The symposium program consists of 8 topics and includes 45 talks. We tried to balance presentations on theory/experiment in a ratio 1:3 in order to include topics related to production of a target material with high-flux reactors, new accelerators and experimental setups, detectors and so on. Working time of the symposium is divided into 10 sessions, each taking approximately 2 hours.

It is our pleasure to express our deepest gratitude to the members of the International Advisory Committee for their creative work and high interest in the symposium.

SUPER-HEAVY NUCLEI: CURRENT STATUS AND FUTURE DEVELOPMENTS

Sigurd Hofmann

GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany and
Institute for Physics, Goethe University, Frankfurt, Germany

An overview will be given on the present status and results of research on super-heavy nuclei (SHN). In more detail current experimental developments will be discussed, which will influence the research on SHN in the nearer future and which, however, will demand extensive technical developments.

Synthesis of superheavy nuclei at limits of stability: ^{239,240}Pu + ^{48}Ca and $^{249\text{-}251}$Cf + ^{48}Ca reactions

V.K. Utyonkov

for the collaboration of:
Joint Institute for Nuclear Research
Oak Ridge National Laboratory
Lawrence Livermore National Laboratory
University of Tennessee Vanderbilt University
Research Institute of Atomic Reactors

Series of experiments aimed at the synthesis of neutron-deficient isotopes of Fl were carried out. In the ^{239}Pu + ^{48}Ca reaction, the new spontaneously fissioning isotope ^{284}Fl was produced for the first time. The cross section of the ^{239}Pu(^{48}Ca, 3n) ^{284}Fl reaction was observed to be about 20 times lower than that predicted by theoretical models and 50 times less than the value measured in the ^{244}Pu+^{48}Ca reaction. In the ^{240}Pu+^{48}Ca experiment performed at the 3*n*-evaporation channel maximum, α-decay energy of ^{285}Fl was measured for the first time and decay properties of its descendants ^{281}Cn, ^{277}Ds, ^{273}Hs, ^{269}Sg and ^{265}Rf were determined in the three decay chains. At 5-MeV higher projectile energy, four decays were assigned to ^{284}Fl. The cross sections at both ^{48}Ca energies are similar and exceed that observed in the reaction with lighter isotope ^{239}Pu by a factor of 10. The decay properties of the synthesized nuclei and their production cross sections indicate rapid decrease of stability of superheavy nuclei with receding from neutron magic number 184.

Forthcoming experiment on the synthesis of the heaviest isotopes of element 118 in the reactions using a target of mixed $^{249\text{-}251}$Cf isotopes with ^{48}Ca projectiles will be discussed.

SHE research at RIKEN/GARIS

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A cold heavy-ion fusion reactions have been used for producing nuclei of the heaviest elements at RIKEN with use of a gas-filled type recoil ion separator GARIS. The heaviest nuclei which we studied were an isotope of the 113th element, ^{278}113, produced in the ^{209}Bi(^{70}Zn, *n*) reaction [1-3]. Unambiguous identification of an atomic number and an atomic mass-number of the isotope based on the genetic correlation was done. Before performing the experiment on element 113, we have done a series of experiment to confirm the experimental results performed at GSI on the atomic numbers 108 (Hs) [4], 110 (Ds) [5], 111 (Rg) [6], and 112 (Cn) [7,8] by using ^{58}Fe, ^{64}Ni, and ^{70}Zn beams on to ^{208}Pb, and ^{209}Bi targets. The results provide firm confirmation to the results obtained at GSI. Some of new spectroscopic information on the nuclei were obtained also.

Study of an actinide based hot fusion reaction are also started. The reaction in study is ^{248}Cm + ^{48}Ca. Similar decay chains to the ones previously observed at FLNR/GFRS and at GSI/SHIP were observed in two different beam energies. The corresponding excitation energies of the compound nucleus ^{296}Lv were 37.5$\pm$1.5 MeV and 41.5$\pm$1.5 MeV. We plan to measure one more point at higher excitation energy to obtain an excitation function of the reaction.

A ^{50}Ti beam is now in development by MIVOC method [9] for the future study of the ^{248}Cm + ^{50}Ti → ^{298}118* reaction.

References:

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Recent progress in the study of the heaviest nuclei in covariant density functional theory

Anatoli Afanasjev
Mississippi State University, USA

The questions of the existence limits and the properties of shell-stabilized superheavy nuclei have been a driving force behind experimental and theoretical efforts to study such nuclei. Unfortunately, theoretical predictions for superheavy nuclei differ considerably. In such a situation, heavy nuclei of actinide region play a role of testing ground for many theoretical approaches. Systematic study of these nuclei allows to estimate theoretical uncertainties in the description of superheavy nuclei. The present status of our understanding of heavy and superheavy nuclei in covariant density functional theory (CDFT) will be presented. I will concentrate on several aspects which define the shell structure, physical observables and stability of heavy and superheavy nuclei. These are single-particle degrees of freedom [1,2,3], pairing interactions [4], rotational excitations [4,5] and fission barriers [2,3,6,7]. I will also revisit the question of shell structure of superheavy nuclei based on the covariant energy density functionals, the global performance of which has recently been established [8]. Similar global studies of superheavy nuclei including deformation effects point towards the possible importance of the neutron shell gap at $N = 184$ [3]; the role of this gap is frequently overlooked in the CDFT studies restricted to spherical shape. In addition, the inner fission barriers are systematically studied in the $Z = 106-130$ nuclei for the first time in CDFT [3]. Theoretical uncertainties in the description of different physical observables are estimated.

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Ancient Map: Island of Stability

William H. Bassichis
Texas A&M University

Fifty years ago computers became large and fast enough to carry out many body calculations for systems such as atoms. The Hartreec Fock method was very successful in explaining atomic structure. Subsequently the method was applied to study the structure of light nuclei with rather surprising success. These calculations began with a somewhat realistic twoc body interaction and treated all the particles selfc consistently. Over 40 years ago these selfc consistent calculations were extended heavier nuclei to study shell effects. Since the known magic numbers were reproduced the calculations were extended beyond the discovered nuclei. From the result binding energies it was predicted that stable nuclei might occur for Z=120 and N=178 or N=184.

Decay Spectroscopy of Element 115 Daughters*

J.M. Gates
Lawrence Berkeley National Laboratory

Over the last 15 years, a collaboration working at the Flerov Laboratory for Nuclear Reactions (FLNR) has reported the discovery of six new superheavy elements (SHE) assigned to atomic numbers *Z*=113-118, and more than 50 new isotopes in reactions of ^{48}Ca beams with actinide targets [1, 2]. Since 2007, experiments conducted at Lawrence Berkeley National Laboratory (LBNL) [3, 4], the GSI Helmholtzzentrum für Schwerionenforschung (GSI) [5-10] and FLNR [11] have confirmed the majority of the decay properties for isotopes produced in ^{48}Ca+actinide reactions. However, while decay properties are well understood, a decade old question remains: how can the atomic numbers of the SHE be confirmed? Nature has not been kind – the SHE isotopes discovered in recent years decay through a series of α decays that terminate in spontaneous fission (SF) without passing through previously known nuclides. With no decay connection to nuclides for which atomic mass, *A* and proton number, *Z* are firmly established, the *A* and *Z* assignments for these new SHE isotopes are based primarily on measurement of excitation functions, cross bombardments and *a* decay systematics. Thus, *A* and *Z* assignments ultimately rely on nuclear mass models and a determination of *Z* (and *A*) independent of the mass models is needed. One method to determine *Z* of an element is through the observation of characteristic *K x*-rays, the energies of which have been accurately and precisely calculated [12-14]. This method has been previously used to identify atomic numbers with *Z*>100 [15], and, though challenging, is a promising avenue in the case of SHE.

In April – June 2013, forty-three decay chains matching those reported for ^{288}115 were produced during a five-week long experiment at Lawrence Berkeley National Laboratory (LBL) using the ^{243}Am(^{48}Ca,x*n*) reaction. The element 115 evaporation residues were separated with the Berkeley Gas-filled Separator [15] and implanted into the Corner-Cube-Clover (C3) detector. The C3 detector is designed for the detection of photons in prompt coincidence with the α-decay of heavy elements (i.e. element 115 and its daughters). A similar experiment at GSI involving the LUND/GSI/LBL collaboration reported 22 correlated decay chains assigned to ^{288}115 [16]. Here we will report results from the LBL experiment interpret the combined data set.

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Production of new neutron rich heavy and superheavy nuclei

V.I. Zagrebaev[1], M.G. Itkis[1], and A.V. Karpov[1]

[1] *Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia*

A possibility for the production of heavy and superheavy (SH) nuclei in different nuclear reactions (fusion of stable and radioactive nuclei and multi-nucleon transfers) will be discussed in the talk. Low values of the fusion cross-sections and very short half-lives of nuclei with Z>120 put obstacles in synthesis of new elements. However the fusion reactions of medium mass projectiles (including RIB) with different actinide targets still can be used for the production of the not-yet-synthesized SH nuclei. The gap of unknown SH nuclei, located between the isotopes which were produced earlier in the cold and hot fusion reactions, could be filled in fusion reactions of ^{48}Ca with available lighter isotopes of Pu, Am, and Cm. Cross sections for the production of these nuclei are predicted to be rather large, and the corresponding experiments can be easily performed at existing facilities [1]. Experiments of such kind were already started in Dubna.

The neutron-enriched isotopes of SH elements may be produced with the use of a ^{48}Ca beam if a ^{250}Cm target would be prepared. In this case we get a real chance to reach the island of stability owing to a possible β^+ decay of ^{291}Fl nucleus formed in the 3n evaporation channel of this reaction with a cross section of about 0.8 pb [1].

Multi-nucleon transfer processes at near barrier collisions of heavy (and very heavy, U-like) ions seem to be most realistic reaction mechanism allowing one to produce new neutron enriched heavy nuclei located in the unexplored upper part of the nuclear map. Our predictions for the production of new neutron rich heavy nuclei in multinucleon transfer reactions will be discussed and new (most promising) experiments will be proposed. A special attention will be paid to the "inverse" quasi-fission mechanism leading to formation of reaction fragments with masses lighter than projectile and heavier than target masses [2].

A new facility (based on selective laser ionization of reaction products) developed currently at the Flerov laboratory and aimed on the production and study of new heavy nuclei produced in the multinucleon transfer reactions will be shortly reviewed.

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THEORETICAL DESCRIPTION OF DECAY PROPERTIES OF SUPERHEAVY NUCLEI

A. Sobiczewski

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Recently, a large amount of experimental data on the decay chains of superheavy nuclei have been collected (e.g. [1-4]).

The objective of this presentation is to illustrate how accurately may the data be described theoretically within a simple approach. For the description, a phenomenological model of Ref. [5], which appeared to be rather realistic, is used. To make the description still more realistic, a special care has been taken to use possibly accurate models in reproducing experimental nuclear masses (and, thus, also decay energies) of heaviest nuclei. A search for such models has been recently undertaken in Refs. [6,7].

Examples of the description of already existing data, as well as of new (predicted) ones are illustrated.

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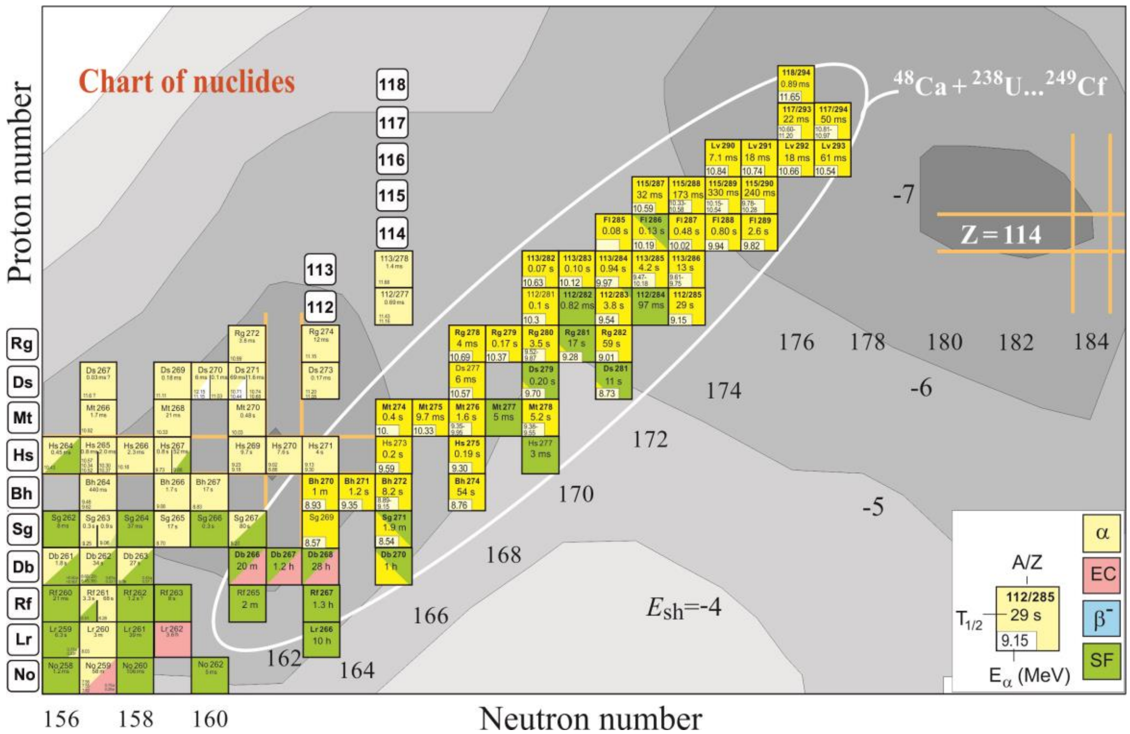
Approaching the Island of Stability: Synthesizing the Heaviest Elements

Mark A. Stoyer for the Dubna/Livermore/ORNL/Vanderbilt/RIAR collaboration



A summary of super heavy element research over the last 10-15 years on the synthesis of elements 113 – 118, including the recent IUPAC acceptance of element names for 114 (flerovium) and 116 (livermorium), will be presented. Elements 113-118 have been synthesized and characterized using fusion-evaporation nuclear reactions of ^{48}Ca beams on actinide targets (^{237}Np, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Bk, and ^{249}Cf, respectively) at the U400 cyclotron located at the Flerov Laboratory of Nuclear Reactions in Dubna, Russia [1]. Recent experiments have concentrated on the production of lighter isotopes of Fl using targets of ^{239,240}Pu. The nuclear properties of the isotopes of these heaviest elements provide experimental information on the extent of the region of enhanced stability near Z=114 and N=184. Future experiments utilizing a mixed ^{249,251}Cf target will be mentioned.

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SPECTROSCOPY OF TRANSFERMIUM ISOTOPES AT DUBNA: RESULTS AND PLANS

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Important information on the structure of Super Heavy Elements (SHE) can come from the study of lighter deformed transfermium (Z ~ 100-106) elements. The cross-section for the formation of these nuclei is many orders of magnitude higher than for Z ≥ 110 so that detailed spectroscopy becomes possible.

The opportunity to have high intensity (> 1 pμA) accelerated beams with A ≤ 50 together with the use of exotic targets provide the possibility to study many aspects of heavy ion induced reactions exploiting new generation of high efficiency, high resolution experimental setups.

In recent years α-, β- and γ- spectroscopy of heavy nuclei at the focal plane of recoil separators (“decay spectroscopy”) has been very intensively developed. The mixing of α decay with γ and β decay spectroscopy allows to investigate single particle states behavior as well as the structure of little known elements in the Z = 100-104 and N = 152-162 region.

With α , γ and β detector arrays, installed at the focal plane of the VASSILISSA separator, detailed spectroscopy of Fm – Lr isotopes was performed during last 10 years. Accumulated experience allowed us to perform ion optical calculations and to design the new experimental set up, which will collect the base and best parameters of the existing separators and complex detector systems used at the focal planes of these installations. New experimental set up (SHELS, the velocity filter) on the basis of existing VASSILISSA separator was developed for synthesis and studies of the decay properties of heavy nuclei. During the last experimental campaign (March 2014) the new double sided silicon detector (DSSD) was used at the focal plane of the SHELS separator (128x128 strips, 100x100 mm^2). The detector demonstrated high stability and ensured a high resolution (0.2 %) of alpha particle registration. In many cases of poor statistics the only method of alpha particle detection with high resolution allow to define energy of transitions (gamma) from excited states to ground state and to evaluate the position of the excited levels in nuclei to be studied.

In the close future it is planned to perform model experiments using method of high resolution alpha spectroscopy and gamma quanta detection to study decay properties of the Rf and Db in the reactions $^{50}Ti + ^{208}Pb \rightarrow ^{257}Rf + 1n$ and $^{50}Ti + ^{209}Bi \rightarrow ^{258}Db + 1n$.

These experiments will help us to prepare full scale spectroscopy experiment aimed to the study of decay properties of the isotopes in the decay chain of $^{288}115$ formed in the complete fusion reaction $^{48}Ca + ^{243}Am \rightarrow ^{288}115 + 3n$.

Fission Barrier of ^{254}No: implications for models and reactions

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Superheavy elements exist only because shell stabilization creates a barrier against fission, which otherwise would not exist. Therefore, the barrier height B_f is a critical property to measure. B_f is dependent on the shell energy and, hence, on the singe-particle spectrum. Given that different theoretical approaches yield divergent single-particle energies (reflected in the much-discussed contradictory magic-gap locations), B_f serves as an incisive test of theory.

Measurements of B_f, most directly through fission thresholds in transfer reactions, were successful up to californium. However, for over 35 years, no measurement for any heavier element has been performed because of the lack of stable targets. To overcome this impasse requires a new approach, which we have used to recently determine[1] B_f for ^{254}No: 6.6 (9) and 6.0 (5) MeV at spins 0 and 15 ħ. We exploit the fact that the ratio $\Gamma_\gamma/(\Gamma_\gamma + \Gamma_{fission})$ provides a proxy for the fission threshold below the neutron separation energy: near and above the saddle energy, the radiative width drops precipitously. The entry distribution, which represents the starting points for gamma decay to the ground state, were measured calorimetrically with Gammasphere at ATLAS, in the ^{208}Pb(^{48}Ca,2n)^{254}No reaction at 219 and 223 MeV. The maximum energy above the yrast line of the entry distributions does not increase with beam energy even though higher energy states are favored by larger level densities. The termination of gamma emission, clearly due to fission, occurs near the saddle energy.

The measured B_f is in good agreement with static barrier predictions of 6.8 MeV from macroscopic-microscopic models based on either the folded Yukawa or Woods-Saxon potentials. In contrast, the predictions of density functional theory (DFT), using either Skyrme or Gogny interactions, are significantly higher: 8.6 – 12.5 MeV. The different theoretical approaches predict different properties of SHE due to discrepant underlying single-particle spectra. It is unlikely to be an accident that the potential-based models also give single-particle spectra in deformed shell-stabilized nuclei that are in much better agreement with experiment that those from DFT. The available data would suggest that DFT, although more fundamental in some sense, is still limited in its predictive power by the hunt for a good effective interaction, which is very much in progress.

The entry distribution measurements also clearly indicate that B_f and, therefore, also the shell-correction energy, remain robust at high spin. Furthermore, the bulk of the cross section in ^{254}No and, by implication, in the synthesis of SHE in fusion-evaporation reactions, lie in the higher partial waves.

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Nuclear charge radii of superheavy nuclei and exotic nuclei from the experimental decay data

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One of fundamental properties of a nucleus is its radius [1, 2]. Experimental information on nuclear charge radii can be obtained by different sources such as electron scattering, muonic atom spectra, isotope shifts, and so on [2, 3]. These methods are successful for the nuclei near the β-stability line. However, it is difficult for them to obtain charge radii of exotic nuclei and superheavy nuclei, because these nuclei are produced by experiments and exhibit short lifetimes so that they are not available as target nuclei. In view of this, we propose a method to determine nuclear charge radii from the decay data [4, 5, 6, 7]. As we all know, α decay is the main decay mode of heavy and superheavy nuclei [4, 5]. We extract their charge radii from the experimental α-decay data by the aid of the well-established α-decay model [8]. The charge distribution of daughter nuclei is determined in the double-folding model to reproduce the experimental α-decay half-lives. The root-mean-square (rms) charge radius is then calculated using the resulting charge distribution. Nuclear radii of heavy and superheavy nuclei with $Z = 98 - 116$ are extracted from the α-decay data [6], for which α decay is a unique tool to probe nuclear sizes at present. This is the fi result on nuclear charge radii of superheavy nuclei based on the experimental α-decay data. Moreover, the rms charge radii of some medium-mass proton-rich nuclei and light neutron-rich nuclei are separately extracted from the experimental data of proton emission and cluster radioactivity in a similar manner [7].

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Candidates for Long Lived High-K Ground States in Superheavy Nuclei

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Two current methods of making superheavy elements in the laboratory: cold and hot fusion reactions, seem to reach their limits. On the other hand, not all superheavy (SH) isotopes Z ≤118 have been produced yet. It might be, that among them hides some surprisingly long-lived one, either in its ground- or excited isomeric state. It is even not excluded that such a long-lived SH state was already produced, but remained undetected. Since detection procedures used at present are adjusted to short-time coincidences, a species living tens of minutes would be very likely missed in the background. Therefore, while pondering upon possible new reactions leading towards the island of stability, it may be worthwhile to search for a long-lived exotic SH configurations. Obvious candidates are high-K isomers or ground-states, for which increased stability is expected due to some specific hindrance mechanisms. On the basis of systematic calculations for 1364 heavy and superheavy nuclei, including odd-systems, we have found a few such candidates for high-K ground states in superheavy nuclei. In order to predict possible exotic configurations one has to have a reliable model to find ground states in odd and odd-odd nuclei. The macroscopic-microscopic model based on the deformed Woods-Saxon single particle potential which we use offers such a reasonable description of SH systems, including known: nuclear masses, Q_α values, fission barriers, ground state deformations, super- and hyper-deformed minima in the heaviest nuclei. Exceptionally untypical high-K intruder contents of the g.s. found for some nuclei accompanied by a sizable excitation of the parent configuration in daughter suggest a dramatic hindrance of the α-decay. A particular situation occurs above double closed subshells: N = 162 and Z = 108 where two intruder orbitals: neutron $13/2^-$ from $j_{15/2}$ and proton $11/2^+$ from $i_{13/2}$ spherical subshells are predicted. These orbitals combine to the 12^- g.s. in Z= 109, N = 163, whose configuration lies ~2 MeV above the g.s. the daughter. This would imply a six order of magnitude increase in α half-life. The double subshell gap at N = 162 and Z = 108 is consistent with experimental Q_α values and predicted by many models. The position of neutron $13/2^-$ and proton $11/2^+$ orbitals above this gap is also common to many models, in particular, the predicted g.s. in ^{272}Mt has exactly the same structure. The calculated configuration-preserving fission barrier in ^{272}Mt is by 6 MeV higher than the one minimized over configurations. Even if configuration is not completely conserved, a substantial increase in fission half-life is expected. There are other orbitals which may produce long-lived configurations, in particular intruder neutron $11/2^-$ and proton $9/2^+$ above N = 152, Z = 102. There is a possibility, that one such high-K ground- or low-excited state may be the longest lived superheavy nucleus. One cannot exclude also that such long-lived superheavy configurations were already produced before, but setup and electronics dedicated to the milliseconds measurements could not detect objects living much longer. This intriguing possibility should be check at first.

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Paving the way to the island of stability
– *superheavy element research at GSI and beyond*

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The search for the next closed proton and neutron shells beyond ^{208}Pb has yielded a number of exciting results in terms of the synthesis of new elements [1,2,3] at the upper end of the chart of nuclides, in the region of exotic high-Z nuclear matter.

Despite these achievements the A and, even more important, Z assignment is still based on indirect evidence. A direct experimental prove is still missing. In a first attempt to measure characteristic x-rays in order to establish the atomic number of the members of ^{288}115 decay chain first promising photon-α correlations have been observed with the decay spectroscopy set-up TASiSpec GSI's gas filled separator TASCA [4].

Despite these achievements the "island of stability" is still out of reach. With projectile and target combinations provided by nature, i.e. stable species the neutron rich superheavy nuclei (SHN) in the predicted region of spherical shell stabilized nuclei cannot be composed. The presently planned next generation rare isotope beam (RIB) facilities aim at providing neutron rich beams for various applications. The projected beam intensities are rather moderate and certainly to low to hope for a possible synthesis of SHN and new superheavy elements (SHE), given the expected low production cross sections. Nevertheless, useful systematic studies can be performed to investigate features of reaction mechanism as a function of isospin towards neutron rich compound systems, and nuclear structure of heavy systems in the neutron rich region between lead and uranium.

The production of those superheavy species is governed by the formation probability as well as by the competition between de-excitation and fission of the hot compound system. Reaction mechanism studies as well as the investigation of specific nuclear structure features provide valuable information for the understanding of the collision details as well as on the stability of the heaviest nuclei. One alternative tool to study the fusion barrier is the investigation of the compound nucleus spin distribution, which has shown to yield detailed information of the distribution of barriers [5]. The competition of fission and α-decay for ground and excited states, the deformation and other nuclear structure features like K isomeric states [6,7] of heavy nuclei contribute to the understanding of the origin of the predicted stabilization of SHE and provide valuable information which are essential to refine the models.

As an alternative production scheme for SHN Zagrebaev and Greiner proposed recently multi nucleon transfer reactions [8]. The high Z/high A tail of the distribution of species produced in the collisions of heavy partners should reach into the region of (possibly new) SHE. In a first test Loveland et al. observed enhanced yields for transtarget reaction products of the order of the predicted yields for the reaction ^{160}Gd + ^{184}W [9].

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Combined Electron and Gamma Spectroscopy of heavy nuclei – optimising the SAGE Spectrometer*

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A growing number of experiments is currently opening up the transfermium region of nuclei for detailed spectroscopic investigations [1,2,3]. In the deformed nuclei in the nobelium region this allows an identification and mapping of single particle orbitals closest to the top end of the nuclear chart.

Initial in-beam measurements in the region focused on γ-ray spectroscopy of even- even nuclei (e.g. ^{252,254}No, ^{250}Fm), studying the ground-state yrast bands and allowing extraction of parameters such as the moments of inertia, and proving the deformed nature of these nuclei. More recently, it has become possible to do combined in-beam gamma ray and conversion electron spectroscopy with the SAGE spectrometer [4]. The first experiments have focused on the study of odd-mass transfermium nuclei and are currently being analysed. These experiments will yield data, which can be used to determine the excitation energies and configurations of quasiparticle states in the region, and to compare them to the predictions of various theories.

Experimentally it is important to have a full understanding of the instrument and GEANT4 simulations play an increasingly important role in the analysis of experimental data [5,6]. An overview of the most recent results and the experimental techniques used will be presented and the SAGE spectrometer in Jyväskylä will be discussed.

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Comments on Superheavy-Element Stability and Production

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I review our new mass calculation FRDM(2012), especially with respect to heavy-element stability, publication in preparation. We have also completed a large-scale calculation of fission-barrier heights for 5239 heavy nuclides [1]. I will put the results in perspective with respect to other calculations (and experiments). I will discuss what are robust conclusions and what are remaining open issues. Reactions leading to superheavy element formation are mainly in two categories: cold fusion and hot fusion. We show that cold-fusion reactions are favored both by the low excitation energies of the compound system, but also because shell effects stabilize the reaction channel by a high ridge in the potential energy surface so that in some cases less or no "extra push" is required to drive the dynamical trajectory inside the fission saddle point and form a compound system [2, 3, 4]. In heavy-ion reactions leading to heavy-element formation it has always been considered advantageous to form sufficiently compact touching configurations so that their shape is inside the fission saddle point. In hot fusion reactions on deformed actinide targets we have therefore proposed that the reaction energies be sufficiently high to correspond roughly to the barrier in the equatorial location [5].

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Microscopic Calculations of Low Energy Fission within the CoMD (Constrained Molecular Dynamics) Model

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The microscopic description of the mechanism of nuclear fission still remains a topic of intense nuclear research. Understanding of nuclear fission, apart from the theoretical many-body point of view, is of importance for energy production, as well as for the transmutation of nuclear waste. Moreover, nuclear fission is essentially the process that sets the upper limit to the periodic table of the elements and plays a vital role in the production of heavy elements via the astrophysical rapid neutron-capture process (r-process). Motivated by the present state of affairs regarding fission research, we initiated a systematic study of low and intermediate energy fission calculations using the code CoMD (Constrained Molecular Dynamics) of A. Bonasera and M. Papa [1]. The code implements an effective interaction with a nuclear-matter compressibility of K=200 (soft EOS) with several forms of the density-dependence of the nucleon symmetry potential. In addition, CoMD imposes a constraint in the phase space occupation for each nucleon (restoring the Pauli principle at each time step of the collision). Proper choice of the surface parameters of the effective interaction has been made to describe fission.

In this work, we will mostly present CoMD calculations for several proton-incuded fission reactions at low and intermediate energy [2] and compare them with recent experimental data. In addition, preliminary data of fusion-fission reactions leading to superheavy compound nuclei will be presented. We found that the CoMD code is able to describe the many-body dynamics of the fission process especially for intermediate-energy fission reactions. Proper adjustment of the parameters of the effective interaction and further improvements of the code are necessary to achieve a satisfactory quantitative description of low-energy fission where shell effects play a definitive role. Toward this goal, an isospin-dependent surface term, as well as a spin-orbit interaction term will be added to the effective interaction.

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Heavy Element Synthesis Reaction Mechanisms

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The remarkable recent progress in the synthesis of new heavy and superheavy nuclei has been made using fusion reactions. These reactions can be divided into two prototypical classes, ``cold" and ``hot" fusion reactions. For each of these types of reactions, one can write an equation for the cross section for producing a heavy evaporation residue, σ_{EVR}, as

$$\sigma_{EVR}(E) = \frac{\pi\hbar^2}{2\mu E}\sum_{\ell=0}^{\infty}(2\ell+1)T(E,\ell)P_{CN}(E,\ell)W_{sur}(E^*,\ell)$$

where E is the center of mass energy, and $T(E,\ell)$ is the probability of the colliding nuclei to overcome the potential barrier in the entrance channel and reach the contact point, P_{CN} is the probability that the projectile-target system will evolve from the contact point to the compound nucleus. W_{sur} is the probability that the compound nucleus will decay to produce an evaporation residue rather than fissioning. The capture cross section is defined as

$$\sigma_{capture}(E) = \frac{\pi\hbar^2}{2\mu E}\sum_{\ell=0}^{\infty}(2\ell+1)T(E,\ell)$$

The separation of the EVR cross section into three individual reaction stages (capture, fusion, survival) is motivated, in part, by the different time scales of the processes. For a quantitative understanding of the synthesis of new heavy nuclei, one needs to understand $\sigma_{capture}$, P_{CN}, and W_{sur} for the reaction system under study.

There have been a number of very successful attempts to predict σ_{EVR} using a variety of approaches that are very robust in that they describe the observed values of σ_{EVR} over many orders of magnitude. However, when one compares the calculated and measured values of $\sigma_{capture}$, P_{CN}, and $W_{sur,}$ one finds significant discrepancies. I will focus on examining these discrepancies from the point of view of an experimentalist.

Capture cross sections are often thought to be predictable within a factor of two. That is unacceptable in that they are easy to measure and such measurements can inform theory. The formalism for calculating W_{sur} is well-known and the principal problem is the uncertainty in the input parameters, mostly the fission barrier heights, especially for highly excited systems with near zero fission barriers. The fusion probability, P_{CN}, is the least known quantity affecting σ_{EVR}. While we are encouraged by recent results of TDHF calculations, I shall present comparisons of measured and predicted values of P_{CN} from more phenomenological models in an attempt to understand this quantity.

Inspired by the suggestions of Zagrebaev and Greiner, many of us have turned our attention to trying to understand the role of multi-nucleon transfer reactions in the synthesis of new n-rich heavy nuclei. Using surrogate reactions such as $^{136}Xe + ^{208}Pb$, we have tested current models for these reactions. Encouraged by these efforts, we now turn our attention to real syntheses of new actinide nuclei.

As nuclear scientists, we are aware of the importance of radioactive nuclear beams. We continue to evaluate the possibilities of using these beams in complete fusion and multi-nucleon transfer studies, being mindful of the need to emphasize production rates and not cross sections.

Isotopic trends in production of superheavy nuclei

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Isotopic trends are studied in the production of superheavy nuclei in actinide-based complete fusion reactions with Ca, Ti, and Cr beams. The evaporation residue cross sections are estimated. We consider the possibilities of production of unknown isotopes of superheavy nuclei in the gap between those produced in cold and hot fusion reactions. The perspectives are studied to use the radioactive beams in producing superheavy isotopes.

Production of Near-Spherical Nuclei in Hot Fusion Reactions

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The discovery of spherical superheavy elements in recent years using ^{48}Ca-induced reactions with actinide targets has stimulated interest in discovering additional new elements. Unfortunately, targets with $Z > 98$ are not generally available, so several experiments have studied whether new elements can be synthesized with projectiles of ^{50}Ti, ^{54}Cr, ^{58}Fe, and ^{64}Ni. This author is not aware of any reports of decays chains from these experiments.

The formation of spherical heavy elements near the $Z = 82$, $N = 126$ shells using projectiles with $Z_p > 20$ has been studied at Texas A&M University. Using lanthanide targets, a wide variety of compound nuclei have been produced with a range of deformations, neutron separation energies, and fission barriers. These reactions provide an analog of superheavy element formation and allow for studying the variation in cross section caused by a number of parameters. Preliminary results for even-Z projectiles are shown in Fig. 1 and indicate a strong dependence of cross section on the average difference between the fission barrier and the neutron separation energy of the compound nucleus. The inclusion of collective enhancements to level density is required to adequately model the data. Fig. 2 shows a preliminary comparison of a ^{48}Ca-induced reaction with several ^{45}Sc-induced reactions. The change of Z_p by one changes the peak cross section by a factor of $\approx 10^3$. These results suggest a rapid decrease in cross section for projectiles with $Z_p > 20$, and a likely increase in the difficulty of discovering new elements.

This talk will summarize the experiments to date and the implications for the discovery of new superheavy elements.

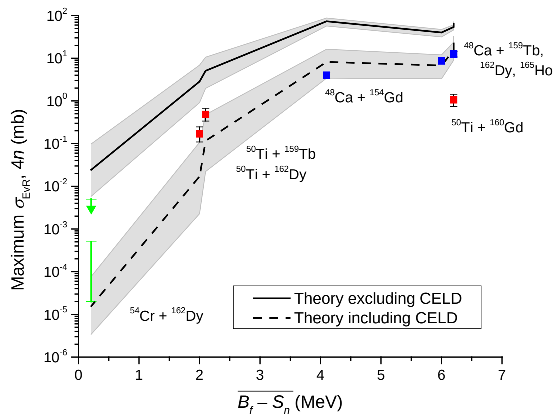

FIG. 1. Peak $4n$ cross section versus the average difference in fission barrier height (B_f) and neutron separation energy (S_n) during the de-excitation cascade for reactions of ^{48}Ca, ^{50}Ti, and ^{54}Cr with lanthanides. Lines represent theoretical calculations with and without collective enhancements to level density (CELD), and the shaded regions show the effect of varying the fission barrier by 0.5 MeV.

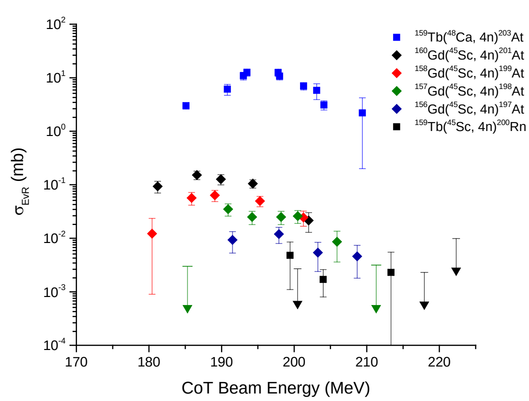

FIG. 2. Comparison of excitation functions for a ^{48}Ca-induced reaction with several ^{45}Sc-induced reactions.

Fusion probabilities in heavy ion induced reactions

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In reactions with heavy ions complete fusion and quasifission (QF) are competing processes. The relative contribution of QF to the capture cross section becomes dominant for superheavy composite systems and compound nucleus formation is hindered by the QF process. The balance between the two processes strongly depends on the entrance channel properties, such as mass-asymmetry, deformation of interacting nuclei, collision energy and the Coulomb factor Z_1Z_2.

Since nuclei with Z>118 cannot be synthesized in ^{48}Ca induced reactions, the study of fusion probabilities in the reactions with Ti, Fe and Ni ions is important for synthesis of heavier superheavy nuclei. The investigation of reaction dynamics with lighter ions allows us to understand more profoundly the reaction mechanisms in dependence on the reaction entrance channel which will give an opportunity to approach this problem in a broader perspective.

The study of mass-energy distributions of binary fragments obtained in the reactions of ^{36}S,^{48}Ca,^{48}Ti, ^{58}Fe and ^{64}Ni ions with the ^{232}Th, ^{238}U, ^{244}Pu and ^{248}Cm at energies below and above the Coulomb barrier will be presented. The experimental data were obtained using the double arm time-of-flight spectrometer CORSET. The properties of mass and energy distributions of fissionlike fragments in dependence on interaction energy have been investigated and compared with the characteristics of the fusion-fission process.

Superheavy nuclei: which regions of nuclear map are accessible in the nearest future

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A possibility for the production superheavy (SH) nuclei in different nuclear reactions will be discussed in the talk. Low values of the fusion cross sections and very short half-lives of nuclei with Z>120 put obstacles in synthesis of new elements. However the fusion reactions of medium mass projectiles (including RIB) with different actinide targets still can be used for the production of the not-yet-synthesized SH nuclei. The gap of unknown SH nuclei, located between the isotopes which were produced earlier in the cold and hot fusion reactions, could be filled in fusion reactions of ^{48}Ca with available lighter isotopes of Pu, Am, and Cm. Cross sections for the production of these nuclei are predicted to be rather large, and the corresponding experiments can be easily performed at existing facilities [1]. Experiments of such kind were already started in Dubna.

The neutron-enriched isotopes of SH elements may be produced with the use of a ^{48}Ca beam if a ^{250}Cm target would be prepared. In this case we get a real chance to reach the island of stability owing to a possible electron capture in ^{291}114 nucleus formed in the 3n evaporation channel of this reaction with a cross section of about 0.8 pb [1].

Multi-nucleon transfer processes at near barrier collisions of heavy (and very heavy, U-like) ions seem to be the most realistic reaction mechanism allowing one to produce new neutron enriched heavy nuclei located in the unexplored upper part of the nuclear map. The predictions for the production of new neutron rich heavy nuclei in multinucleon transfer reactions will be given. A special attention will be paid to the "inverse" quasi-fission mechanism leading to formation of reaction fragments with masses lighter than projectile and heavier than target masses [2].

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Recent spectroscopic results near the Z=100, N=152 closed shells

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Spectroscopy of trans-fermium nuclei around the Z=100 and N=152 deformed shell gaps has been an active area of research worldwide. Observed rotational bands and K-isomers provided information on deformation and single-particle structure in this region. The deduced properties of trans-Fermium nuclei can serve as a testing ground for models which are used to describe the heaviest nuclei. Recently, the energy-spin entry distribution in ^{254}No was measured using Gammasphere and was used to determine the fission barrier directly [1]. Also, two K isomers were observed for the first in the fissile N=150 isotone ^{254}Rf using the Fragment Mass Analyzer at ANL and the Berkeley Gas-filled Separator at LBNL [2]. Required sensitivity to very short decay times was achieved by employing a digital acquisition system. The two isomers were assigned the $K^{\pi}=8^{-}$, ν^2(7/2[624], 9/2[734]) 2-quasi-neutron and the $K^{\pi}=16^{+}$,{ν^2(7/2[624],9/2[734π,)]^2(7/2[514],9/2[624])} 4-quasi-particle configurations. Surprisingly, the half-life of the 2-quasi-particle isomer is 4 orders of magnitude shorter than for similar isomers in the lighter N=150 isotones. Also, both the 2-quasi-particle and the 4-quasi-paerticle isomer decay primarily by γ-ray emission implying that the fission from the isomeric states is significantly hindered relative to the ground-state fission in ^{254}Rf. This unique case can shed light on the role of pairing and K-number conservation in the fission process.

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SHE Research with Rare-Isotope Beams – Challenges and Perspectives

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The main goals for SHE research in the field of nuclear physics are: reaction studies for SHE synthesis, synthesis of new isotopes at the borderlines of the known region, and nuclear structure investigations in the transfermium region. In this contribution we will discuss to which extent the use of rare-isotope beams can contribute to these questions.

The main advantage of the use of rare-isotope beams is the possibility for systematic reaction studies over a large region of isotopes to learn about macroscopic and microscopic effects on the nuclear synthesis, especially production cross sections. The first generation of experiments in the trans-fermium region will certainly include systematic reaction studies such as fusion-fission- and transfer reactions to find new ways and to optimize projectile-target combinations for SHE synthesis. Specifically transfer reactions in the near-Coulomb-Barrier region need a more detailed and systematic investigation.

Demanding are structure investigations. A first step are systematic mass measurements to map the nuclear chart and to extract shell correction energies and fission barriers which helps to improve nuclear models and their possible application to learn more about the upper end of the r-process nucleosynthesis path. In-beam studies are a challenging tool for nuclear structure studies and can be made already at reasonable beam intensities. Structure studies in the transition region from liquid drop stabilization to the shell region should also be possible with moderate intensities.

We will give some examples for the investigation of isotopes in and beyond the fermium region at the SuperFRS-LEB using a new experimental scheme for large-scale isotope investigations involving the MRTOF technique. The challenge and limitations of SHE studies at ISOL facilities will be addressed and compared to the possibilities with the next generation SHE factories. The general problem of SHE research at RI facilities besides the limited beam intensity is the availability of beam time, which needs a solution to fully profit from the use of RI beams for SHE research. This problem will be briefly addressed in this contribution.

Probing the Stability of Superheavy Nuclei with Radioactive Ion Beams

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The location of the next spherical shell closures beyond Z = 82, N = 126 is still an open question. According to model predictions shell closures are expected at Z = 114 or 120 or 126 and N = 184, but existing experimental data cannot give a final answer. Known nuclei with Z = 114 are too neutron-deficient with respect to the N = 184 shell and nuclei with Z = 120 and beyond are still unknown. An option for studying superheavy nuclear systems in the region Z = 120 and with neutron numbers up to 184 becomes possible with the availability of intermediate heavy radioactive ion beams (RIBs) at Coulomb barrier energies. Fusion-evaporation residue cross-sections for isotopes in this region are in the sub-picobarn range and RIB intensities are small compared to the intensities of stable beams. However, the nuclear stability of superheavy systems and a possible influence of shell closures can also be probed by studying quasi-fission and fusion-fission reactions which have large cross-sections up to (10 – 100) mb. For example, the height of fission barriers is reflected by the competition between quasi-fission and fusion-fission.

The HIE-ISOLDE facility at CERN will provide in near future suitable RIBs with energies up to 5.9 MeV/nucleon. HIE-ISOLDE is presently assembled and will deliver first beams in autumn 2015. We have an approved proposal for a new experimental program at HIE-ISOLDE, which aims to study deep inelastic reactions in superheavy systems. As a first experiment we will investigate reactions of ^{A}Rb + ^{209}Bi ($Z_{Rb} + Z_{Bi} = 120$). HIE-ISOLDE can provide neutron-rich Rb beams which will allow to reach the total neutron number N = 184. The stability of the di-nuclear system and a possible influence of shell effects will be explored by investigating fusion-fission and quasi-fission reactions as a function of beam energy and neutron number of the projectile. As detection system we will use the CORSET setup from FLNR Dubna which allows for measuring the time-of-flight and energy of the reaction products and with this enables the determination of A and total kinetic energy TKE. The A and TKE distributions of quasi-fission and fusion-fission products, in turn, reveal information about the evolution of the nuclear system and the influence of shell closures.

Dynamics of Quasifission and Fission*

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We discuss the latest TDDFT calculations of quasifission and scission dynamics. Quasifission is the primary reaction mechanism that prevents the formation of superheavy elements in heavy-ion fusion experiments. We show recent results and analysis of quasifission calculated using the microscopic time-dependent Hartree-Fock theory [1-3]. Studied systems include ^{40,48}Ca + ^{238}U and ^{50,54}Cr + ^{180,186}W. Results for mass-angle-distributions (MAD) and contact times are presented as a function of orientation of the deformed nuclei with respect to collision axis as well as a function of impact parameter. We compare calculated MAD's to the corresponding experimental distributions. We discuss the dependence of various observables on isospin and elucidate the advantage of using neutron-rich nuclei in fusion experiments leading to superheavy elements. For the first time, we provide a microscopic calculation of fragment excitation energies. We also discuss the calculation of moments of inertia and the possibility of using TDHF to calculate P_{CN} values. With regard to scission dynamics we present results that show the effect of non-adiabaticity in comparison to the adiabatic treatment [4].

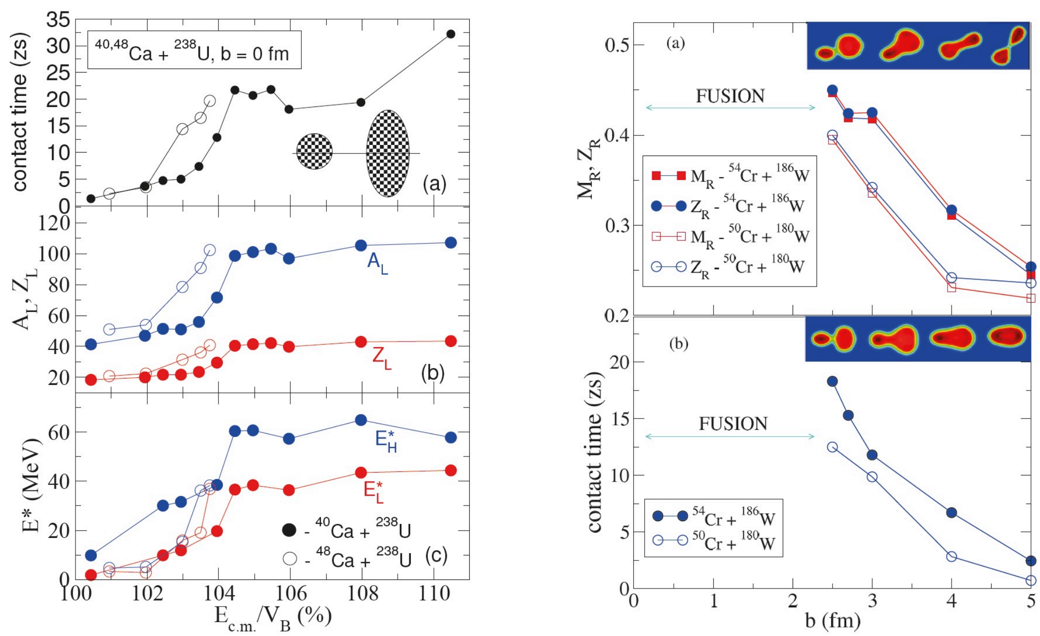

FIG. 1: Sample quasifission results for the reaction ^{40,48}Ca + ^{238}U, ^{50}Cr + ^{180}W, and ^{54}Cr +$^{1\,86}$W systems.

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New experimental approach to the super and hyper nuclei search

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Abstract

It is well known that the cross sections for super-heavy nuclei production are extremely low (σ≈ 1 pb for synthesis of Z=112 nucleus and σ≈ 0.5 pb for synthesis of Z=118 nucleus). For even heavier nuclei one can expect that the cross section is dropping into the region of tens of fb This creates a serious limitation for the technique being used so far. Moreover, the available combinations of the neutron to proton ratio of a stable projectiles and targets are very limited and it is difficult to be optimistic about the possibility to reach the island of stability of super heavy elements using complete fusion reactions with a stable projectiles. In this context, a new experimental investigation of mechanisms other than complete fusion of heavy nuclei and a novel experimental technique are introduced to our super and hyper nuclei search.

In-beam fission study at JAEA

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We will present results on in-beam fission experiments at the JAEA tandem facility. The first subject is the study of fusion-fission and quasifission in the reactions using actinide target nucleus ^{238}U and various projectile nuclei for the synthesis of super-heavy nuclei [1]. From the measurement of fission fragment mass distributions, effects of static deformation of ^{238}U on fusion were found. We will promote similar experiments using ^{248}Cm target, where we also installed neutron detector arrays to measure neutrons accompanied by fission to study reaction dynamics.

We also started an experiment to study multi-nucleon transfer reactions. The reaction would open access to neutron-rich heavy nuclei. As a first step we are measuring the fission fragment mass distributions for nuclei produced in the multi-nucleon transfer reactions in ^{18}O + ^{232}Th, ^{238}U, and ^{248}Cm. The data will be discussed in the framework of fluctuation-dissipation model [2].

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Prospects for Laser Spectroscopy at Superheavy Elements

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Laser spectroscopic methods will be reviewed which are of potential interest for the investigation of atomic and ionic level structures of superheavy elements. The latter are defined here as trans-fermium elements with Z > 100 for which no experimental atomic or ionic level structure information is known so far, and which cannot be bread in high flux nuclear power reactors via successive neutron capture. Potential laser spectroscopic methods are described, both as principles as well as illustrated with examples of real experiments. The methods include single ion spectroscopy in Paul traps [1], laser induced fluorescence spectroscopy (LIF) [2], radiation detected optical pumping (RADOP) [3], radioactive decay detected resonance ionization spectroscopy (RADRIS) [4, 5], and ion-guide-detected resonance ionization spectroscopy (IGRIS) [6]. With the exception of the first all take advantage of storage of the ions or atoms in rare gas traps.

The developed experimental methods can, in principle, also be employed for the study of ion chemical reactions with gas admixtures like O_2, as well as to perform ion mobility measurements [7]. Both provide complementary information on the electronic structure of superheavy ions. First attempts on this road of research will be reviewed as well if time is left.

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Chemical studies of the heaviest elements

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Chemical properties of the heaviest elements with Z>100 can only be measured in experiments with single atoms. Such studies give access to probing the structure of the periodic table and hence to studying the influence of relativistic effects – caused by the high nuclear charge – on chemical properties.

In my presentation, I will focus on recent highlight examples demonstrating the status and discuss the perspectives of the field. These include

- redox studies of No [1] and Lr [2] and a measurement of the first ionization potential of Lr [3]
- the synthesis of a Sg carbonyl complex [4] and its impact for SHE chemical studies
- the special role of Fl [5,6], which is currently among the hottest topics in SHE chemistry.

The expansion of the periodic table, leading to new elements, eventually becoming available for chemical studies, are of prime interest as well. I will briefly discuss the recent experiments performed at GSI Darmstadt on elements 115 [7], 117 [8] as well as the status of the search for elements Z=119 and 120.

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ADVANCED THEORETICAL STUDIES FOR CHEMICAL IDENTIFICATION OF THE SUPERHEAVY ELEMENTS

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A number of interesting experiments have recently been conducted on the gas-phase behavior of the heaviest elements 112 (Cn) and 114 (Fl) with respect to their homologs Hg and Pb [1,2]. Also, first attempts of the chemical characterization of element 113 were reported [3]. The aim of those investigations was to find out whether the new elements behave similarly to or differently from the lighter homologs in the chemical groups that may take place due to extremely strong relativistic effects on their electron shells.

Theoretical chemical studies render assistance to those sophisticated experiments with single atoms: they try to predict the behavior of the superheavy elements (SHE's) and help interpret experimental results [4]. For the gas-phase chromatography experiments, straightforward theoretical predictions of adsorption enthalpies, ΔH_{ads}, of the SHE systems on surfaces of detectors of the chromatography column were made in the past on the basis of cluster calculations for adsorption of atoms on metal surfaces (e.g., gold [5]), or physisorption models for adsorption of atoms and molecules on inert surfaces [6]. Periodic codes were until recently not suited for the solid state, or adsorption phenomena investigations on SHE's. With further developments of the relativistic quantum theory and computational algorithms, treatment of those phenomena has now become possible for $Z \leq 120$ using, e.g., the ADF code [7]. Accordingly, we started relativistic ADF BAND calculations of ΔH_{ads} of Hg/Cn, Pb/Fl, and Tl/element 113 on a gold and quartz surfaces using this program package. Also, very accurate calculations for smaller systems of the SHE's have been carried out using the DIRAC relativistic code [8].

In the talk, examples of such studies on the SHE's and their homologs are presented. A dramatic influence of relativistic effects on the properties and experimental behavior of the heaviest elements is discussed for these interesting cases. Perspectives of the theoretical studies in view of future experiments and new experimental techniques are outlined.

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Superheavy Element Chemistry from Switzerland

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More than 40 new isotopes of Superheavy Elements (SHE, Z>103) have been discovered in the last 10 years at the Flerov Laboratory of Nuclear Reactions, Dubna, Russia in ^{48}Ca induced nuclear fusion reactions with actinides. These discovery experiments observed isotopes of transactinides from Rf-118 with half-lives between milliseconds and several hours. Thus, an even broader experimental playground opened up for chemical investigations. These radiochemical experiments shall assess chemical properties of SHE and reveal the influence of relativistic effects in their electron structure, thus probing the structure of the most fundamental chemical ordering scheme available for elements – the periodic table. In appreciation of the main goal of the symposium, this report will be dedicated to gas phase chemical developments investigations that have potential for future highlight-research in this field:

A) Following the first glimpses on chemical properties of transactinides – Cn-Fl – those classical gas chromatography investigation schemes are revisited. Some developments of other gas phase chemical systems potentially suitable for the investigation of elements Cn, Fl, 113, 115, and Lv will be presented.

B) The recent observation of carbonyl compounds for elements of the transition metal series paves the way for the in-depth investigation of low oxidation states of these elements and further metal-organic chemistry, probably more sensitively assessing relativistic effects;

C) Recent developments are presented, showing our track to sub-second chemistry with SHE in vacuum potentially allowing for various experimental approaches.

D) Finally, potential problems shall be discussed arising from the low production cross sections for SHE requiring highly intensive heavy ion beams likely available at the newly build accelerator facilities and thus asking for new target technologies and further efficient background suppression.

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Chemical studies of the heaviest elements at JAEA

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Studies on chemical properties of the heaviest elements with atomic numbers $Z > 100$ are being performed using the JAEA tandem accelerator. Investigation of the chemical properties of such elements offers unique opportunities to obtain information about trends in the periodic table of the elements at the limits of nuclear stability, and to assess the influence of relativistic effects on chemical properties.

Redox studies of the heaviest elements are expected to give valuable information on valence electronic states influenced by strong relativistic effects, such as oxidation states and redox potentials. We conducted redox experiments of the heaviest elements based on an atom-at-a-time scale using a newly developed flow electrolytic column chromatographic method: oxidation of nobelium (No) and reduction of mendelevium (Md) [1, 2]. The new experimental approach, electrochemistry, to the heaviest elements with single atoms is briefly introduced.

The first ionization potential (IP_1) is an atomic property, which most sensitively reflects the outermost electronic configuration. Precise and accurate determination of the IP_1 provides significant information on the binding energy of the valence electrons and, thus, on increasingly strong relativistic effects. Recently, we successfully measured the first ionization potential of the heaviest actinide element lawrencium (Lr) using a surface ionization technique coupled to a mass separator. We will outline the experimental method and a result obtained from it. Prospects for the future studies on chemical properties of the heaviest elements at JAEA will be briefly discussed.

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Production and fabrication of actinide targets for super-heavy element research*

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Since 2000, six new super-heavy elements with atomic numbers 113 through 118 have been synthesized in hot fusion reactions resulting from ^{48}Ca beams on actinide targets. These experiments, developed and implemented [1,2] at the Joint Institute for Nuclear Research in Dubna, Russia, have directly or indirectly produced more than 330 nuclei of these elements and 50 new isotopes, substantially expanding our understanding of super-heavy nuclei and providing new information on the nuclear physics and chemistry of nuclei with extreme numbers of protons and neutrons. Many of these actinide materials have been obtained from Oak Ridge National Laboratory (ORNL) and from the Research Institute for Advanced Reactors (RIAR) at Dmitrovgrad, Russia.

Actinide target materials for super-heavy element research, including ^{242}Pu, ^{244}Pu, ^{243}Am, ^{245}Cm, ^{248}Cm, ^{249}Cf, and ^{249}Bk, are only available in limited quantities. Production, processing, and handling of actinide materials require specialized facilities including high-flux reactors and large-scale radiochemical capabilities that are available in only a few research centers worldwide. In this presentation, the production and chemical processing of heavy actinide materials for super-heavy element research is described, together with current availabilities of these materials and related target fabrication techniques. The impact and potential of actinide target materials in super-heavy element research are reviewed, including approaches for increased production of rare actinides such as ^{249}Bk, ^{251}Cf, and ^{254}Es.

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Investigation of the possibilities

of heavy actinide isotopes production in high-flux reactor PIK

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High Flux reactor PIK with the power 100 MW is now under construction in Gatchina near St.Petersburg. The power operation of the reactor is scheduled to 2018 year. Now the scientific program of the reactor is under consideration. The reactor has light water trap – the Center Experimental Channel (CEC) - where the thermal neutron flux is reached 5×10^{15} $cm^{-2}s^{-1}$. The cadmium ratio is equal to 8 in the central of the CEC. The CEC has its own coolant loop. The heat load on the samples in the CEC may be as high as 200 kW. There is a possibility to reload samples during the reactor operation. The reactor PIK has also places for samples irradiation in the reactor core where neutron spectrum differs considerably from the one in the center of the water trap.

In this work we are investigating the possibility of the production of long-lived isotopes of Cm, Bk, Cf and Es from different targets according to various scenario of irradiation. We have considered the samples irradiation in the CEC, in the core and both. The amount of different isotopes that can be produced in the reactor PIK has been obtained. The similar calculations have also been made for the reactor HFIR (USA). Comparison of the production rates has been carried on.

One of the main troubles in calculation of heave actinides production rates is the lack of nuclear reaction data. We have made random statistical evaluation of the ambiguities in the production rate for the most interesting isotopes and have found the main reactions and branching ratios that influence its production most of all.

Fabrication and characterization of actinide targets for super-heavy element studies

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For the production of neutron-rich isotopes of the super-heavy elements (SHE) up to Z=120 hot fusion reactions of actinide target nuclei such as ^{238}U, $^{242/244}$Pu, ^{248}Cm, ^{249}Bk and ^{249}Cf with light ion beams like ^{18}O, ^{22}Ne, ^{26}Mg, ^{48}Ca, ^{50}Ti or ^{54}Cr are applied. Be- or Ti-foils with a thickness in the µm-range are used as backing in order to prevent the production of nuclides whose decay interferes with the unambiguous identification of single SHE atoms, such as α-particle emitters or nuclides with a spontaneous fission decay branch. In order to decrease the thermal and mechanical stress on the target during irradiations with high beam intensities (up to 2 $\mu A_{particle}$) a rotating target is usually applied. In many cases the required actinide target material is available only in very limited amounts. Thus, the main requirements for the actinide target fabrication process are:

- Chemical purification of the material prior to deposition in order to reduce the background signals in the detection system from unwanted reaction products
- Backing foils should be pin-hole free and of uniform thickness over the entire target area
- Easy and complete recovery and subsequent chemical purification of the used actinide target material because of its scarcity and price
- A small and simple set-up of process
- High deposition yield

For the production of actinide targets painting is still used in selected cases to obtain thin layers with the requested thickness. However, targets produced with this technique might suffer from poor stability of the layer in long-term irradiation cycles. Sputtering can be used to produce layers of metallic uranium (^{238}U) on Ti or carbon backings. This method is limited by the availability of a (metallic) sputter-target. Taking into account the previously mentioned limitations Molecular Plating (MP) is currently the only production method for actinide targets in cases where the desired actinide material is available only in very limited amounts or possess a high specific activity. MP is well suited for the preparation of actinide targets on metallic (and non-metallic) backing materials with deposition yields approaching 100 %. Deposition is performed from organic solution applying a current density of 1-2 mA/cm^2. Under these conditions target thicknesses of 500-1000 µg/cm^2 are possible applying a single deposition step.

Characterization of targets (pre- and post-irradiation) is of utmost importance for the determination of physics parameters (overall yield, layer thickness and -homogeneity) and – equally important - for understanding the process of deposition (chemical composition of the deposited material, layer stability and -morphology). For yield determination α-particle spectroscopy, γ-spectroscopy and Neutron Activation Analysis (NAA) is frequently applied. Layer homogeneity can be checked with Radiographic Imaging (RI). Layer characterization with modern analytical techniques (e.g. XRF, XPS, SEM, AFM) is essential to understand target performance under long-term irradiations and to improve the current fabrication technology. To reach this goal a joint effort of the different laboratories involved in target preparation is irrevocable. This research should be conducted in close collaboration between the target makers, the target users and the accelerator specialists.

Actinide Materials at Oak Ridge National Laboratory

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Various actinides of interest to the super heavy element (SHE) community for the production of radioactive targets are present in limited quantities at Oak Ridge National Laboratory (ORNL). Possible recovery, production, and purification of select isotopes, such as ^{251}Cf, ^{249}Bk, and ^{248}Cm, will be discussed.

A californium product that was decay enriched in ^{251}Cf was recovered in 2012 and used to prepare targets for SHE discovery experiments. Californium-251 is a neutron-rich isotope capable of serving as ideal target material in SHE research for the potential discovery of heavier isotopes of Z=118. The enriched ^{251}Cf material was recovered from 17 of the aged ^{252}Cf neutron sources in storage at ORNL. These sources have decayed for over 30 years, thus providing material with a very high ^{251}Cf-to-^{252}Cf ratio. After the source capsules were opened, the californium was recovered, purified and then electrodeposited onto thin titanium foils for use in hot fusion experiments at the Joint Institute for Nuclear Research in Dubna, Russia. Additional aged sources are stored at ORNL and can potentially be recovered and used in future SHE experiments.

The production of ^{249}Bk at ORNL has always been in connection with the production of ^{252}Cf. The amount expected from future californium campaigns is only ~10 mg every two years. At this level of production, it will not be possible to meet the quantity of ^{249}Bk needed for future SHE targets. Production techniques, designed specifically for the production of ^{249}Bk using enriched ^{248}Cm targets and short irradiations periods have been proposed.

At ORNL, the current supply of highly enriched ^{248}Cm is primarily from the decay of ^{252}Cf. Because the half-life of ^{252}Cf is much shorter than the other isotopes of Cf produced during reactor irradiation, the resulting Cm daughter products are rich in ^{248}Cm and this Cm can be readily harvested. The current inventory of highly enriched ^{248}Cm (95 wt%) material at ORNL is 80 mg. Recovery of ^{248}Cm is planned to continue at ORNL from both the decay of new ^{252}Cf and from the processing of aged ^{252}Cf sources which will provide some additional small quantities (mg) of high weight percent (80-95 wt%) ^{248}Cm during the next few years.

FLNR SHE Factory

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The study of nuclear physical and chemical properties of recently discovered superheavy elements (SHE, Z = 112–118) as well as synthesis of new elements (Z>118) remain one of the most crucial tasks in modern science.

The new nuclides were synthesized in the fusion reactions between accelerated ^{48}Ca ions and nuclear targets ^{238}U, ^{237}Np, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Cf [1] and ^{249}Bk [2].

Further development implies the construction of a first-ever SHE factory at JINR FLNR. Ideas incorporated in the project of SHE Factory are associated with developing experimental base in several directions. These directions are:

- Construction of new powerful accelerator of stable and long-living isotopes in mass range A=10-100 with intensity up to 10 pμA and energy up to 8 MeV/nucleon;
- Construction of new experimental building and infrastructure for placing accelerator with five channels for transportation of beams to 1200-m^2 experimental hall, equipped with systems of shielding and control matching the 2 class of operations with radioactive materials;
- Development of new separating channels and development of new detection modules (including use of the already existing ones) for the study of nuclear, atomic and chemical properties of new elements;
- Production of new target materials and development of techniques of making targets with high thermal and radiation stability.

During the first phases (2015-2017) the scientific and technical studies are aimed at getting answers to key questions that determine further research at SHE FACTORY. This research includes the following:

- Study of the nuclei at the border of the «Stability island of SHE». Synthesis of neutron-deficient isotopes of Fl (Z=114) in reactions ^{239,240}Pu+^{48}Ca and of new isotopes of element 118 in reactions $^{249\text{-}251}$Cf+^{48}Ca;
- Change from ^{48}Ca to beam of ^{50}Ti with aim of preparing experiments on the synthesis of elements 119 and 120. Model experiment on the synthesis of the isotope ^{285}Fl in reactions ^{240}Pu+^{48}Ca and ^{238}U+^{50}Ti;
- Preparation of experiments at SHE FACTORY aiming on study of chemical behavior of elements 112-118 compared to their light homologues. Running control experiments with beam of ^{48}Ca. Development of separator and instrumentation.

The work was carried out with the financial support from the Russian Foundation of Basic Research (project code # 13-03-12205-ofi-m).

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The Super Separator Spectrometer (S^3) for the very high intensity beams of SPIRAL2

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And the S^3 collaboration

The Super Separator Spectrometer (S^3) will receive the very high intensity stable ion beams from the superconducting LINAG accelerator of SPIRAL2, with energies ranging from 0.75 to 14.5 MeV/u and currents beyond 1 pµA. 16 Letters of Intent have been submitted by a large physics community [1]. Special emphasis is on the study of rare nuclei, such as superheavy elements and neutron-deficient isotopes, produced by fusion evaporation reactions. S^3 includes a rotating target to sustain the high-energy deposition, a two-stage separator (momentum achromat followed by a mass spectrometer) that can be coupled to the implantation-decay station SIRIUS or to a gas catcher[2].

After reporting the present status of LINAG accelerator, SPIRAL2 project and S3, we propose a discussion on the target's issues with some results from GANIL beam tests irradiation.

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The Facility for Rare Isotope Beams

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The next generation radioactive beam facility in the U.S. is the Facility for Rare Isotope Beams (FRIB) which is currently being established at Michigan State University. FRIB is based on a 200 MeV/u 400kW superconducting linear accelerator. Initial capabilities include fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration. The science program of FRIB will cover discoveries about the properties of rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

FRIB will most likely not contribute to the direct search for new superheavy elements, however, the availability of high intensity reaccelerated neutron-rich beams could be used to extend the nuclear chart towards more neutron-rich superheavy nuclides.

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R&D activities towards a future cw LINAC at GSI

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Until 2017 the Universal Linear Accelerator (UNILAC) serves as a powerful high duty factor (25%) accelerator, providing heavy ion beams for the ambitious experiment program at GSI. Perspectively the UNILAC is designated as a high current synchrotron injector for FAIR (Facility for Antiproton and Ion Research). Beam time availability for SHE-research will be decreased due to the limitation of the UNILAC providing a proper beam for FAIR simultaneously. To keep the GSI-SHE program competitive on a high level, an upgrade program of the injector was initialized. As a result of a long term cost to performance benefit analysis a new energy variable sc cw-LINAC [1] in combination with the upgraded injector is assumed to meet the demands of the SHE-experimental program at its best [2]. Significant higher beam intensities will be provided and lead to an increase of the SHE production rate. The first LINAC section (financed by HIM and partly by HGF-ARD-initiative) comprising a sc CH-cavity embedded by two sc solenoids will be tested in 2015 as a demonstrator [3,4]. After successful testing, the construction of an advanced cryo module [5,6] comprising four additional CH cavities is foreseen. As an intermediate step towards an entire cw-LINAC the use of a double of two CH-cavities is planned: A shorter 8 cell cavity [7] should be mounted directly behind the demonstrator cavity inside the cryostat. The design of the cw LINAC based on shorter sc CH-cavities [8] would minimize the overall technical risk and costs. Besides, with this cavity an optimized operation of the whole LINAC especially with respect to beam quality could be achieved. The recent linac layout as well as the status of the demonstrator project and the first layout of the advanced test bench will be presented.

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Nuclear Structure revealed by High-Precision Mass Measurements

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High-precision mass measurements are a well-established method to investigate the nuclear structure evolution in exotic nuclides. Binding energies and indicators such as nucleon separation energies that can be derived from masses reveal nuclear structure features such as shell closures or the onset of deformation. Recent advances in slowing down high-energy beams from different nuclear reactions in buffer gas cells have opened the door to extend precision measurements in ion traps to essentially all elements. Mass measurements with Penning traps which provide masses with supreme accuracy reaching a level of 10^{-8} or below even for radionuclides are now also feasible for the heaviest elements. Based on the first direct mass measurements of nobelium and lawrencium isotopes performed with SHIPTRAP at GSI [1] the strength of the neutron subshell closure at N=152 has been mapped by the two-neutron shell gap [2]. Another feature of direct mass measurements is to provide firm anchor points pinning down alpha-decay chains in the mass surface. However, such precision measurements are technically very challenging in particular due to extremely low production rates. Advanced ion-manipulation methods and next generation-buffer gas stopping cells will allow us to push towards heavier elements in the future. In this contribution I will discuss the application of high-precision mass measurements for nuclear structure studies and review the recent SHIPTRAP experiments as an example.

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High efficiency recoil spectrometer for Superheavy Element Factory

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The experimental results of the last decade have shown a significant increase in stability in the region of superheavy nuclei.

Substantial increase in half-life of newly synthesized nuclei, as well as products of their sequential alpha decay gives us an opportunity for detailed study of the properties of these extremely exotic nuclei located on the limits of the Periodic Table.

Superheavy Element Factory, which is under construction in JINR Dubna will noticeably increase the production of heaviest nuclei. In this context a system that will be able to most effectively and rather fast accept products of complete fusion reactions becomes extremely important.

The concept of a new, highly efficient and selective spectrometer, designed for separation, collection and follow-up spectroscopy of the heaviest evaporation residues will be presented.

Opportunities to study the SHE production mechanism with rare isotopes at the ReA3 facility

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The new ReA3 reaccelerated beam facility at the National Superconducting Cyclotron Laboratory (NSCL) will provide high quality radioactive ion beams (RIBs), produced from fast fragmentation reactions, at energies around the Coulomb barrier. A gas-catcher, charge breeding ion source, and a linear accelerator have been developed to stop, ionize, and re-accelerate the RIBs at energies up to 3-6 MeV/u. Potentially, any RIB that can be produced from the fast fragmentation reactions will now be available for study at energies around the Coulomb barrier. These radioactive isotopes can have exotic properties such as neutron/proton skins, halos, or unexpected changes in their shell structure.

Heavy-ion fusion induced with medium mass RIBs remains almost completely unexplored as only three fusion reactions using RIBs, between fluorine (Z=9) and tin (Z=50), have ever been measured. A research program focused on the study of SHE relevant reactions induced with RIBs is being developed. New experimental devices at the ReA3 facility will offer the opportunity to explore the capture, fusion, and quasifission processes with neutron- and proton-rich beams. An overview of the ReA3 facility and available experimental devices will be presented.

Isospin Dependence of Quasifission and Heavy-ion Fusion with Neutron Rich RIBs

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The formation of super-heavy elements (SHEs) [1] is inhibited, by several orders of magnitude, by the premature breakup of the di-nuclear system via quasifission [2, 3]. The role of the variables influencing fusion and its complementary competitor quasifission have been investigated through the measurement of the mass-angle distributions of the binary fragments arising from a heavy-ion reaction [4-7]. Most recently the neutron richness of the composite system [7] was found to influence the quasifission flux.

Prior studies on the role of isospin in quasifission have produced conflicting results [8-12]. Our work [7] points to an increase in the fusion probability with increasing isospin, and favors the use of the neutron-rich projectiles for the production of heavy and super-heavy elements. I will present these results and also an overview of the Coincident Fission Fragment Detector (CFFD), a device being built at the ReA3 facility of the National Superconducting Cyclotron Laboratory. The CFFD provides a high efficiency, flexible and portable platform to study heavy-ion fusion reactions with stable and radioactive ion beams (RIBs).

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On-line separators for the Dubna Superheavy Element Factory

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Production cross sections of superheavy elements (SHE) with Z = 112 ÷ 118 in fusion reactions are in the range of a few picobarns or less. To get access to heavier nuclides and carry out a detailed study on their properties, a sufficient increase in the beam intensity and the development of separators providing the necessary background suppression are needed.

This is the main goal of the construction at the JINR's Flerov Laboratory of a first-ever SHE factory based on the high-current heavy-ion cyclotron DC280, having an experimental hall of 1000 m^2 designed in compliance with class II radiation safety requirements for work with high active targets made of transuranium isotopes.

By choosing the separation principle, we have analyzed cinematic characteristics of different products for several hundred reactions leading to the formation of heavy nuclei. Unfortunately, the use of only magnetic fields is inapplicable for fusion reactions. Thus, electrostatic separators (energy selectors), velocity filters, and gas-filled systems were considered. Further analysis showed that it is reasonable to construct 3 separators optimized for specific tasks:

I. The universal gas-filled separator for the synthesis and study of properties of heavy isotopes and the investigation of reaction mechanisms. The ion-optical layout QDQQD is chosen for this set-up. The R&D and technical design were conducted, and the parameters of magnetic elements were determined. The negotiations with potential manufacturers are currently underway.

II. The velocity filter is chosen for a detailed spectroscopic study of heavy isotopes. This separator, named SHELS, is manufactured, equipped and installed for testing and use at the beam of the U400 cyclotron. Upon the completion of the construction of the SHE factory, it will be moved into a new experimental hall. (See a special report of A. Yeremin to this conference).

III. To study radiochemical properties of SHE, extremely high suppression factors are not needed. One needs to work with thick targets at high beam intensities. Thus, we consider different versions of a simplified gas-filled QDQ system, gas-filled solenoid or multipole magnets. Coupled with a reaction product collection (RPC) chamber or a gas catcher, this set-up will serve as a pre-separator for further chemical separation and precise mass measurements, respectively.

Using LISE++ for heavy ion reactions at low energies

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The program LISE++ [1] is designed to predict intensities and purities for the planning of future experiments using radioactive beams with in-flight separators, as well as for tuning experiments where the results can be quickly compared to on-line data. Projectile fragmentation, fusion–evaporation, fusion–fission, Coulomb fission, and abrasion–fission reactions can be used as the production reaction mechanism to simulate experiments at beam energies close to the Coulomb barrier and above.

A relatively new model [2] for fast calculations of fusion–fission fragment cross sections and kinematics has been developed in LISE++ and tested in inverse kinematics experiment [3,4] at GANIL using an Uranium beam. Using these results the production mechanism at low energies has been significantly revised in the LISE++ framework that allows to obtain information about different channels and more accurately calculate compound formation cross sections. Four energy loss models, five ionic charge state models implemented in the code allows to cover a very broad energy region.

Large progress has also been achieved in ion-beam optics with the introduction of elemental blocks that enable a new type of configuration, labeled "extended (or elemental)" in addition to the classic "sector" configuration. Optical matrices can now be calculated within LISE++ (up to second order), directly input by the user, or linked to COSY maps (up to fifth order). This enables a detailed analysis of the transmission, useful for fragment separator design, and is a powerful tool to calculate angular acceptances, and display ion-beam optics characteristics.

Extended configurations of setups operating at low energy region such as "SHELS" (FLNR/JINR) (see Fig.1), "PRISMA" (LNL) (see Fig.2), "MARS" (TAMU), "LISE" (GANIL), "MSP144+Q2" (FLNR/JINR) have been recently developed [5] and incorporated in the LISE++ package.

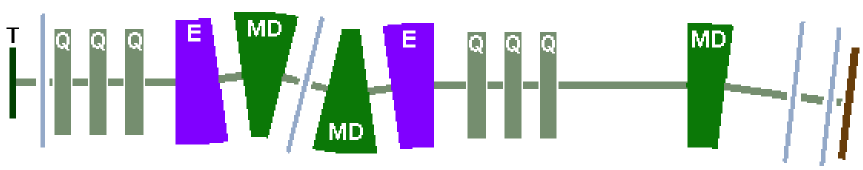

Fig.1. Layout of the "SHELS" separator (FLNR/JINR) in LISE++

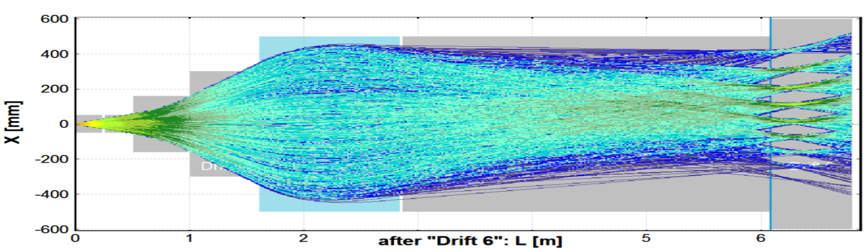

Fig.2. "PRISMA" (LNL) horizontal envelopes of ^{128}Xe ions produced in the reaction ^{136}Xe(6.4 MeV/u)+Pb

In relation to low energy physics these new LISE++ features will be demonstrated using some examples, and new developments such as transmission through gas-filled separators will be discussed.

The LISE++ package which includes also the PACE4, Global, Charge, Spectroscopic calculator codes can be downloaded freely from the following site: http://lise.nscl.msu.edu.

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Microsecond Activity from α-emitters observed at the DGFRS with Digital Electronics

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The "Hot Fusion Island" is formed by over 50 super heavy nuclei identified in fusion-evaporation reactions between ^{48}Ca beams and actinide targets [1–3]. Most of these nuclei have been discovered in experiments at the Dubna Gas Filled Recoil Separator (DGFRS). These studies have been recently augmented by using a new highly segmented Si detector and digital detection system [4] commissioned by the ORNL-UTK team and implemented at the DGFRS. The system has robust analysis capabilities, especially for very short lived activities.

A useful benchmark for this detection system has been the measurement of Th activities from the ^{48}Ca+^{nat}Yb reaction studied at the DGFRS. The direct observation of α-decay from 1-μs activity of ^{219}Th has been demonstrated for the first time at the DGFRS along with other similarly short lived activities. This system also led to the observation a spontaneous fission event that otherwise may not have been counted with analog electronics. This capability may be essential for experiments at the future SHE Factory at JINR.

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