Quest for Superheavy Elements

Christoph E. Düllmann

Johannes Gutenberg University Mainz, 55099 Mainz, Germany
GSI Helmholtz Center for Heavy Ion Research, 64291 Darmstadt, Germany
Helmholtz Institute Mainz, 55099 Mainz, Germany

c.e.duellmann@gsi.de

1. Introduction

Extrapolations based on the nuclear shell model performed in the 1960s led to the prediction of the existence of heavy elements in a region of the nuclear chart far away from nuclei known at the time [1]. These elements were coined "superheavy elements" (SHE) and owe their existence entirely to nuclear shell effects, which stabilize them against immediate spontaneous fission (SF). The search for these artificial elements, situated on an “island of stability” far removed from the heaviest elements found on earth has been a strong driving force in superheavy element research. The quest for ever heavier elements is still on and the question concerning the heaviest element that can be produced is still awaiting an answer. This is intimately connected with aspects of nuclear stability, but also with the ability (or inability) to synthesize ever heavier elements.

The main centers where SHE research is a key priority include the GSI Hemholtz-zentrum für Schwerionenforschung (GSI) in Darmstadt, Germany, the Flerov Laboratory for Nuclear Reactions (FLNR) in Dubna, Russia, the RIKEN in Wako, Japan, and Lawrence Berkeley National Laboratory (LBNL) in Berkeley, CA, USA.

As of today, the International Union of Pure and Applied Chemistry (IUPAC) recognized the first 112 chemical elements and elements 114 and 116 [2] as discovered. Recently, the names flerovium (Fl) and livermorium (Lv) were proposed for these last two elements [3], respectively. The observation of all elements with atomic number, Z up to 118 has been reported with Z=118 being the heaviest one currently claimed element [4].

Recent overview articles on different aspects of superheavy element research can be found in the special issue of Radiochimica Acta on occasion of the "International Year of Chemistry" at http://www.oldenbourg-link.com/toc/ract/99/7-8 and are freely available for download, and also, e.g., in [5-7].

Beyond the closed spherical shells at Z=82 and N=126, deformed shell closures, e.g., at Z=108 and N=162 have been identified [8], but the location of the next spherical shell closure is still open and there is no consensus concerning their location among different theoretical frameworks. While macroscopic-microscopic models favor Z=114/N=184, relativistic mean-field approaches generally prefer Z=120/N=172 and self consistent Skyrme Hartree-Fock calculations point at Z=126/N=184. It may well turn out that a rather extended shell-stabilized region is present in the superheavy element region, rather than localized shell closures, as are well known in the lighter areas of the chart of nuclides.

Besides the hunt for ever heavier elements, superheavy element research includes approaches that focus on a variety of properties of superheavy elements, e.g., their nuclear structure or their chemical properties, from both, an experimental as well as a theoretical perspective.

In my first lecture, I will introduce the participants to SHE research in general.

2. Superheavy element research at GSI – a unique combination of facilities for a rich research program

In my second lecture, I will focus on SHE activities at the GSI Darmstadt and the University of Mainz.

GSI features a world-unique combination of experimental facilities that allows addressing key questions in this research field. These include the two recoil separators SHIP [9, 10] and TASCA [11-13], the multi-coincidence spectroscopy setup TASISpec [14], the Penning-trap mass spectrometer SHIPTRAP [15] as well as a dedicated chemistry beamline, where, e.g., chemical properties of elements 106 [16] and 108 [17] as well as nuclear structure [8] and nuclear reaction aspects [18] of nuclei in the vicinity of the deformed shell closures at Z=108 and N=162. A recent overview article on these studies can be found in [19]. All setups can be operated with any kind of combination of beams and targets, including targets consisting of highly radioactive rare isotopes of transuranium elements, which are produced at the Institute for Nuclear Chemistry at the University of Mainz [20].

The uppermost region of the chart of nuclides is depicted in the figure below, where the main research areas pursued at the GSI (described in more detail in [7]) are indicated.

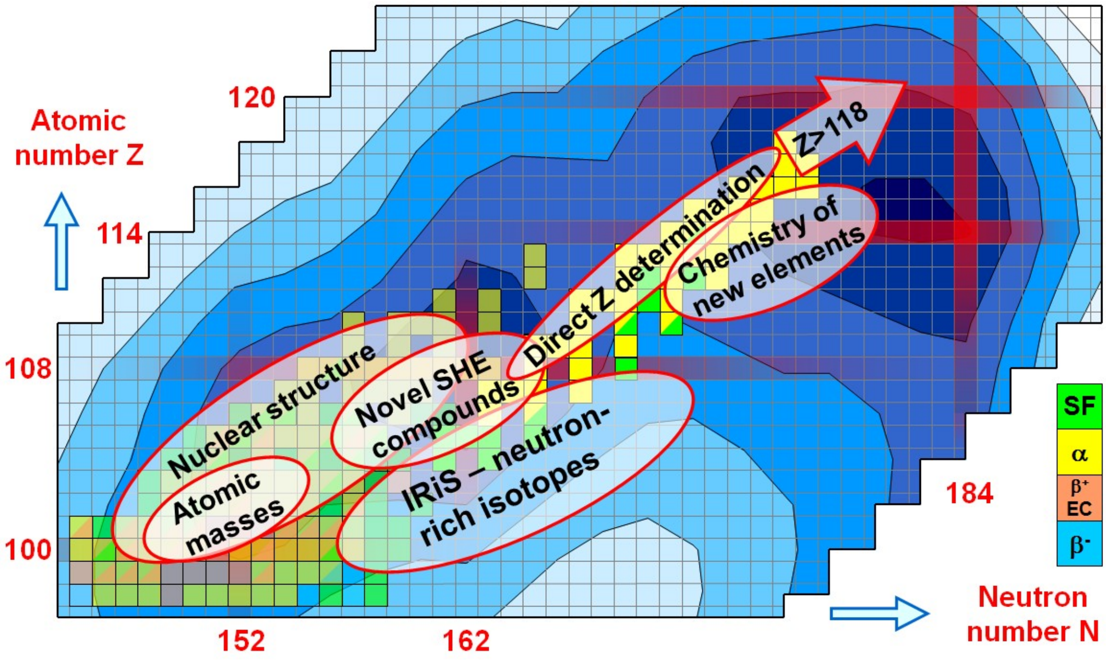

Figure (reproduced with permission from [7], "Superheavy elements at GSI: a broad research program with element 114 in the focus of physics and chemistry" by Ch.E. Düllmann, Radiochimica Acta 2012, © 2012 Oldenburg Wissenschaftsverlag GmbH):

Cut-out of the chart of nuclides in the region of the heaviest elements. The blue contours are calculated shell correction energies in MeV according to a macroscopic-microscopic model [21]. The "island of stability" is located near Z=114 and N=184, indicated in red. The proton magic number Z=120 as it follows from relativistic mean field model calculations is also indicated in red, along with the deformed shell closures at N=152,162 and Z=108. Experimentally observed nuclei are indicated as colored boxes with the color indicating the decay mode as given in the lower right. Nuclei connected by correlated α-decay-chains to previously known nuclei are indicated in transparent, while the nuclei observed in ^{48}Ca-induced fusion reactions with actinide targets are given in full color. The various research activities at the GSI are shown on the respective areas of the chart of nuclides.

SHE topics that are currently being studied at GSI include:

-synthesis of the heaviest elements with a recent highlight being the observation of element 114 [12, 13] at the Transactinide Separator and Chemistry Apparatus (TASCA) and element 116 at SHIP [22],
-reaction studies [23],
-nuclear structure investigations with a focus on nuclear isomerism in deformed nuclei with Z~100-110 [14, 24, 25],
-the direct determination of the atomic number of the heaviest elements [7],
-chemical properties of the transactinide elements ($Z \geq 104$) [26], and
-direct mass measurements beyond fermium [27]. A recent highlight from this research field includes measurements of $^{252\text{-}254}$No [15], which represent the first direct measurements of nuclei beyond uranium.

Most recently, highly exciting but at the same time extremely demanding experiments aiming at discovering new elements beyond Z=118 dominate the SHE research program at the GSI, and the status of these experiments will be presented at the school.
A news feature on the first of these experiments can be found at [28] and on the "Periodic Table of Videos" at [29].

References

[1] W. D. Myers, and W. J. Swiatecki, Nucl. Phys. **81**, 1 (1966).
[2] R. C. Barber *et al.*, Pure Appl. Chem. **83**, 1485 (2011).
[3] http://www.iupac.org/web/nt/2011-12-01_name_element_114_116.
[4] Yu. Oganessian, Radiochim. Acta **99**, 429 (2011).
[5] Yu. Oganessian, J. Phys. G **34**, R165 (2007).
[6] S. Hofmann, Lect. Notes Phys. **764**, 203 (2009).
[7] Ch. E. Düllmann, Radiochim. Acta **100**, 67 (2012).
[8] J. Dvorak *et al.*, Phys. Rev. Lett. **97**, 242501 (2006).
[9] G. Münzenberg *et al.*, Nucl. Instrum. Methods **161**, 65 (1979).
[10] S. Hofmann, Rep. Prog. Phys. **61**, 639 (1998).
[11] A. Semchenkov *et al.*, Nucl. Instrum. Methods B **266**, 4153 (2008).
[12] Ch. E. Düllmann *et al.*, Phys. Rev. Lett. **104**, 252701 (2010).
[13] J. M. Gates *et al.*, Phys. Rev. C **83**, 054618 (2011).
[14] L.-L. Andersson *et al.*, Nucl. Instrum. Methods A **622**, 164 (2010).
[15] M. Block *et al.*, Nature **463**, 785 (2010).
[16] M. Schädel *et al.*, Nature **388**, 55 (1997).
[17] Ch. E. Düllmann *et al.*, Nature **418**, 859 (2002).
[18] J. Dvorak *et al.*, Phys. Rev. Lett. **100**, 132503 (2008).
[19] A. Türler, Radiochim. Acta **100**, 75 (2012).
[20] K. Eberhardt *et al.*, Nucl. Instrum. Methods A **590**, 134 (2008).
[21] A. Sobiczewski, I. Muntian, and Z. Patyk, Phys. Rev. C **63**, 034306 (2001).
[22] S. Hofmann *et al.*, GSI Scientific Report 2010, 197 (2011).
[23] S. Heinz *et al.*, Eur. Phys. J. A **38**, 227 (2008).
[24] F. P. Heßberger, Phys. At. Nucl. **70**, 1445 (2007).
[25] F. P. Heßberger *et al.*, Eur. Phys. J. A **41**, 145 (2009).
[26] M. Schädel, Angew. Chem. Intl. Ed. **45**, 368 (2006).
[27] M. Block *et al.*, Eur. Phys. J. D **45**, 39 (2007).
[28] D. Clery, Science **333**, 1377 (2011).
[29] http://www.periodicvideos.com/videos/feature_120.htm.