SHE Research at GSI — Achievements and Plans

G. Münzenberg[*,a,b]

[a]*Gesellschaft für Schwerionenforschung, GSI mbH, Planckstr. 1, 64291 Darmstadt, Germany*
[b]*Johannes Gutenberg-Universität Mainz, Germany*

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Experimental methods for heavy element research will be presented. Recent experimental results are discussed together with recent theoretical predictions. New instrumental developments and future plans will be discussed.

1. Introduction

Heavy-element research explores the borderline of the nuclear chart towards its upper end where the strong Coulomb force acting between the many protons dominates the nuclear stability and finally terminates the number of elements by instability against fission. The longstanding question is whether nuclei can exist beyond that macroscopic limit only by microscopic stabilization through shell effects. These superheavy elements are predicted for the next double shell closure above lead located at $Z = 114$ and $N = 184$,[1] according to the early predictions, and $Z = 120$, $N = 184$ for recent calculations.[2,3]

A first exciting experimental result related to this question was the discovery of the shell stabilized elements seaborgium and hassium[4,5] which are part of a microscopic stabilized region of deformed nuclei centered at $Z = 108$ and $N = 162$.

Element 112, the heaviest element unambiguously identified at present[6] by the parent-daughter α-α correlation method is already quite close to the superheavy region in proton number. Recent results published by the Dubna group indicate the discovery of elements 114 and 116, already located in the predicted superheavy region.[7] The presently known nuclides of the transfermium elements are shown in the portion of the chart of nuclei presented in Figure 1.

The principal experimental problems of heavy-element research are the small production rates of less than one atom per week achievable with the present technical possibilities and the short half-lives ranging down to milliseconds.[8] Therefore the key technique used for the discovery of the heaviest known elements relies on the investigation of single atomic nuclei[9] separated in-flight and identified by the parent-daughter correlation method.

To further explore the region of superheavy elements a number of experimental developments are needed such as more intense heavy-ion beams to produce a number of atoms in few weeks of experiment and a direct mass and element determination identification to identify the neutron rich nuclei around the superheavy double shell closure, far away from the known transactinide isotopes, and not reachable by α-decay chains proceeding from these superheavy nuclides.

2. Production of Superheavy Elements

All artificial elements beyond fermium have been first created by complete fusion of heavy ions. Two types of reactions have been used successfully so far: the cold heavy-ion fusion of lead or bismuth targets with appropriate projectiles of the most neutron rich isotopes available, such as ^{64}Ni and ^{70}Zn for the production of elements 110, 111, or 112, and the hot fusion of actinide targets[7] such as ^{244}Pu or ^{248}Cm with ^{48}Ca projectiles to produce elements 114 and 116.

Cold fusion is characterized by a low excitation energy of the compound nucleus of 10 MeV to 15 MeV, while hot fusion leads to excitation energies of typically 30 MeV to 40 MeV. As the fissility increases for the heaviest elements the survival probability becomes of increasing importance towards the heaviest elements, cold compound systems are expected to have an enhanced survival probability.[10] As a consequence cold fusion should be favorable to create the heaviest elements.

On the other hand fusion of massive systems is hindered in the entrance channel by the large Coulomb force which acts between target and projectile and the rearrangement of the large number of nucleons on the way from the dinuclear to the mononuclear system. In the frame of this picture the synthesis of very heavy nuclei[11] by cold fusion is less favored than the use of the more asymmetric systems used in the actinide concept. The question whether the entrance channel effects or the survival probability dominate the production cross section of the heaviest systems is still debated and not solved theoretically on a quantitative basis.

The production cross sections for the elements 104 to 112 decrease by a factor of about 10 per two elements down to 1 picobarn for element 112 as shown in Figure 2. The corresponding production rates are of the order of one atom per month.

With a usable target thickness of 10^{18} atoms cm^{-2} and beam intensities of 10^{14} s^{-1} as expected for the new high-current accelerators, rates of one atom per ten hours are expected, necessary for a solid exploration of the superheavy element region beyond element 112.

Radioactive beam facilities of the first generation will deliver beams of intensities of the order of 10^{8} s^{-1} to 10^{9} s^{-1} and allow to access the nanobarn region, appropriate for the light transactinides. Production cross sections may be enhanced by isospin effects[8] as observed for the production of e.g. nobelium and element 110. Radioactive beams and targets will give access to neutron rich species in the interesting transition region between the deformed nuclei near $N = 162$ and the spherical nuclei in the vicinity of $N = 184$. The long half-lives of the neutron rich nuclei will allow for chemical studies and atomic physics investigations. These long-lived nuclei may undergo β decay or, if the shell stabilization in the transition region becomes too small, undergo spontaneous fission (see Reference 8).

Models to predict the production cross sections for superheavy elements are under development.[12] Up to now they have only limited predictive power. It is generally accepted that clusters, e.g. shells in target and projectile, as proven for the fusion with ^{208}Pb and ^{209}Bi targets, enhance the fusion probability. Similar arguments[7] hold for the use of the doubly magic ^{48}Ca. The stabilization of shell effects against fission of the compound system could not been convincingly proven up to now.

3. Recent Experimental Developments

In-flight separation is the method now established in heavy-element research, and used successfully in the discovery experiments of all trans-seaborgium elements. Gas filled magnetic separators and kinematic separators including energy- and velocity filters are in use.[13] The separation time is of the order of

*E-mail: g.muenzenberg@gsi.de.

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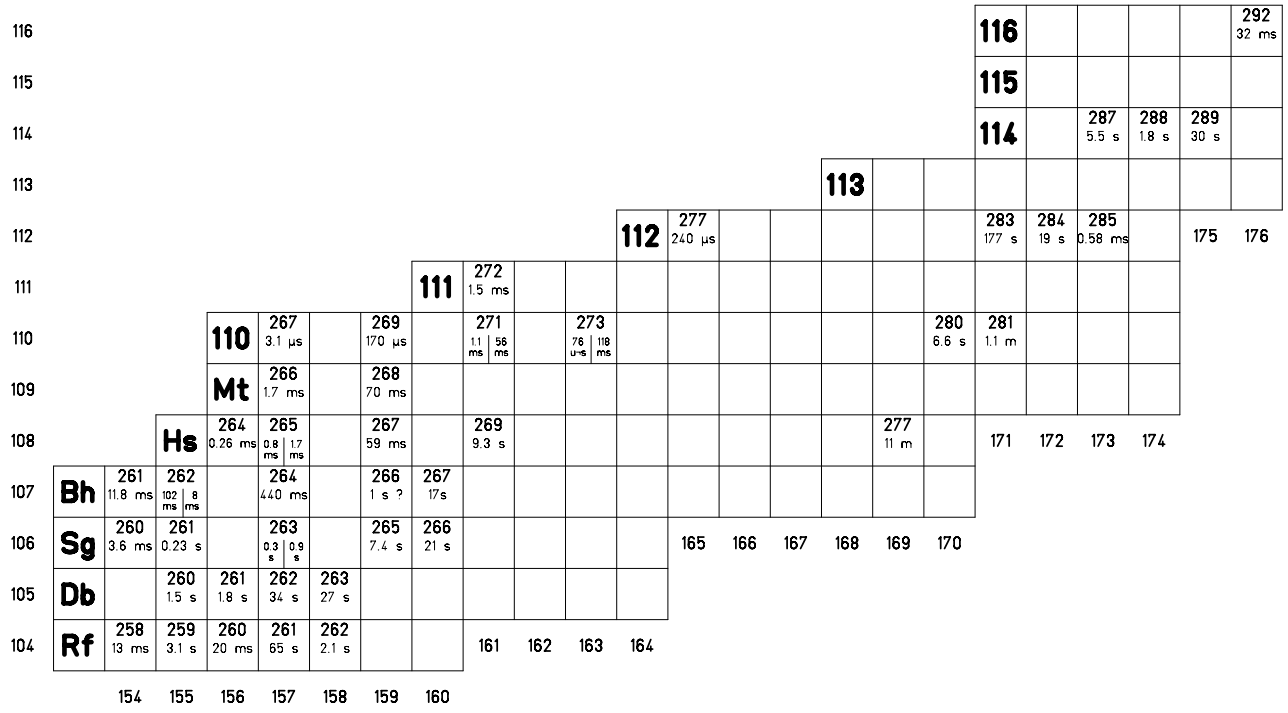

Figure 1. The upper end of the nuclear chart with the known isotopes and the experimental half-lives of the transactinides as it appears today.[8]

microseconds.

The advantage of in-flight separation is that the unretarded, energetic nuclei are implanted into silicon detectors where their decay is observed in situ. This opens the possibility for ultra-sensitive single-atom physics. Identification is based on the nuclear decay characteristics. For the heaviest elements these are long α-decay chains, in some cases they are terminated by spontaneous fission.

The method used presently for the unambiguous identification of new nuclides and even elements is based on the connection of these decay sequences to known nuclides. The identification of element 112 relies on the known isotopes of element 106 and below. Figure 3 shows the discovery chain of element 112. It should be noted here that the other chain presented in Reference 6 could not be reproduced in a re-analysis of the data. The synthesis of the elements 111 and 112 was successfully repeated, the data are published in Reference 14.

The recent chemical investigation of hassium yielded α-decay data on the isotopes ^{269}Hs which are in full agreement to the data from Reference 6 and support the discovery of element 112 (see contribution of A. Türler to this conference).

The synthesis of $Z = 114$ in the fusion of ^{244,242}Pu with ^{48}Ca has been reported from Dubna. Very recently the discovery of a decay sequence in the reaction ^{248}Cm plus ^{48}Ca, leading to the previously known 114 chain has been announced (see contribution of Yu. Ts. Oganessian to this conference).

The assignment of the elements beyond $Z = 112$ is primarily based on general arguments such as excitation energy of the compound nucleus, consistency checks of decay energy and half-lives, and comparisons of the data to theoretical models. Their unambiguous identification according to the rules of IUPAC remains a problem.[15]

New strategies for SHE identification need being developed. Solutions are: the production of presently unknown neutron rich

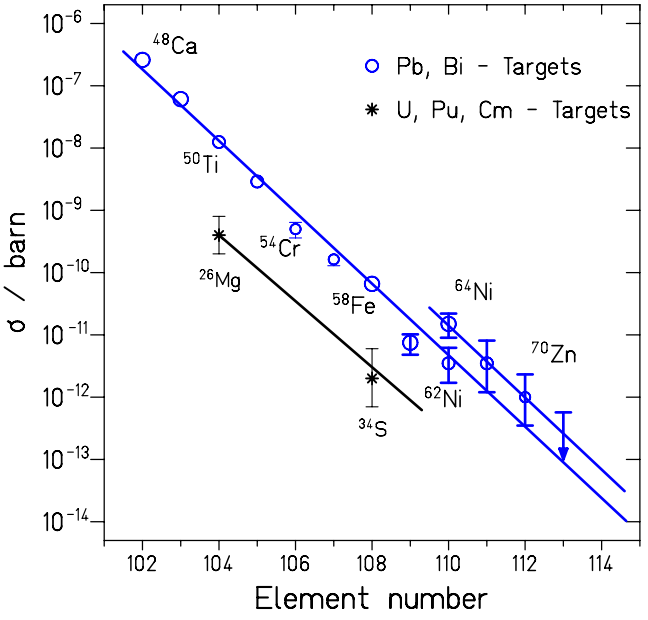

Figure 2. Production cross sections for the production of the transfermium elements.[8]

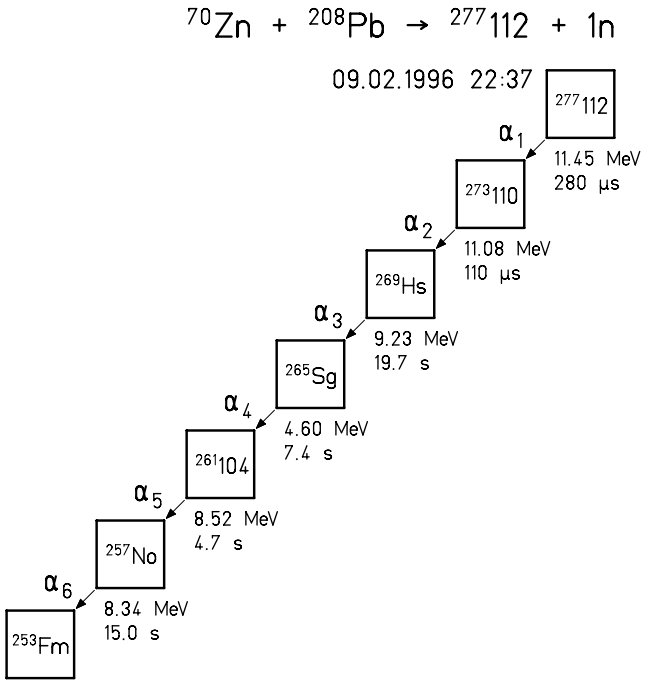

Figure 3. The α chain observed for element 112.[8]

daughter nuclei at the ends of the α chains with actinide targets or with neutron rich beams of unstable nuclei, direct determination of the mass number by mass measurements in traps, time-of-flight spectrometers, or with calorimetric detectors. For the determination of Z chemical methods are being developed (see contribution of M. Schädel to this conference).

4. The Shell Region around Hassium

The experimental data show two general features:
— in the transactinide region above rutherfordium α decay dominates,
— the half-lives increase strongly towards the neutron rich isotopes as can be observed nicely in the isotopic chains of seaborgium and hassium where the half-lives increase by three orders of magnitude up to about 20 s for the most neutron rich species.
Both observations are in contrast to our expectation from a macroscopic description where fission, prevailing already for the rutherfordium isotopes, would dominate in the tansactinide region and half-lives would continuously decrease.

The enhancement of stability[4] of the elements beyond rutherfordium ($Z = 104$) is the exciting discovery in heavy-element research. Theory explained this experimental result in terms of a shell stabilization created by a hexadecapole deformation.[16,17] The centre of this shell region is predicted for $Z = 108$ and $N = 162$ as shown in Figure 4 where the landscape of shell corrections for the transfermium elements[16] is displayed. The decay chains from element 112 give a clear proof for the existence of the $N = 162$ shell in the decay-time intervals as well as in the Q_α values.[8] The discovery of this new species of shell nuclei, interconnecting the transuranium- and the superheavy elements create the basis of present transactinide research in physics and chemistry.

The location of the spherical superheavy nuclei is currently an open question. Macroscopic-microscopic models tend to predict the magic proton number $Z = 114$, relativistic mean field models prefer $Z = 120$, whereas Skyrme-Hartree Fock models also predict $Z = 126$. The neutron shell is predicted for $N = 184$, and partly also for $N = 172$. A detailed comparative investigation of different forces has been carried out by Bender et al. in selfconsistent calculations.[2,3]

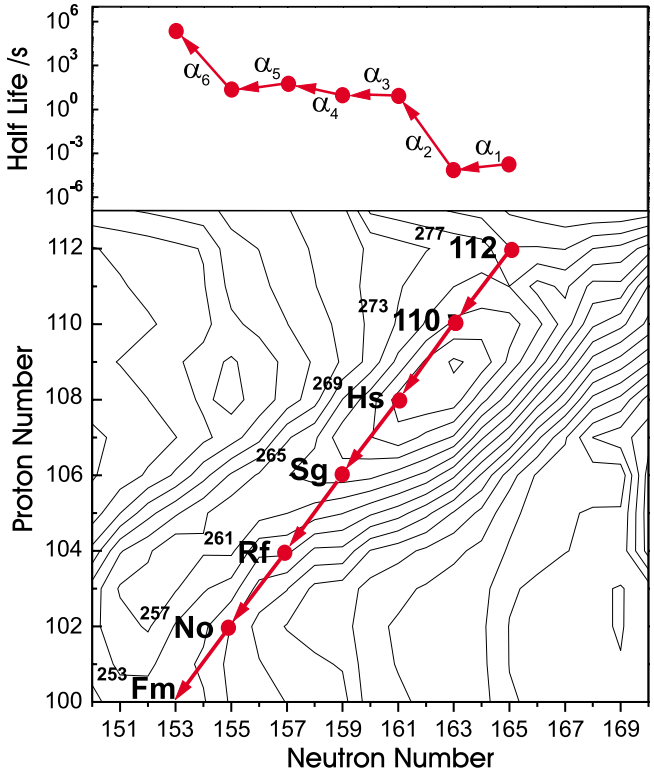

Figure 4. The calculated microscopic corrections of the heaviest elements.[16] The path of the decay chains from elements 112 are indicated. The upper panel displays the measured correlation times for one of the chains.

5. Perspectives

With the elements seaborgium and beyond the predicted new species of shell nuclei has been discovered. They close the gap between the transuranium elements and the predicted spherical superheavy shell closure. The unexpectedly long half-lives observed experimentally open up the possibilities for new types of experiments such as the extension of heavy-element chemistry beyond the present limit of hassium as well as the application of ion traps for precision experiments including direct mass determination or the investigation of atomic properties of the heaviest elements. SHIPTRAP, an ion trap attached to SHIP, is completed.

A key problem is the production of superheavy nuclei. New types of reactions need being explored. Three paths to superheavy elements seem favorable[18]: the cold fusion with lead and bismuth targets, the hot fusion with actinide targets, and as the third, and only scarcely investigated path, the symmetric fusion or reversed fission.[7] Presently only the cold fusion has been explored systematically, for the hot, actinide based fusion, data are available. Neutron rich radioactive beams will help to access hitherto not accessible regions of neutron rich isotopes of the transfermium elements, important to understand structure and stability against fission and to possibly extract data for a better understanding of the upper end of the r-process path. Reaction studies with radioactive beams will contribute to the solution of the synthesis problem.[19]

To proceed to new elements and to investigate their properties, high current accelerators are needed. The present situation clearly shows that identification of the elements beyond $Z = 112$ needs new developments. The parent-daughter correlation method will not be applicable. Solutions under development are bolometric detectors and time-of-flight spectrometers to identify the atomic mass and chemical methods to fix the nature of the chemical element. For short-lived species, chemical investigations can be carried out on a long-lived member of the decay chain as proven in the chemical investigation of hassium.

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