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A Brief Overview of Recent Activities in Superheavy Element Research at GSI

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The research on superheavy elements is of great interest in atomic and nuclear physics as well as in chemistry. One the one hand side these very exotic nuclides at the upper end of the nuclear chart owe their very existence to nuclear shell effects that stabilize them against immediate disintegration by spontaneous fission. On the other hand these elements experience very strong relativistic effects that impact their electronic structure and their chemical properties. At the GSI Darmstadt and the Helmholtz-Institute Mainz a comprehensive approach is followed addressing all these different research areas in experiments utilizing a suite of experimental installations. These comprise the recoil separators SHIP and TASCA, the Penning trap mass spectrometer SHIPTRAP, the chemistry beam line ARTESIA, and numerous versatile setups for gas-phase chemistry, laser spectroscopy, mass spectrometry, and decay spectroscopy of the heaviest elements. In this article select recent highlights are briefly reviewed and some of the most relevant developments for future experiments are addressed.

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1. Introduction

The research of superheavy elements (SHE)[2] has attracted interest from atomic and nuclear physics as well as from chemistry for many decades. Since the early predictions of these exotic elements that owe their existence to nuclear shell effects in the late 1960s [1,2,3,4] tremendous efforts have been undertaken to synthesize ever-heavier elements trying to reach the so-called island of stability [5,6,7]. In addition, more and more sophisticated experiments have been set up to determine their nuclear, atomic, and chemical properties. Key questions driving these activities are to determine the location and extension of the island of stability and how the well-known architecture of the periodic table will change due to strong relativistic effects.

In a description based on a liquid drop model nuclei with proton numbers of $Z \approx 104$ and above are no longer stable against spontaneous fission and would thus disintegrate immediately. However, the binding energy gained by nuclear shell effects results in their survival even with as many as 118 protons according to the latest claims for the synthesis of such elements by collaborations working at the Flerov Laboratory in Dubna/Russia [8]. Theoretical predictions for the location of the island of stability, linked to the next spherical shell closures beyond ^{208}Pb, still differ between proton numbers Z = 114, 120, 126 and neutron numbers N = 172, 184 depending on the nuclear model used [9,10,11,12]. Moreover, nuclear models predict the shell effects in superheavy nuclei (SHN) to be rather smeared out in comparison to lighter nuclei so that extended regions of shells stabilization rather than distinct magic numbers are expected [13,14].

Strong relativistic and quantum electrodynamics effects experienced by the electrons in very heavy atoms make them a prime laboratory for atomic physics and chemistry [15,16,17]. These effects influence the atomic structure and the chemical properties significantly and lead to very distinct properties. For example, Pitzer predicted about 40 years ago that elements Fl, a member of group 14 in the periodic table and a homolog of Pb, might be an inert gas [18]. In order to improve our understanding of all aspects of superheavy elements, joint theoretical and experimental efforts are required pushing to the limits of the nuclear chart and the periodic table. It is crucial not only to continue the quest for the island of stability, but also to perform in-depth studies of the atomic, chemical, and nuclear properties of the heaviest known elements. To this end, state-of-the-art techniques in single-atom chemistry [16], laser spectroscopy [17], nuclear decay spectroscopy [19], and high-precision mass measurements [20] are employed. However, a major experimental challenge faced in all investigations of the heaviest elements arises from the low rates at which they are produced in nuclear fusion reactions at today's accelerator facilities. Thus, the experimental techniques have to be pushed to their sensitivity limits and the setups to the maximum efficiency. At the same time new accelerators providing higher primary beam intensities in combination with advanced target technologies are required.

1.1 Production and separation

The elements above uranium up to fermium (Z = 100) can be bred in high-flux nuclear reactors by successive neutron capture and subsequent beta decay, still in weighable quantities. Heavier elements, however, have to be produced by nuclear fusion-evaporation reactions. Those

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[2] In this article SHE are considered as transactinide elements with atomic number $Z > 103$.

are commonly distinguished according to the resulting excitation energy of the compound nuclear system formed: Reactions of medium-heavy ion beams from ^{48}Ca to ^{70}Zn with Pb and Bi targets are referred to as ‘cold’ fusion, whereas reactions of beams like ^{48}Ca or ^{50}Ti with actinide targets are referred to as ‘warm’ or ‘hot’ fusion reactions. Depending on the excitation energy the compound nucleus evaporates one or two neutrons (cold fusion) up to four or five neutrons (hot fusion). The production rates achievable with present accelerators range from a few particles per second for microbarn cross sections down to about one particle every few days for of picobarn cross sections at primary beam intensities of about 5 x 10^{12} particles per second. The synthesis of superheavy elements is reviewed in several recent articles; see for example [5,6,7]. A prerequisite for the investigation of such exotic nuclides is the efficient separation of the evaporation residues from the primary beam. To this end electromagnetic recoil separators are utilized. At the GSI in Darmstadt/Germany two such separators that nicely complement each other are presently operated. The velocity filter SHIP separates the reactions products from the primary beam according to their velocity by electromagnetic fields in vacuum with typical flight times of two to three microseconds [21]. SHIP has been used for the discovery of the elements with Z=107-112 [22]. SHIP is very well suited for decay spectroscopy due to a low gamma ray and neutron background in the focal plane. The compact gas-filled separator TASCA in a dipole-quadrupole-quadrupole configuration separates the ions according to their magnetic rigidity in about 1 mbar helium gas (or hydrogen-helium mixtures) [23]. It provides high transmission efficiency for reaction products from (more asymmetric) reactions with projectiles like ^{48}Ca and ^{50}Ti and actinide targets such as ^{243}Am, ^{249}Bk, and ^{249}Cf and a short flight time of about one microsecond. It has been used for example to perform experiments on elements with Z=114, 115, and 117 recently [24,25,26].

1.2 Search for new elements with Z > 118

The heaviest element for whose existence experimental evidence was reported by collaborations working at JINR in Dubna/Russia is element $Z = 118$ [5,7]. In the past decades a large body of experimental data on nuclides assigned to elements with atomic numbers from $Z =$ 113-118 has been reported [5,7,24,25,26]. The cross sections for the production of these nuclides have been surprisingly constant on a level of 1-10 picobarn. In recent years independent experiments performed at LBNL Berkeley [27], at TASCA [24] and at SHIP at GSI [28] have confirmed the observed decay chains from Dubna to a large extent. The latest result in this context was the observation of two decay chains in a two-week irradiation of a ^{249}Bk target with ^{48}Ca at TASCA [26]. The data are in agreement with results observed at Dubna and assigned to $Z = 117$ [29]. However, despite all the recent experimental progress the assignment of these elements is mainly based on cross bombardments and alpha decay systematics, while a direct experimental determination of the atomic number of any of these elements has yet to be made. This is of particular importance for the odd-Z elements $Z = 113,115,117$ with their intricate decay schemes. One method for Z identification is provided by α-x-ray spectroscopy as attempted for element 115 recently [25]. An alternative would be a direct mass (number) measurement in combination with α-spectroscopy as for example planned at LBNL [30].

For the synthesis of new elements with atomic number $Z > 118$ heavier beams than ^{48}Ca have to be used, for example ^{50}Ti or ^{54}Cr. This is expected to result in a significant reduction of the cross section to a level of 0.01-0.1 picobarn for the synthesis of $Z = 119$, 120 according to recent theoretical predictions [31]. In all experimental attempts for the synthesis of elements with Z = 119,120 made so far no event was observed leading to cross section limits as low as about 0.1 picobarn [32]. Thus, experiments for the synthesis the next new elements will have to reach sensitivities on the ten-femtobarn level. To accomplish this in a reasonable beam times new accelerators are required that provide at least one order of magnitude higher beam intensities. At GSI and HIM a project for a new continuous-wave linac is underway. The status of the so-called demonstrator of this superconducting machine is described in [33, 34].

1.3 Decay Spectroscopy of the heaviest elements

In order to determine the evolution of single particle energies in the heaviest elements decay spectroscopy is a powerful tool [19]. Due to the limited yields for the nuclides of interest high-statistics experiments are presently feasible to the region of neutron-deficient isotopes in the region $Z = 100$, $N = 152$, and to a lesser extent in the region around $Z = 108$, $N = 162$. Using in-beam spectroscopy techniques for example rotational bands have been observed up to ^{256}Rf [35] providing experimental information about the deformation of these nuclides.

At GSI a comprehensive decay spectroscopy program of neutron-deficient nuclides with atomic numbers from $Z = 100$-108 has been performed in the focal plane of the recoil separator SHIP and a large body of data has been obtained in systematic studies [36]. In addition, studies of so-called K-isomers have been performed even up to Ds (Z=110) [37]. Recently the TASISpec detector system has been constructed [38]. This versatile alpha-gamma spectroscopy setup has been optimized for the use in focal plane of TASCA and offers very high gamma efficiency due to a compact detector geometry that allows placing up to five Ge detectors around the implantation region. TASISpec was employed for α-photon spectroscopy on decay products originating from $Z = 115$ in the irradiation of a ^{243}Am target with ^{48}Ca beam at TASCA [25]. This experiment was originally designed to determine the atomic number experimentally by characteristic x-rays and indeed two Candidates compatible with x-rays have been observed tin the decay of Mt, but due to limited statistics and unfavorable multipolarities of the relevant transitions an unambiguous Z assignment was not possible yet [25]. However, valuable nuclear structure information was obtained in the region of the heaviest elements that is important for the improvement of nuclear models.

1.4 Mass spectrometry

High-precision mass measurements are a well-established technique to study the nuclear structure evolution in exotic nuclides [39]. The mass itself provides the binding energy and by mass differences like the nucleon separation energies one can identify for example the location of shell closures and the onset of deformation. In regions of (unknown) nuclides far off stability masses often provide a first indicator of new nuclear structure effects. Penning trap mass spectrometry (PTMS) is presently the technique yielding the highest precision on a level of about 10^{-11} for stable nuclides and on the order of 10^{-8} for radionuclides [40,41]. The elements above fermium (Z=100) produced by fusion reactions are meanwhile also accessible by PTMS in combination with buffer gas stopping techniques [20]. This has been recently demonstrated in pioneering experiments on nobelium and lawrencium isotopes around N=152 [42,43] with the SHITRAP Penning trap mass spectrometer that is installed behind the velocity filter SHIP at GSI. These measurements have allowed mapping the strength of shell effects at N=152 precisely

[43], a weak deformed shell closure. In addition these first direct mass measurements in nuclides above uranium have provided reliable anchor points in this mass region [44] fixing the position of decay chains in the mass surface. They have also improved the masses on many other nuclides in the region by exploiting well-established decay links [44]. The same approach was followed in conjunction with recent measurements of Am, Pu, and Cf isotopes at TRIGATRAP where the mass of 84 nuclides could be improved [45].

The major challenge in extending these measurements to more exotic and heavier elements is given by the very low production rates. Thus, two key developments are under way at SHIPTRAP in order to further improve the efficiency and sensitivity of PTMS further. First, a cryogenic stopping cell has been set up to increase the stopping and extraction efficiency [46]. In addition, a detection setup for single-ion mass measurements based on the Fourier-transform ion-cyclotron resonance technique is under development [47].

1.5 Developments towards laser spectroscopy of the heaviest elements

Precision measurements of atomic properties such as level energies, lifetimes of atomic, states, and transition strength can be obtained using laser spectroscopy techniques. In addition, hyperfine spectroscopy gives access to nuclear properties such as the spin as well as magnetic and quadrupole moments in a nuclear model-independent way. The measurements of isotope shifts of spectral lines provide access to changes in the mean square charge radius and thus allow studying nuclear deformation. In recent years a large number of new data have been obtained on more and more isotopic chains across the nuclear chart [41, 48]. However, in the region of the heaviest elements experimental information on the atomic structure is available yet. For fermium, the last element that be obtained in weighable quantities, several atomic levels had been identified [49] and also hyperfine spectroscopy was performed even though the individual hyperfine components could not be resolved [50]. In order to study the heavier elements that can only be produced online in small quantities, the established methods have to be adapted pushing them to their limits in sensitivity and efficiency. Resonance ionization spectroscopy (RIS) is one of the most sensitive methods for laser spectroscopy of radionuclides. The radiation-detected RIS variant where the laser created ions are detected by their nuclear decay is suitable for cases when nothing on the electronic structure is experimentally known and production rates minute. This has been demonstrated in studies of short-lived Am fission isomers [51].

Recently, a setup optimized based on this RIS method along with a versatile laser system based on Excimer-pumped dye lasers has been installed at GSI. The setup has been designed and optimized for laser spectroscopy of the element nobelium. This element has a favorable electronic structure and can be still produced with relatively high yields. Commissioning experiments performed on ytterbium, the chemical homologue of nobelium, have shown that an overall efficiency sufficient for a level search in nobelium can be achieved [52]. In addition, the evaporation temperature of nobelium from a tantalum filament has been measured laying the ground for the atomic level search in nobelium [53]. State-of-the-art theoretical models predict the $^1P_1$ level at about 30000cm^{-1}, but with a rather uncertainty on the order of 1000 cm^{-1} limited by electron-electron correlations. Hence, for a typical bandwidth of the employed lasers on the order of 1 cm^{-1} a large range has to be covered in such a search experiment. Once an atomic level has been found additional levels can be searched for and eventually the ionization potential can be determined from a Rydberg series. Presently, in this region only the ionization potential of Lr (Z=103) is experimentally known [54], however only with moderate precision that be further improved in future laser spectroscopic measurements. Later on isotope shift measurements of different spectral lines in the neighboring isotopes of ^{254}No can be performed to determine their deformation. Such measurements will complement the results obtained from decay spectroscopy nicely.

1.6 Conclusions

Research on the heaviest elements remains at the forefront of nuclear and atomic physics and chemistry at accelerator-based research facilities worldwide. Besides the ongoing quest to conquer the island of stability that demands the construction of new accelerators and improving the experimental devices and method further. The research groups at the GSI and HIM are active in all relevant areas following a comprehensive approach in SHE research. In particular the full suite of world-class equipment provides a sound basis for cutting-edge science also in the near future.

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