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8th Workshop on
Recoil Separator for Superheavy Element Chemistry
October 14, 2009, GSI, Darmstadt, Germany

Program & Abstracts

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all contributions incl. five minutes discussion time
** Workshop photo at the top of ESR

Development of a new gas-filled recoil ion separator GARIS-II

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Introduction

One of the world's most active gas-filled typed recoil separator GARIS is operating at RIKEN. The separator has been used as a powerful tool for nuclear decay spectroscopy of superheavy element (SHE) nuclides produced via Pb/Bi-based fusion reactions (cold fusion). Recently, GARIS has gained some experience in more asymmetric actinide-based reactions (hot fusion) with the aim of studying physical and chemical properties of SHE. A gas-jet transport system coupled to GARIS as a pre-separator is a promising tool for next-generation SHE chemistry, i.e., identifying SHE nuclides under low background conditions with high efficiency of the gas-jet transport. However, we also encountered some difficulties in these hot fusion studies. First, transmission in GAIRIS becomes much lower for actinide-based asymmetric reactions, due to multiple scattering of the recoil ion by the filling gas atoms. Second, the background rate at the focal plane detector is 100~1000 times higher than the cold fusion case. Third, GARIS cannot transport recoil ions with Z>110 produced via ^{248}Cm-based fusion reactions as considering an equilibrium charge state in a helium gas by our empirical data.

Design & Characteristics

We designed a new gas-filled recoil ion separator GARIS-II [1]. GARIS-II was designed on the basis of extensive experiences with construction, development, and operation of GARIS. A gas-jet transport system coupled to GARIS-II as a pre-separator will be a promising tool for next-generation superheavy element chemistry, i.e., identifying SHE nuclides under low background conditions with high efficiency of the gas-jet transport. GARIS-II consists of five magnets arranged in a Qv-D-Qh-Qv-D configuration. This configuration is the first design for the purpose of SHE study. Ion optical characteristics were analyzed using the computer code TRANSPORT [2]. The solid angle is increased from 12.2 to 20.2 msr, approximately 1.7 times higher than GARIS. The total path length of the separator is 5.12 m. GARIS-II will be able to use various filled gas, such as He and He/H2 mixture. The separator will be able to transport the recoil ion with magnetic rigidity Bρ=2.44 Tm.

Q_v	Max field grad.	12.2 T/m
	Bore radius	150 mm
	Pole length	330 mm
D	Pole gap	150 mm
	Max field	1.69 T
	Deflecting angle	30 deg
	Radius of central ray	1440 mm
	Entrance angle	0 deg
	Exit angle	30 deg
Q_h	Max field grad.	4.70 T/m
	Bore radius	300 mm
	Pole length	250 mm
Q_v	Max field grad	5.27 T/m
	Bore radius	300 mm
	Pole lenght	450 mm
D	Pole gap	200 mm
	Max field	0.86 T
	Deflecting angle	7 deg
	Radius of central ray	2850 mm
	Entrance angle	0 deg
	Exit angle	-7 deg

Table 1 Characteristics of GARIS-II [1]

References

[1] D. Kaji et al.: RIKEN Accel. Prog. Rep. **42**, (2009) [In print].

[2] K. L. Brown et al.: SLAC Report **91** Rev. 1, 1974.

Element 114 produced in ^{48}Ca + ^{242}Pu at LBNL

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Production of numerous superheavy elements (SHE) in ^{48}Ca irradiations of actinide targets was reported by the Dubna Gas Filled Recoil Separator (DGFRS) group in past years [1]. Independent verification of these observations has been of paramount importance, but confirmation experiments failed to produce SHE in ^{48}Ca induced reactions. We report on the first successful independent verification of the production of element 114 in the reaction ^{48}Ca(^{242}Pu,3-4n)^{287,286}114 at a center-of-target energy of 244 MeV. Two genetically correlated decay chains were observed during 8-day experiment at the Lawrence Berkeley National Laboratory's (LBNL) 88-Inch Cyclotron. Based on the observed decay properties these decay chains were attributed to decay of ^{287}114 and ^{286}114 produced in 3n and 4n channel, respectively. Decay modes, lifetimes, and decay energies are consistant with those reported by the DGFRS group. The 1.4 pb cross sections measured in this work for both the 3n and 4n channels are lower than 3.6 pb and 4.5 pb, respectively, reported by the DGFRS group.

[1] Yu. Ts. Oganessian *et al.*, J. Ohys. G **34**, R165 (2007)

Experiment ^{48}Ca + ^{249}Bk and the Future Plans of Superheavy Elements Investigations in FLNR

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In experiments with accelerated ions of ^{48}Ca isotopes of superheavy elements with Z = 111 - 116 and 118 have been synthesized [1].

Synthesis of the element with Z=117 is necessary for producing the data concerning properties of more than 15 new superheavy isotopes which will be observed in decay chains.

The most perspective for synthesis of element Z=117 is the reaction ^{48}Ca + ^{249}Bk. This experiment is now running at the FLNR U400 cyclotron using the gas-filled recoil separator in collaboration with Oak-Ridge and Livermore national laboratories in the USA and the Institute for atomic reactors in Dimitrovgrad in Russia. Study of nuclear properties of new isotopes, and of chemical properties of superheavy elements with Z = 111, 113 are planned.

Another alternative is studying of reaction ^{50}Ti + ^{243}Am. However, the expected formation cross section of isotopes of element Z=117 will be lower, than in the case of berkelium target. For elaboration of optimum conditions of carrying out of experiments with ^{50}Ti and heavier ions the significant volume of preparatory researches will be conducted.

"Symmetric" combinations like ^{86}Kr+^{180}Hf, ^{136}Xe+^{136}Xe, ^{136}Xe+^{208}Pb, ^{150}Nd+^{150}Nd, and also reactions of type U + U, will be studied with the use of combined physical and radiochemical methods.

Realization of the offered program of scientific researches requires:

- modernization of cyclotrons U400 and U400M,
- a new experimental hall,
- new experimental set-ups,
- creation of a high-intensity accelerator of heavy ions.

For investigation of SHE the project of a new gas-filled separator having the optical configuration Q-D-Q-Q-D is prepared.

[1] Yu. Oganessian. J. Phys. G: Nucl. Part. Phys. **34** (2007) R165–R242

Measuring absolute transmission values of the RITU gas-filled separator

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Absolute transmission values through the RITU gas-filled recoil separator [1] has been measured in the Accelerator Laboratory of the University of Jyväskylä for several different fusion evaporation residues. For the transmission measurements three different stable isotope beams, ^{20}Ne, ^{40}Ar and ^{84}Kr, were taken from K130 cyclotron and for each beam several different target materials were used. In all reactions well known isotopes in mass region 170-190 were produced mostly in neutron evaporation channels. Also the pressure of the Helium gas was varied in the range between 0.2 and 1.8 mbar to achieve the largest transmission for each reaction. A reaction channel was identified using the JUROGAM Ge-detector array. At the RITU focal plane multi-wire proportional counter (MWPC) and double sided Silicon-strip detector (DSSD) were used to register the transmitted fusion products. Production yields for reactions channels used were large enough so that gamma-gamma coincidences could be used to achieve clear identification also without recoil tagging which is crucial when measuring the absolute transmission.

In the reaction $^{168}Er(^{20}Ne,4n)^{184}Pt$ the transmission of 7 % through the RITU to MWPC was obtained for ^{184}Pt. In the more symmetric reaction $^{150}Sm(^{40}Ar,4n)^{186}Hg$ the transmission was around 46 % and in the most symmetric reaction $^{92}Mo(^{84}Kr,2n)^{174}Pt$ the transmission was around 90 %. However, when symmetric reaction were used more scattered beam reached the focal plane. The optimal gas pressure was observed to be a function of reaction asymmetry. The magnetic rigidity of the products was seen to decrease monotonically in function of increasing gas pressure.

Additionally to the measured experimental transmissions, also the physical processes causing observed behavior will be discussed in more detail. Some principles of gas-filled separator modeling will be presented and results of simple fusion kinematics and ion-optical models applied to the studied reactions will be compared to the measured results.

References:
[1] M. Leino et al., Nucl. Instr. and Meth. B 99 (1995) 653

Performance of the gas filled separator TASCA – the $^{48}Ca + ^{206,207,208}Pb$ reactions

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A large variety of nuclear reactions were used during the commissioning phase of the TransActinide Separator and Chemistry Apparatus (TASCA). Among those, reactions of ^{48}Ca beam with Pb targets with masses 206, 207 and 208 leading to nobelium isotopes played an important role not only to characterize and understand TASCA but also to establish a well known reference system for the upcoming superheavy element program.

In this contribution, data will be discussed which were obtained with a SHIP-type position-sensitive Si-strip detector and data acquisition system, as it was used during the commissioning experiments

The main characteristics of TASCA such as optimized settings, transmission for nobelium isotopes as the $^{48}Ca + ^{206,207,208}Pb$ fusion-evaporation products, suppression factors for other reaction products and primary/scattered beam will be discussed for both modes of TASCA operation, The high transmission mode (HTM) and the small image-size mode (SIM).

Mean charges of the nobelium ions were determined in the helium and hydrogen filling-gas of TASCA at different pressures around 1 mbar. The observed dependence of the mean charge of nobelium ions on gas pressure was evaluated quantitatively. In addition, the results on the observed mean charge of nobelium ions in mixtures of helium and hydrogen gases will be presented.

TASISpec - Heading Towards the First Experiment

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A new nuclear spectroscopy setup called TASISpec (*TA*sca in *S*mall *I*mage mode *Spec*troscopy) was designed and commissioned in 2008. It exploits TASCA's unique so-called small image mode where the produced SHE can be focused into an area of less than 3 cm in diameter. This provides the possibility to place composite Ge-detectors very closely around the focal plane, resulting in a highly efficient detection of γ-rays and X-rays in coincidence with implanted SHE.

The test setup as used in the commissioning experiments in 2008 is illustrated in Fig.1A. It has been explored using a handful of different reactions to establish the properties of the setup. Furthermore, different electronics schemes have been used to optimise the device and enhance its versatility.

In the G-PAC meeting in February 2009 TASISpec was granted seven days of main and 28 days of parasitic beam time. The main beam experiment is planned to take place in the beginning of 2010 and will be used to run the $^{207}Pb(^{48}Ca,2n)^{253}No$ reaction to fully establish the tentative decay scheme [1], which is illustrated in Fig.1B. While new G-PAC proposals are going to be based on the experimental characterisation of TASISpec arising from that run, ideas for subsequent physics cases are going to be presented. The parasitic beam time will be used to explore different possible beam-target combinations as well as hardware and software improvements for future SHE experiments with this detection system.

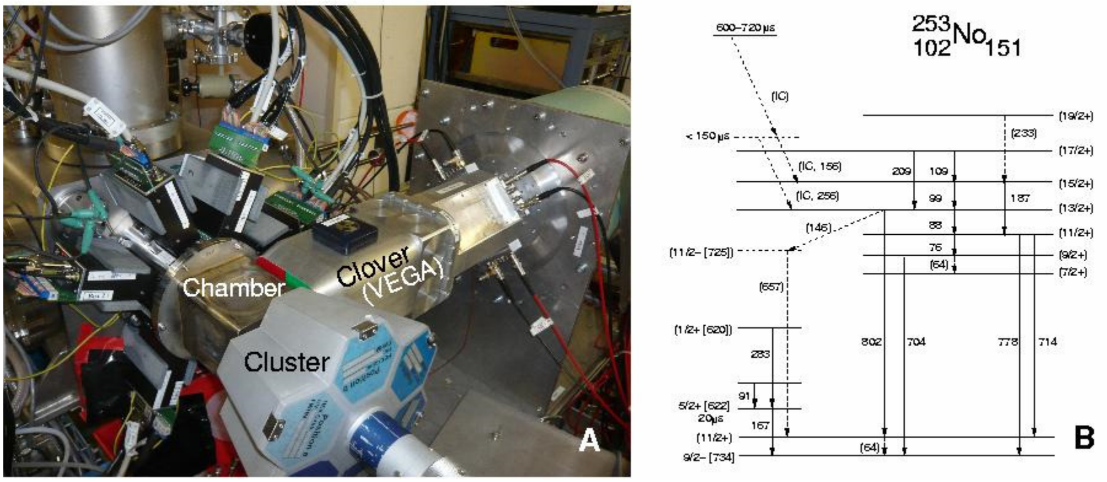

Figure 1: A) The TASISpec set-up installed at the focal plane of TASCA. B) The tentative decay scheme of ^{253}No from Ref.[1].

[1] F.P. Hessberger, Physics of Atomic Nuclei **70**, 1445 (2007).

[1]Thanks to the RISING collaboration for the use of detectors and electronics.

Studies of the reaction $^{244}Pu(^{48}Ca,3\text{-}4n)^{288,289}114$ at TASCA

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In the past few years, the new gas-filled TransActinide Separator and Chemistry Apparatus TASCA was installed and commissioned at the GSI in Darmstadt. The year 2008 marked the transition from commissioning towards a science-driven program. As a first highlight experiment in the region of the heaviest elements, the reaction $^{244}Pu(^{48}Ca,xn)^{292-x}114$ was studied in the Summer of 2009.

During the past decade, the Dubna Gas-Filled Recoil Separator (DGFRS) group reported the discovery of new elements up to 118. Only a minor part of these claims has been independently verified so far.

The main goal of our experiment was broader than pure replication of published data. The studied reaction is claimed to lead to the superheavy element 114 with a rather large cross section of about 5 pb. The isotopes produced in the 3n and 4n channel of this reaction, $^{289}114$ and $^{288}114$, respectively, are reported to be long-lived enough for gas-phase chemical experiments with reported half-lives of $T_{1/2}$ ($^{289}114$) = $2.6^{+1.2}_{-0.7}$ s and $T_{1/2}$ ($^{288}114$) = $0.80^{+0.27}_{-0.16}$ s. As an experiment on the chemistry of element 114 is scheduled at TASCA for September 2009, a preceding experiment verifying the cross section and lifetimes of the foreseen isotopes was paramount. Even more so as all of the independent verification experiments reported cross sections lower than those reported from Dubna.

Measurements of an (at least partial) excitation function to reliably determine the maximum cross section of the $^{48}Ca+^{244}Pu$ reaction as well as of the magnetic rigidity of the produced element 114 isotopes in pure He with good statistics together with the desire for more accurate nuclear data of the evaporation residues were most important in the design of the experiment.

At the workshop, a preliminary account of the experiment will be given.

SHE related developments at GANIL: latest experiments, S^3 and targets

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In a near future, GANIL facility will be upgraded with a superconducting linear accelerator, LINAG which would deliver very high intensity stable beams of heavy ions and deuterons. On one hand, this deuterons beams impinging on a converter will produce neutrons which will induce fission of UCx targets. So the SPIRAL2 fission fragments beams will provide very high intensities of heavy, neutron rich ions. Specially, $^{137\text{-}141}$Xe isotopes will be accelerated with intensities above 10^{10} pps. They could allow for the production of new neutron rich super-heavy isotopes.
In this framework, using the LISE Wien filter for separation, we have studied the fusion reaction of a ^{136}Xe high intensity beam on a ^{124}Sn target in order to produced Rf through the 1-3 neutron evaporation channels. The experimental process and the latest results of this experiment will be detailed.

On the other hand, S^3 (Super Separator Spectrometer) is a device designed for experiments with the very high intensity stable beams of LINAG, which will be built in the framework of SPIRAL2. These beams, which will provide in a first phase of SPIRAL2 ions with A/q = 3, can reach intensities exceeding 100 pμA for lighter ions - A < 40 - 50.

These unprecedented intensities open new opportunities in several physics domains, e.g. super-heavy and very-heavy nuclei, spectroscopy at and beyond the drip-line, isomers and ground state properties, multi-nucleon transfer and deep-inelastic reactions and why not chemistry ?
The Super Separator Spectrometer S^3 includes a rotating target to sustain the high power deposition, a two stages separator (momentum achromat) and spectrometer (mass spectrometer). Various detection set-ups are foreseen, especially a delayed α, γ, and electron spectroscopy array and a gas catcher coupled to a low energy branch.

The S3 project will be reported and an emphasis will be done on the need of targets with their requested development such as CACAO project.

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*The authors emphasize that S^3 is the work of a wide collaboration from which they are the spokespersons. They thank all the present and future contributors of this project.

UNILAC upgrade programme for the SHE research

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In order to increase the average beam intensities for the super heavy–element research at GSI, an upgrade program of the High Charge State Injector (HLI) consisting of three steps is in progress. The first step will take place in 2009 by replacing the old Radio Frequency Quadrupole-accelerator (RFQ). The new one features increased beam acceptance and duty factor capabilities up to 100%, while the present RFQ is limited to 25%. The main upgrade will be a new superconducting ion source of ECR type. This source is expected to deliver about one order of magnitude higher beam intensities and to allow the use of higher charge states. In order to use the new source alternatively to the CAPRICE ion source operated now, a second Low Energy Beam Transport line is now in the design phase. Its commissioning is planned for 2011.

With these upgrade measures the HLI will be able to deliver intense ion beams at 1.4 Mev/u continuously. The existing UNILAC will reasonably not be capable of more than 50% duty factor. Moreover, simultaneous operation of high duty factor beams interleaved with short pulses with very high rf amplitudes is not favourable. Therefore it is intended to work out a new high energy linac fed by the upgraded HLI. This linac should accelerate the highly charged ions with charge-to-mass ratio of 1/6 with up to 100% duty cycle. The output beam energy will be adapted to experiments at the Coulomb barrier and will be variable from 3.5 MeV/u to 7.5 MeV/u. The energy spread at the exit is foreseen not to exceed 3 keV/u over the whole energy range.

A superconducting linac, operated at 100% duty factor and delivering high luminosities on the target, is a very attractive solution for this machine.

Direct Mass Measurements of Transuranium Elements with SHIPTRAP

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for the SHIPTRAP collaboration

Nuclear ground state properties represent key information on nuclear matter at the borderline of nuclear existence. The region of the superheavy elements that owe their stability to shell effects is of particular interest. In the last decades new elements up to Z = 118 have been synthesized on route towards the next spherical shell closures above ^{208}Pb that are predicted around Z ≈ 120 and N ≈ 184. For a deeper understanding of the structure of superheavy elements accurate data on the properties of nuclides in the region Z > 100 such as half-lives, masses, and energies of excited states are crucial. These nuclides are now accessible for high-precision mass measurements with the Penning trap mass spectrometer SHIPTRAP at GSI. In 2008, the first direct high-precision mass measurements of the nobelium isotopes $^{252-254}$No (Z = 102) have been performed. Recently the experiments have been extended to ^{255}Lr. The experiments are very challenging due to the low production rates of less than one ion per second that was entering the SHIPTRAP stopping cell in the case of ^{255}Lr. Our experiments are the first direct mass measurements in the region above uranium. The new, directly measured nobelium masses provide accurate reference points in this mass region and by α-decay links accurately determine the masses of heavier nuclides up to Ds (Z = 110). The experiments have paved the way for a new class of high-precision experiments on transactinides with ion traps. In combination with laser spectroscopy and trap-assisted decay spectroscopy new accurate data on ground state properties of transactinides are now in reach.

In-beam Spectroscopy at Cave X8?

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on behalf of the AGATA Collaboration

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Following the start-up phase and about a year of physics experiments at Legnaro National Laboratory, the pan-European Advanced GAmma-Ray Tracking Array (AGATA) is envisaged to be operational at GSI in spring 2011, primarily for in-beam studies of relativistic radioactive ion beams in the focal plane of the Fragment Separator (FRS) until about mid 2013. The limited SIS/FRS beamtime enables in addition unique experimental programmes at the UNILAC with these extremely powerful composite and segmented Ge-detectors at GSI. One such option could be recoil-decay tagging experiments in cave X8; the AGATA Ge-modules would cover part of the target area, TASCA is used to separare reaction products of interest, and the existing Munich DSSSD (TASCA high transmission mode) or TASISpec (TASCA small image mode) in the TASCA focal plane are used to tag the rare primary ‘needles’. Note that any such programme should focus on ‘GSI-only’ beams combined with unsurpassed instrumentation.

Synthesis of superheavy nuclei: A search for new production reactions

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Frankfurt Institute for Advanced Studies, Frankfurt, Germany

Nuclear reactions leading to the formation of new superheavy elements and isotopes will be discussed in the talk. “Cold” and “hot” synthesis, fusion of fission fragments, transfer reactions, and reactions with radioactive ion beams have been analyzed along with their abilities and limitations. We found that there are several very promising possibilities for the synthesis of new superheavy elements and isotopes. First of all, the titanium beam (instead of ^{48}Ca) and actinide targets may be used to move forward up to element 120. The estimated evaporation residue cross sections are rather low (at the level of 0.1 pb) but quite reachable at available setups. If the experiments with a titanium beam will confirm our expectations, then we have to find a possibility to increase the beam intensity and the detection efficiency (by a total of one order of magnitude) and go on to the chromium and iron beams aiming at elements 122 and 124. The use of light- and medium-mass neutron-rich radioactive beams may help us to fill the gap between the superheavy nuclei produced in the hot fusion reactions and the continent of known nuclei. Such a possibility is also provided by the multi-nucleon transfer processes in low-energy damped collisions of heavy actinide nuclei, if the shell effects really play an important role in such reactions. Moreover, in these reactions the neutron-rich superheavy nuclei located in the middle of the island of stability might be also produced with noticeable cross sections. The production of superheavy elements in fusion reactions with accelerated fission fragments looks less encouraging. Only if an extremely high beam intensity were to be attained would the chances increase.