STUDY OF SUPERHEAVY ELEMENTS

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Abstract

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 ‘SuperHeavy Elements’ (SHEs). Experimental methods are described, which allowed for the identification of elements produced on a cross-section level of about 1 pb. The decay data reveal that for the heaviest elements, the dominant decay mode is alpha emission, not fission. Decay properties as well as reaction cross-sections are compared with results of theoretical investigations.

ESTUDIO DE ELEMENTOS SUPERPESADOS

Resumen

El modelo nuclear de capas predice que el próximo nivel doblemente mágico más allá de ^{208}Pb ocurre para un número atómico Z = 114, 120 o 126 y para un número de neutrones N = 172 o 184. El objetivo más importante de estos experimentos es la exploración de la región de elementos superpesados esféricos. En el trabajo se describen los métodos experimentales que permitieron identificar los elementos producidos para un valor de la sección eficaz de aproximadamente 1 pb. Los datos de decaimiento revelan que para los elementos más pesados el modo dominante es la emisión alfa y no la fisión. Las propiedades de decaimiento así como las secciones eficaces se comparan con resultados de estudios teóricos.

Key words: lead 208, neutrons, protons, reaction kinetics, shell models, transactinide element

Status of experiments

For the synthesis of heavy and superheavy elements (SHE) fusion-evaporation reactions are used. Two approaches have been successfully employed. Firstly, reactions with medium mass ion beam impinging on targets of stable Pb and Bi isotopes (cold fusion). These reactions have been successfully used to produce elements up to Z = 112 at GSI [1] and to confirm these experiments at RIKEN [2] and LBNL [3]. Using a ^{209}Bi target the isotope ^{278}113 was recently synthesized at RIKEN [2]. Secondly, reactions between lighter ions, especially with beams of ^{48}Ca, and radioactive actinide targets (hot fusion) have been used to produce more neutron rich isotopes of elements from Z = 112 to 116 and 118 at FLNR [4,5]. Figures 1 and 2 summarize the data as they are presently known or under investigation.

Besides the discovery of the existence of these high-Z elements, two more important observations emerged. Firstly, the expectation that half-lives of the new isotopes should lengthen with increasing neutron number as one approaches the island of stability seems to be fulfilled. Secondly, the measured cross-sections for the relevant nuclear fusion processes reach values up to 5 pb, which is surprisingly high. Furthermore, they seem to be correlated with the variation of shell-correction energies as predicted by macroscopic-microscopic calculations [6,7].

A number of excitation functions was measured for the synthesis of elements from nobelium to darmstadtium using cold fusion reactions. Some of the curves are shown together with the two data points for ^{277}112 in figure 3. Maximum evaporation residue cross-sections (1n channel) were measured at beam energies well below a contact configuration, where projectile and target nucleus come to rest according to the fusion model by Bass [8].

Excitation functions for hot fusion reactions were measured recently at FLNR [4]. The data for the reaction ^{48}Ca + ^{244}Pu ’ $\rightarrow$ ^{288}114 + 4n is shown in the lowest panel in figure 3. Here, the peak is located well above the contact configuration calculated from a mean value of the nuclear potential of the deformed target nucleus. This shift as well as the increased width of the curve (10.6 MeV instead of 4.6 MeV FWHM for ^{265}Hs) are in accord with an orientation effect on fusion using

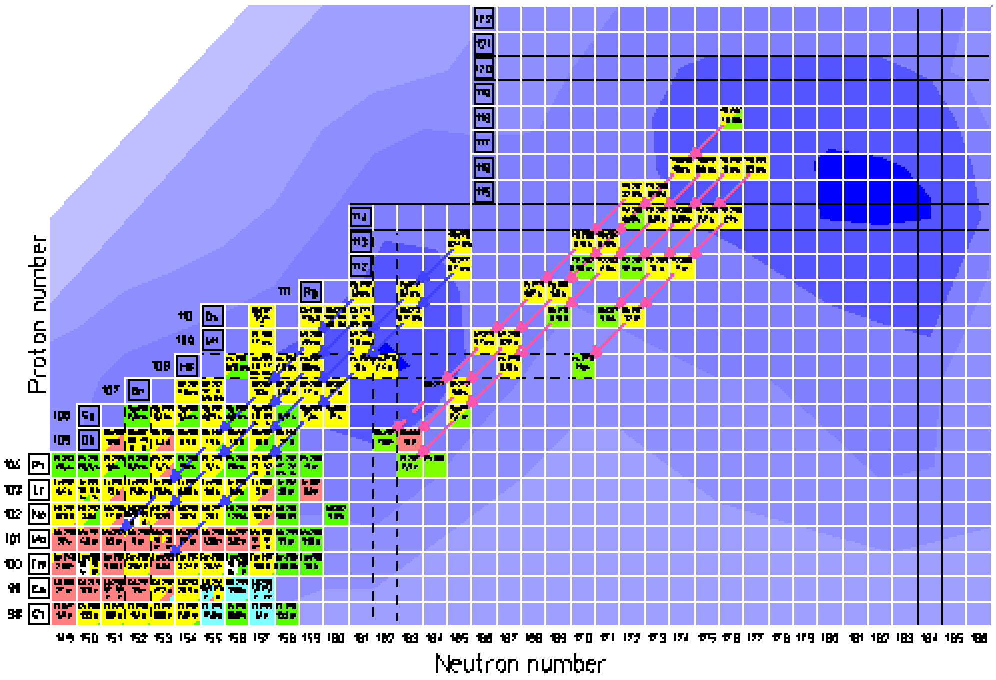

Figure 1. Upper end of the chart of nuclei showing the presently known nuclei in colors attributed to their decay mode: α decay yellow, β⁺ decay red, β⁻ decay blue, spontaneous fission green, and γ decaying isomers white. Also given are the measured half-lives and α decay chains observed in experiments. The background structure in blue color shows the calculated shell correction energy according to the macroscopic-microscopic model with minimum values of -7 MeV (darkest blue) for both deformed nuclei at Z = 108, N = 162 and spherical superheavy nuclei at Z = 114, N = 184. The intensity of the blue color is reduced with increasing shell correction energy in steps of 1 MeV.

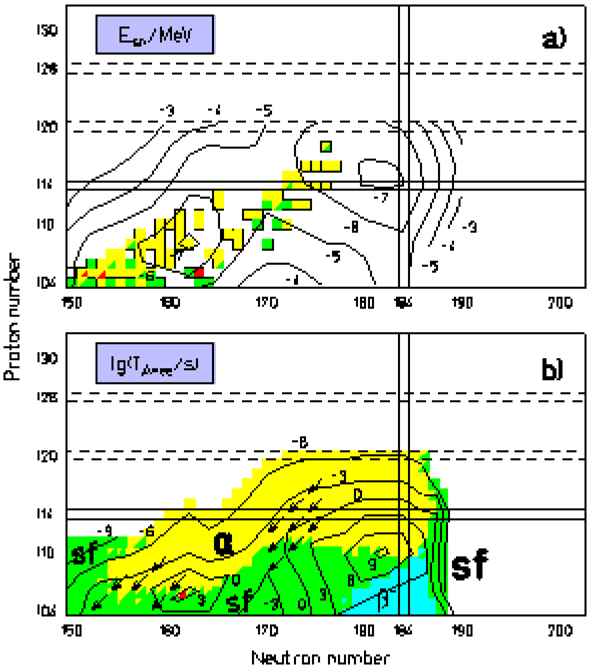

Figure 2. Calculated ground-state shell correction energy (a) and dominating partial half-lives for α, β⁺ or EC, β⁻ decay and spontaneous fission (SF) of even-even nuclei (b). The calculated data were taken from refereces [6,7]. The squares in (a) show the isotopes of heavy and superheavy elements, which are known or presently under investigation, and the arrows in (b) mark the measured decay chains. In all cases the decay chains end, in agreement with theoretical predictions, at nuclei decaying by SF.

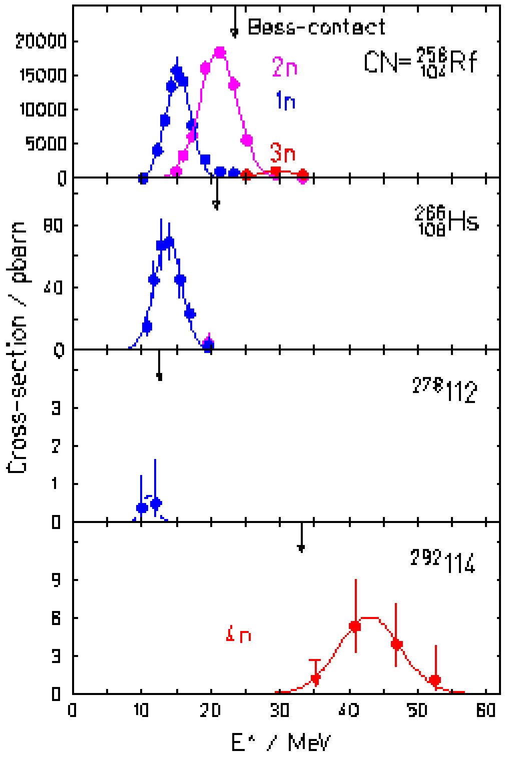

Figure 3. Excitation functions measured at SHIP for the synthesis of elements Rf and Hs plus two data points measured for Z = 112 using cold fusion reactions (^{208}Pb target) [1] and at the DGFRS of FLNR for the synthesis of element Z = 114 [4] using hot fusion reaction (^{244}Pu target). The arrows mark the excitation energy for reactions, when the kinetic energy of the projectile is just sufficient high to reach a contact configuration according to the fusion model by Bass [8]. The excitation energies were calculated using binding energies for the compound nuclei from reference [9].

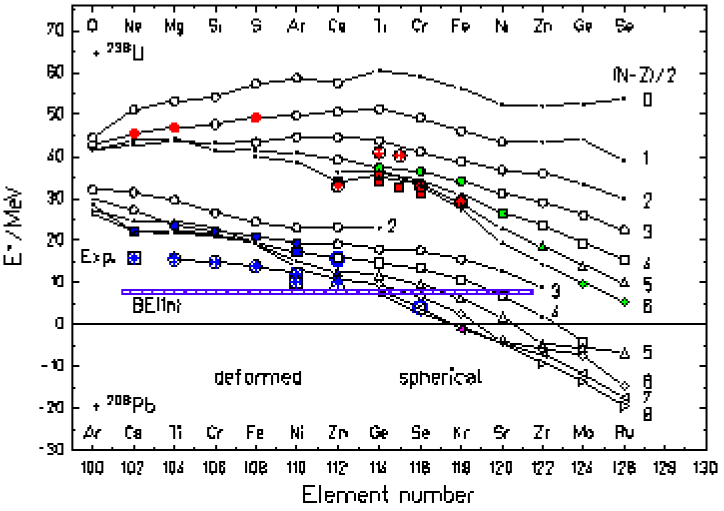

Figure 4. Excitation energy of compound nuclei for fusion starting from a contact configuration. For explanation of the symbols see text.

a deformed target nucleus. The shift to higher energy indicates collisions in direction of the short deformation axis. Although a realistic fusion barrier is not yet available and details of the fusion process resulting in SHE's are not yet completely understood, we already can investigate various reactions concerning the Q value, including radioactive projectiles. For the interesting cases the projectiles are not extremely neutron rich and their binding energy is known. The binding energy of SHE's from various models is in sufficient agreement. Therefore the uncertainty of the Q value is estimated to be a few MeV only.

In a first step we consider the excitation energy of various reactions using targets of ^{208}Pb and ^{238}U and preferably stable projectiles. The results are plotted in figure 4. The lines connect projectiles with the same isospin. Larger symbols denote stable, the smaller dots radioactive projectiles. The excitation energy was calculated for beam energies so that a contact configuration is reached according to the Bass model [8]. Data for which maximum cross-sections were measured (marked by 'Exp.') are even below that energy, halfway to the limiting (for the 1n channel) one neutron binding energy.

Striking is the decrease of the excitation energy below the 1n-binding energy at about element 114. For that reason we studied the reaction ^{82}Se + ^{208}Pb '$\rightarrow$ ^{290}116 at excitation energies from 0 to 10 MeV in order to search for a possible radiative capture channel. The result was negative, cross-section limits of 5 pb were reached at four different beam energies [10].

In the case of element 118 synthesis the reaction ^{86}Kr + ^{208}Pb even gets endothermic. A surplus of kinetic energy is needed beyond the minimum necessary for reaching a contact configuration in order to evaporate one neutron. This feature was interpreted as 'unshielded' fusion reaction [11].

The extraordinary low excitation energy for the reaction using ^{48}Ca beam and ^{238}U target is obvious from the upper bunch of curves. Also with uranium target the reaction gets colder with increasing element number. The excitation energy reaches values close to the 1n-binding energy near element 124 using a ^{76}Ge beam. The reactions using actinide targets, which are often described as 'hot' fusion according to the excitation energy of about 40 MeV for synthesis of elements up to about 110, change into 'cold' fusion for the heavier elements. This could be a promising aspect for the synthesis of SHE's near Z = 126 (which is one of the predicted closed proton shells) using actinide targets.

In the case of ^{208}Pb as a target a surplus of 30 MeV of kinetic energy is necessary at these high element numbers in order to obtain excitation energy high enough for emission of one neutron. However, such high kinetic energies will probably lead to dissipation of energy already in early stages of the fusion process. An increase of deep inelastic processes will result.

Using more neutron rich radioactive projectiles (higher values of isospin as shown in figure 4) does not, in general, result in lower excitation energies at the fusion barrier. In contrary, the excitation energy rises again (see figure 7 in reference [12]). An open question is how the stronger binding energy of the protons and, vice versa, the low binding energy of the neutrons will influence the fusion process, especially the first stages which are governed by transfer of nucleons.

It was pointed out in the literature [13] that closed shell projectile and target nuclei are favorable for the synthesis of SHEs. The reason is not only a low (negative) 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 proceeds along cold fusion valleys, where the reaction partners maintain kinetic energy up to the closest possible distance. Recent theoretical studies are able to reproduce the measured data. That work is continued by various groups (see e.g. [14,15] and references therein) aiming to work out reliable predictions for the production cross-sections of SHEs.

CONCLUSION 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 to 116 and 118 obtained in Dubna using hot fusion reactions seem to break this trend when the region of spherical superheavy elements is reached.

The progress towards the exploration of the island of spherical SHEs is difficult to predict. Despite the exciting new results, many questions of more general character are still awaiting an answer. New experimental developments will not only make it possible to perform experiments aimed at synthesizing new elements in reasonable measuring times, but will also allow for a number of various other investigations covering reaction physics and spectroscopy.

One can hope that, during the coming years, more data will be measured in order to promote a better understanding of the stability of the heaviest elements and the process that leads to fusion. A microscopic description of the fusion process will be needed for an effective explanation of all measured phenomena in the case of low dissipative energies. Then, the relationships between fusion probability and stability of the fusion products may also become apparent.

An opportunity for the continuation of experiments in the region of SHEs at decreasing cross-sections affords, among others, 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 and for studying the transition from deformed heavy nuclei to spherical SHEs already at about darmstadtium. The study of fusion reactions with regard to the initiating transfer processes using radioactive neutron rich beams is of high interest.

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.

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