ELSEVIER

Nuclear Physics A734 (2004) 93–100

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

Properties of heavy nuclei measured at the GSI SHIP

S. Hofmann[ab], F.P. Heßberger[a], D. Ackermann[ac], S. Antalic[d], P. Cagarda[d], B. Kindler[a], P. Kuusiniemi[e], M. Leino[e], B. Lommel[a], O.N. Malyshev[f], R. Mann[a], G. Münzenberg[ac], A.G. Popeko[f], S. Śaro[d], B. Streicher[d], A.V. Yeremin[f].

[a]Gesellschaft für Schwerionenforschung (GSI), D–64220 Darmstadt, Germany

[b]Physikalisches Institut, J.W. Goethe-Universität, D–60054 Frankfurt, Germany

[c]Institut für Physik, Johannes Gutenberg-Universität, D–55099 Mainz, Germany

[d]Department of Nuclear Physics, Comenius University, SK–84248 Bratislava, Slovakia

[e]Department of Physics, University of Jyväskylä, FIN–40351 Jyväskylä, Finland

[f]Flerov Laboratory of Nuclear Reactions, JINR, RU–141 980 Dubna, Russia

The nuclear shell model predicts that the next doubly magic shell-closure beyond ^{208}Pb is at a proton number Z = 114, 120, or 126 and at a neutron number N = 172 or 184. The outstanding aim of experimental investigations is the exploration of this region of spherical 'Super-Heavy Elements' (SHEs). The measured decay data reveal that for the heaviest elements, the dominant decay mode is α emission, not fission. Decay properties as well as reaction cross-sections are compared with results of theoretical investigations. Finally, plans are presented for the further development of the experimental set-up and the application of new techniques. At a higher sensitivity, the exploration of the region of spherical SHEs now becomes feasible, more than thirty years after its prediction.

1. EXPERIMENTAL RESULTS

In this section, recent results are presented dealing with the confirmation of elements 110 to 112. Detailed presentations of the properties of elements 107 to 109 and of earlier results on elements 110 to 112 were given in previous reviews [1–3].

Element 110, now officially named darmstadtium [4], Ds, was discovered in 1994 using the reaction ^{62}Ni + ^{208}Pb $\rightarrow$ ^{270}Ds* [5]. A total of three decay chains were measured (see also remarks at the end of this section). The main experiment was preceded by a thorough study of the excitation functions for the synthesis of ^{257}Rf and ^{265}Hs in order to determine the optimum beam energy for the production of darmstadtium. The data revealed that the maximum cross-section for the synthesis of hassium was shifted to a lower excitation energy, different from the predictions of reaction theories.

The heavier isotope ^{271}Ds was synthesized with a beam of the more neutron-rich isotope ^{64}Ni [2]. The important result for the further production of elements beyond meitnerium was that the cross-section was enhanced from 2.6 pb to 15 pb by increasing the neutron

doi:10.1016/j.nuclphysa.2004.01.018

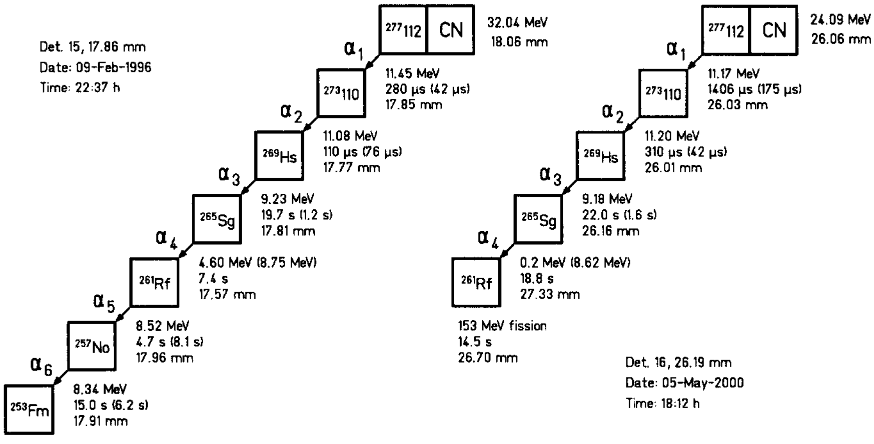

Figure 1. Two decay chains measured in experiments at SHIP in the cold fusion reaction ^{70}Zn + ^{208}Pb $\rightarrow$ ^{278}112*. The chains were assigned to the isotope ^{277}112 produced by evaporation of one neutron from the compound nucleus. The lifetimes given in brackets were calculated using the measured α energies. In the case of escaped α particles the α energies were determined using the measured lifetimes.

number of the projectile by two, which gave hope that the cross-sections could decrease less steeply with more neutron-rich projectiles. However, this expectation was not proven in the case of element 112.

The even-even nucleus ^{270}Ds was synthesized using the reaction ^{64}Ni + ^{207}Pb [6]. A total of eight α-decay chains was measured during an irradiation time of seven days. Decay data were obtained for the ground-state and a high spin K isomer, for which calculations predict spin and parity 8^+, 9^- or 10^- [7]. The new nuclei ^{266}Hs and ^{262}Sg were identified as daughter products after α decay. Spontaneous fission of ^{262}Sg terminates the decay chain.

Element 111 was synthesized in 1994 using the reaction ^{64}Ni + ^{209}Bi $\rightarrow$ ^{273}111*. A total of three α chains of the isotope ^{272}111 were observed [8]. Another three decay chains were measured in a confirmation experiment in October 2000 [9].

Element 112 was investigated at SHIP using the reaction ^{70}Zn + ^{208}Pb $\rightarrow$ ^{278}112* [10]. The irradiation was performed in January-February 1996. Over a period of 24 days, a total of 3.4×10^{18} projectiles were collected. One α-decay chain, shown in the left side of Fig. 1, was observed resulting in a cross-section of 0.5 pb. The chain was assigned to the one neutron-emission channel. The experiment was repeated in May 2000 aiming to confirm the synthesis of ^{277}112 [9]. During a similar long measuring time, but using slightly higher beam energy, one more decay chain was observed, also shown in Fig. 1. The measured decay pattern of the first four α decays is in agreement with the one observed in the first experiment.

A new result was the occurrence of fission which ended the second decay chain at ^{261}Rf.

A spontaneous-fission branch of this nucleus was not yet known, however, it was expected from theoretical calculations. The new results on ^{261}Rf were proven in a recent chemistry experiment [11,12], in which this isotope was measured as granddaughter in the decay chain of ^{269}Hs.

A reanalysis of all decay chains measured at SHIP since 1994, a total of 34 decay chains was analyzed, revealed that the previously published first decay chain of ^{277}112 [10] (not shown in Fig. 1) and the second of the originally published four chains of ^{269}Ds [5] were spuriously created. Details of the results of the reanalysis are given in Ref. [9].

The excitation function of the reaction ^{54}Cr + ^{208}Pb was studied recently (June 2003, see Sect. 3). At high beam currents of up to 1 pμA the target was continuously monitored using the scattering of 20 keV electrons at the target material [13]. Successfully tested was a PbS target (melting point 1118° C) produced by depositing the target material on a carbon backing which was heated to several 100° C [14]. By heating the backing during evaporation, the formation of a crystalline needle structure of PbS was avoided, which would result in uncontrolled energy loss of the projectiles. Using the 'heated' PbS target, a 1n-excitation function was measured, which was identical to the previously measured one obtained with a metallic Pb target.

2. NUCLEAR STRUCTURE AND DECAY PROPERTIES

The basic step which is necessary for the determination of the stability of SHEs is the calculation of the ground-state binding energy. As a signature for shell effects, we can extract from various models the shell-correction energy by subtracting a smooth macroscopic part (derived from the liquid-drop model) from the total binding energy. In macroscopic-microscopic models the shell-correction energy is of course the essential input value which is calculated directly from the shell model. The shell-correction energy is plotted in Fig. 2a using the data from Ref. [15]. Two equally deep minima are obtained, one at Z = 108 and N = 162 for deformed nuclei with deformation parameters $\beta_2 \approx 0.22$, $\beta_4 \approx -0.07$ and the other at Z = 114 and N = 184 for spherical SHEs. Different results are obtained from self-consistent Hartree-Fock-Bogoliubov (HFB) calculations and relativistic mean-field models [16–19]. They predict for the spherical nuclei shells at Z = 114, 120 or 126 (indicated as dashed lines in Fig. 2) and N = 184 or 172, with shell strengths being also a function of the amount of nucleons of the other type.

For the calculation of partial spontaneous fission half-lives the knowledge of ground-state binding energies is not sufficient. It is necessary to determine the fission barrier over a wide range of deformation. The most accurate data were obtained for even-even nuclei using the macroscopic-microscopic model [15,20]. Partial spontaneous fission half-lives are plotted in Fig. 2b.

Partial α half-lives decrease almost monotonically from 10^{12} s down to 10^{-9} s near Z = 126 (Fig. 2c). The valley of β-stable nuclei (marked by black squares in Fig. 2d) passes through Z = 114, N = 184 [21]. At a distance from the bottom of the valley, the β half-lives decrease gradually down to values of one second.

The interesting question arises, if and how the uncertainty related with the location of the proton and neutron shell closures will change the half-lives of SHEs. Partial α and β half-lives are only insignificantly modified by shell effects, because the decay process occurs

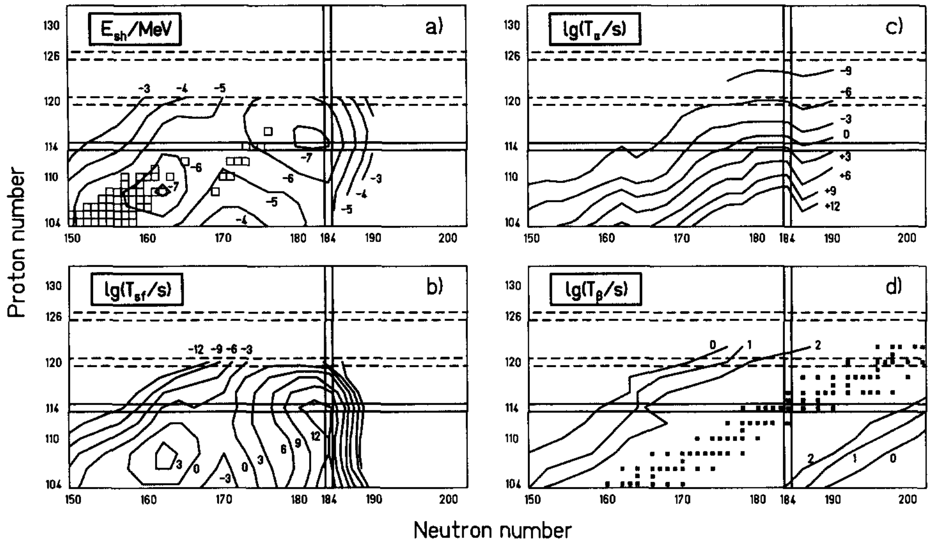

Figure 2. Shell-correction energy (a) and partial spontaneous fission, α and β half-lives (b-d). The calculated values in (a)–(c) are taken from Ref. [15,20] and in (d) from Ref. [21]. The squares in (a) mark the nuclei presently known or under investigation.

between neighboring nuclei. This is different for fission half-lives which are primarily determined by shell effects. However, the uncertainty related with the location of nuclei with the strongest shell-effects and thus longest partial fission half-life at Z = 114, 120 or 126 and N = 172 or 184, is inconsequential concerning the longest 'total' half-life of SHEs. The regions for SHEs in question are dominated by α decay. And α decay will be modified by only a factor of up to approximately 100, if the double shell closure will not be located at Z = 114 and N = 184.

The line of reasoning is, however, different concerning the production cross-section. The survival probability of the compound nucleus (CN) is determined among other factors significantly by the fission-barrier. Therefore all present calculations of cross-sections suffer from the uncertainty related with the location and strength of closed shells.

3. CROSS-SECTIONS, FUSION VALLEYS AND EXCITATION ENERGY

The main features which determine the fusion process of heavy ions are (1) the fusion barrier and related beam energy and excitation energy, (2) the ratio of surface tension versus Coulomb repulsion, which determines the fusion probability and which strongly depends from the degree of asymmetry of the reaction partners (the product Z_1Z_2 at fixed $Z_1 + Z_2$), (3) the impact parameter and related angular momentum, and (4) the ratio of neutron evaporation versus fission probability of the CN. In fusion of SHEs the product Z_1Z_2 reaches extremely large and the fission barrier extremely small values. In addition, the fission barrier is fragile at increasing excitation energy and angular momen-

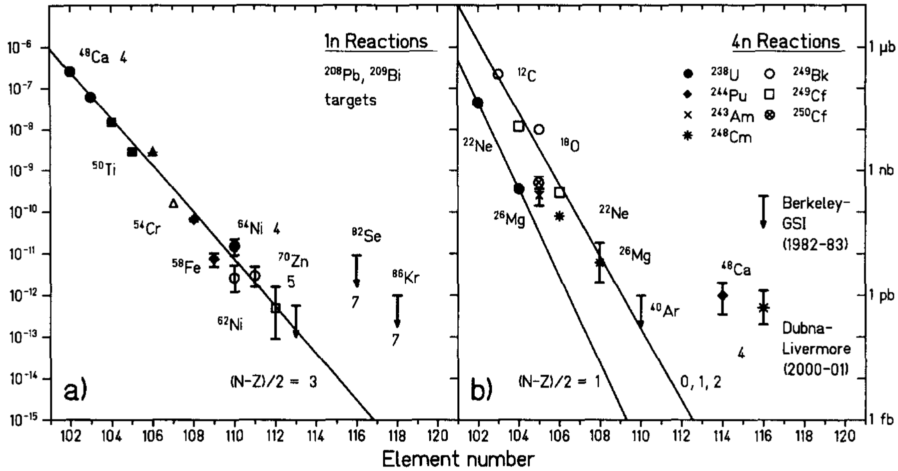

Figure 3. Measured cross-sections and cross-section limits for reactions using ^{208}Pb and ^{209}Bi targets and one neutron evaporation (a) and for reactions using actinide targets and four neutron evaporation (b).

tum, because it is solely built up from shell effects. For these reasons the fusion of SHEs is hampered, whereas the fusion of lighter elements is advanced through the contracting effect of surface tension.

The effect of Coulomb repulsion on the cross-section starts to act severely for fusion of elements beyond Fm. From there on a continuous decrease of cross-section was measured from microbarns for the synthesis of nobelium down to picobarns for the synthesis of element 112. The data obtained in reactions with ^{208}Pb and ^{209}Bi for the 1n evaporation channel at low excitation energies of about 10–15 MeV (therefore named *cold fusion*) and in reactions with actinide targets for the 4n channel at excitation energies of 35–45 MeV (*hot fusion*) are plotted in Fig. 3. Interesting for further investigation of SHEs are the relatively high cross-sections measured for the synthesis of elements 114 and 116 (4n channel) [22–24]. In both cases the obtained values of about 0.5 pb are considerably larger than expected from the trend set by fusion of the lighter elements. An explanation could be a relatively high and wide fission barrier of the CN, which is created by strong shell effects in the region of spherical SHEs. Note in this context that the experimental sensitivity increased by three orders of magnitude since the 1982-83 search experiments for element 116 using a hot fusion reaction [25].

A number of excitation functions was measured for the synthesis of elements from rutherfordium to darmstadtium using Pb and Bi targets [3]. For the even elements these data are shown in Fig. 4. The figure includes the recently (June 2003) measured excitation function of the reaction ^{54}Cr + ^{208}Pb and an update of the previously [5] obtained data of ^{50}Ti + ^{208}Pb.

The maximum evaporation residue cross-section (1n channel) was measured at beam energies well below a fusion barrier calculated in one dimension [26]. At the optimum

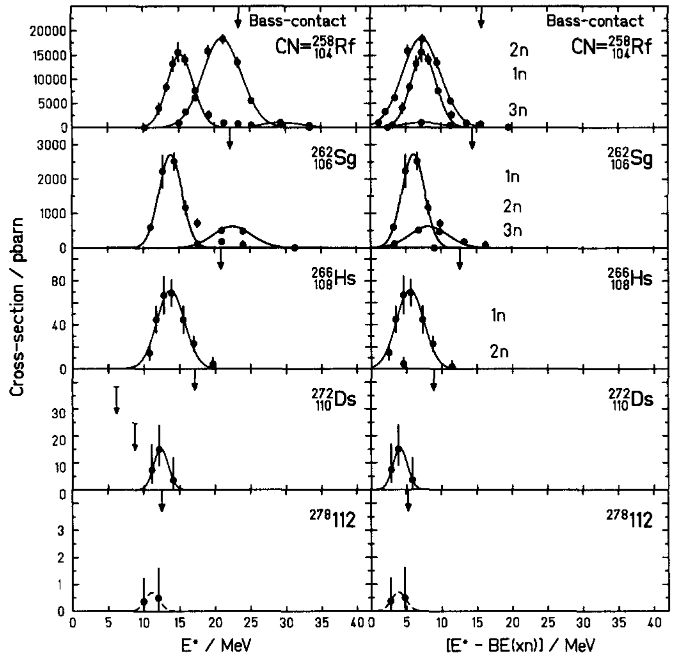

Figure 4. Measured even element excitation functions based on ^{208}Pb targets.

beam energy projectile and target nuclei are just reaching the contact configuration in a central collision. The relatively simple fusion barrier based on the Bass model [26] is too high and a tunnelling process through this barrier cannot explain the measured cross-section.

Various processes are possible and are discussed in the literature which result in a lowering of the fusion barrier. Among these transfer of nucleons and excitation of vibrational degrees of freedom are the most important [27–36]. The theoretical studies are also aimed at reproducing the known cross-section data and further extrapolating the calculations into the region of spherical superheavy nuclei. The measured cross-sections for the formation of ^{257}Rf up to ^{277}112 are reproduced almost within about a factor of 2 by the various models. However, there are significant differences in the cross-section values for the synthesis of spherical SHEs at and beyond Z = 114.

In the case of actinide targets, the target nucleus is strongly deformed and the height of the Coulomb barrier is a function of the orientation of the deformation axes. The reaction ^{48}Ca + ^{248}Cm was studied in Dubna [22,23], and evidence for the 4n channel was obtained at a beam energy resulting in an excitation energy of 30.4 – 35.8 MeV. Excitation functions were not yet measured.

It was pointed out in the literature [37] that closed shell nuclei as projectile and target are favorable for fusion of SHEs. The reason is not only a low reaction Q value and thus low excitation energy, but also that fusion of such systems is connected with a minimum of energy dissipation. The fusion path propagates along cold fusion valleys on the potential energy surface, where the reaction partners keep kinetic energy up to the closest possible distance. In this view the difference between *'cold'* and *'hot'* fusion is not only a result from different values of the excitation energy, but there exists also a qualitative difference. This is on the one side based on a well ordered fusion process along paths of minimum dissipation of energy (cold fusion), and on the other side on a process governed by the formation of a more or less energy equilibrated CN (hot fusion). This qualitative explanation is well in agreement with the results from experimental studies of quasi-fission and compound-nucleus fission [38].

SUMMARY AND OUTLOOK

The experimental work of the last two decades has shown that cross-sections for the synthesis of the heaviest elements decrease almost continuously. However, recent data on the synthesis of element 114 and 116 in Dubna using hot fusion seem to break this trend when the region of spherical superheavy elements is reached.

An opportunity for the continuation of experiments in the region of SHEs at decreasing cross-sections will be afforded, among others, by further accelerator developments. High current beams and radioactive beams are options for the future. At increased beam currents, values of tens of particle μA's may become accessible, the cross-section level for the performance of experiments can be shifted down into the region of tens of femtobarns, and excitation functions can be measured on the level of tenths of picobarns. High currents, in turn, call for the development of new targets and separator improvements. Radioactive ion beams, not as intense as the ones with stable isotopes, will allow for approaching the closed neutron shell $N = 184$ already at lighter elements. Interesting will be the study of the fusion process using radioactive neutron rich beams.

The half-lives of spherical SHEs are expected to be relatively long. Based on nuclear models, which are effective predictors of half-lives in the region of the heaviest elements, values from microseconds to years have been calculated for various isotopes. This wide range of half-lives encourages the application of a wide variety of experimental methods in the investigation of SHEs, from the safe identification of short lived isotopes by recoil-separation techniques to atomic physics experiments on trapped ions, and to the investigation of chemical properties of SHEs using long-lived isotopes.

ACKNOWLEDGEMENTS

We are much indebted to the UNILAC staff for making all efforts to provide our experiments with intense and stable beams over periods of several weeks. We are also grateful to H.G. Burkhard and H.J. Schött for taking care of the mechanical devices and electrical components at SHIP and to W. Hartmann, J. Klemm, J. Steiner of the GSI target laboratory for preparation of the target wheels. Many thanks also to the colleagues from the department of experimental electronics and data acquisition. We are particularly grateful for fruitful discussions with N.V. Antonenko, E.A. Cherepanov, S. Ćwiok, V.Yu. Denisov, W. Greiner, P.H. Heenen, M.G. Itkis, P. Möller, A.K. Nasirov, W. Nazarewicz, W. Nörenberg, Yu.Ts. Oganessian, W. Scheid, R. Smolanczuk and A. Sobiczewski.

REFERENCES

1. G. Münzenberg, Rep. Prog. Phys. A 51 (1988) 57.
2. S. Hofmann, Rep. Prog. Phys. A 61 (1998) 639.
3. S. Hofmann and G. Münzenberg, Rev. Mod. Phys. 72 (2000) 733.
4. IUPAC 42nd General Assembly, Ottawa, Canada, 9-17 August 2003.
5. S. Hofmann et al, Z. Phys. A 350 (1995) 277.
6. S. Hofmann et al, Eur. Phys. J. A 10 (2001) 5.
7. S. Cwiok et al, Phys. Rev. Lett. 83 (1999) 1108 and private communication.
8. S. Hofmann et al, Z. Phys. A 350 (1995) 281.
9. S. Hofmann et al, Eur. Phys. J. A 14 (2002) 147.
10. S. Hofmann et al, Z. Phys. A 354 (1996) 229.
11. Ch.E. Düllmann et al, Nature 418 (2002) 859.
12. A. Türler et al, Eur. Phys. J. A 17 (2003) 505.
13. R. Mann et al, to be published.
14. B. Kindler et al, to be published.
15. R. Smolanczuk and A. Sobiczewski, Proc. XV. Nucl. Phys. Divisional Conf. on Low Energy Nuclear Dynamics, St.Petersburg, Russia, 1995, p.313, World Scientific, Singapore, 1995.
16. S. Cwiok et al, Nucl. Phys. A 611 (1996) 211.
17. G.A. Lalazissis et al, Nucl. Phys. A 608 (1996) 202.
18. K. Rutz et al, Phys. Rev. C 56 (1997) 238.
19. A.T. Kruppa et al, Phys. Rev. C 61 (2000) 034313.
20. R. Smolanczuk et al, Phys. Rev. C 52 (1995) 1871.
21. P. Möller et al, Atomic Data and Nucl. Data Tables 66 (1997) 131.
22. Yu.Ts. Oganessian et al, Phys. Rev. C 63 (2000) 011301.
23. Yu.Ts. Oganessian et al, Phys. Atomic Nuclei 64 (2001) 1349.
24. Yu.Ts. Oganessian et al, Nature 400 (1999) 242.
25. P. Armbruster et al, Phys. Rev. Lett. 54 (1985) 406.
26. R. Bass, Nucl. Phys. A 231 (1974) 45.
27. Y. Aritomo et al, Phys. Rev. C 59 (1999) 796.
28. E.A. Cherepanov, Pramana J. Phys. 53 (1999) 619.
29. R. Smolanczuk, Phys. Rev. C 59 (1999) 2634.
30. R. Smolanczuk, Phys. Rev. Lett. 83 (1999) 4705.
31. G. Giardina et al, Eur. Phys. J. A 8 (2000) 205.
32. V.Yu. Denisov and S. Hofmann, Phys. Rev. C 61 (2000) 034606.
33. G.G. Adamian et al, Nucl. Phys. A 678 (2000) 24.
34. G.G. Adamian et al, Phys. Rev. C 62 (2000) 064303.
35. R. Smolanczuk, Phys. Rev. C 63 (2001) 044607.
36. V.I. Zagrebaev, in Proc. Int. Workshop on Fusion Dynamics at the Extremes, Dubna, Russia, 2000, p. 215, World Scientific, 2001.
37. R.K. Gupta et al, Z. Phys. A 283 (1977) 217.
38. M.G. Itkis et al, in Proc. Int. Workshop on Fusion Dynamics at the Extremes, Dubna, Russia, 2000, p. 93, World Scientific, 2001.