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Production of Superheavy Elements in Symmetric Reactions

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Abstract

The cold fusion reactions leading to superheavy elements (SHE) with Z=104-116 have been considered in our model recently [2]. Here we briefly discuss this model and extend our consideration to fusion reactions between similar a target and projectile. The available experimental cross-sections are well described.

1 Introduction

The synthesis of superheavy elements (SHEs) was and still is an outstanding research object. The properties of SHEs are studied, both theoretically and experimentally [1-7]. In two series of experiments the heaviest elements from 107 to 109 and from 110 to 112 were synthesized at GSI-Darmstadt by using cold fusion reactions [1]. In the cold fusion, SHEs are produced by reactions of the type X+(Pb,Bi) $\rightarrow$ SHE+1n at subbarrier energies. The excitation energy of a compound nucleus formed by cold fusion is low, $\approx$ 10–20 MeV. It was measured that the center-of-mass kinetic energy of reaction partners, leading to elements with $Z \leq 112$, corresponds to the fusion barrier or is even less [1]. The experimental study of an excitation function for the SHE production becomes increasingly difficult due to very small cross-sections and narrow width of the excitation function [1].

In the Ref. [2] we present a model for description of measured excitation functions for the SHE production in cold fusion reactions. The maximum position and the width of the excitation function for cold fusion reactions X+^{208}Pb,^{209}Bi leading to elements with Z=104-112 are well described in [2], see also Fig. 1. Within our approach [2] the process of the SHE formation proceeds in three stages: (*i.*) The capture of two spherical nuclei and the formation of a common shape of the two touching nuclei. Low-energy surface vibrations and a transfer of few nucleons are taken into account at the first step of the reaction. (*ii.*) The formation of a spherical or near spherical compound nucleus. (*iii.*) The surviving of an excited compound nucleus during evaporation of neutrons and γ-ray emission which compete with fission. A reduction of the fission barrier was taken into account, which arises from a reduction of shell effects at increasing excitation energy of the compound nucleus.

One of the heaviest systems experimentally studied over a wider range of excitation energy is ^{58}Fe+^{208}Pb $\rightarrow$^{265}Hs+n [1], the data are shown in Fig. 1. The experimental data are compared with several modifications of our model. In the simplest case, using tunneling through a one-dimensional barrier and the WKB method, the model strongly underestimates the experimental fusion cross-sections. Better agreement is obtained, when the neutron transfer channels from lead to iron are taken into account. Similarly, the cross-sections increase if the low-energy 2^+ and 3^- surface vibrational excitations of both projectile and target are included in the calculations, see Fig. 1. The best results are obtained by considering transfer and vibrations simultaneously. The values of parameters and other details are presented in Ref. [2]. In our model [2] we have two fitting parameters as well as other parameters, which are taken from experimental data and other calculations, see for detail [2]. Note that we are able to describe data for reactions ^{58}Fe+^{207}Pb $\rightarrow$^{264}Hs+n (see Fig. 1) and ^{58}Fe+^{209}Bi $\rightarrow$^{266}Mt+n (see Fig. 11 in [2]) by using the same fitting parameters which we fixed for reaction ^{58}Fe+^{208}Pb $\rightarrow$^{265}Hs+n.

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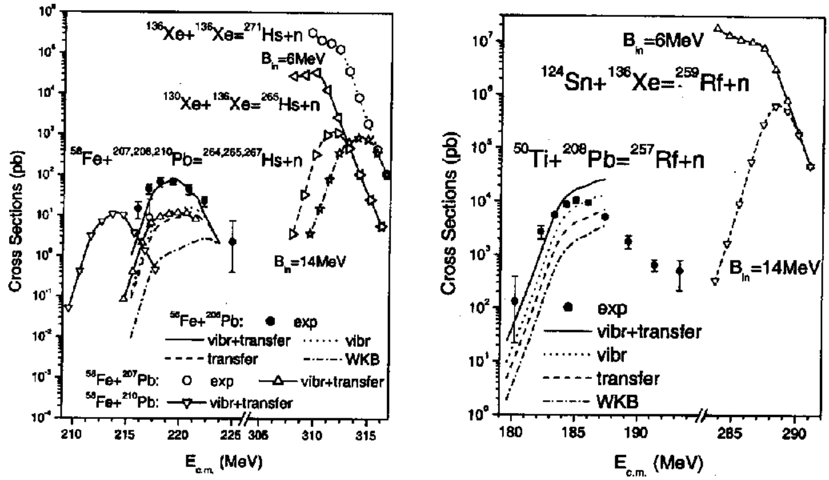

Figure 1: Calculated excitation functions for the reactions ^{58}Fe+^{207,208,210}Pb $\rightarrow^{264,265,267}$Hs+n and ^{130,136}Xe+^{136}Xe $\rightarrow^{265,271}$Hs+n (left) and ^{50}Ti+^{208}Pb $\rightarrow^{257}$Rf+n and ^{124}Sn+^{136}Xe $\rightarrow^{259}$Hs+n (right). The continuous curve shows the results which take into account for both the low-energy 2^+ and 3^- vibrations and the neutrons transfer channels. For reactions ^{58}Fe+^{208}Pb $\rightarrow^{265}$Hs+n and ^{50}Ti+^{208}Pb $\rightarrow^{257}$Rf+n the dotted and the dashed curves show the results based on solely the 2^+ and 3^- vibrations and the neutron transfer channels, respectively. The results of the one-dimensional WKB approach last two reactions are shown by the dash-dotted curves. The results of calculations including both vibrations and transfer enhancements obtained for other reactions are additionally marked by symbols, see assignments in figs. The experimental data are taken from [1,3].

2 Production of SHE in Nearly Symmetric Heavy Ion Collisions

It is also possible to produce SHE in collisions of similar nuclei. For example, the nuclide ^{265}Hs can be formed in both reactions ^{58}Fe+^{208}Pb $\rightarrow^{265}$Hs+n and ^{130}Xe+^{136}Xe $\rightarrow^{265}$Hs+n. The excitation functions for reactions ^{130,136}Xe+^{136}Xe $\rightarrow^{265,271}$Hs+n obtained in our model for different values of the inner barrier $B_{\rm Sph} = 6$ MeV and 14 MeV are presented in Fig. 1.

We can describe the touching configuration and shape evolution of nearly symmetric systems by using the shape parametrization $R(\vartheta) = R(p,q)[1 + p\sum_{\ell=2,\ell\neq 4}^{9} \beta_\ell Y_{\ell 0}(\vartheta) + q\beta_4 Y_{40}(\vartheta)]$, where $p = q = 1$ at the touching point of two spherical colliding ions and the deformation parameters β_ℓ are fixed at the touching point. The volume of the nucleus is constant during the shape evolution. The potential energy surface for the reaction the ^{130}Xe+^{136}Xe$\rightarrow^{266}$Hs is presented in Fig. 2.

As mentioned before, we made calculations of synthesis of the SHE using nearly symmetric reactions for two different values of the inner barrier. The value of the inner barrier $B_{\rm Sph} = 6$ MeV is close to that of the adiabatic fission barrier, see Fig. 2. Note that the potential energy surface for ^{266}Hs in Fig. 2 has a strong slope from touching point (bottom right corner) to the quasi-fission direction (upper right corner). It is possible to evaluate the exact value of the inner barrier and the branching ratio between compound nucleus formation and quasi-fission processes by studying the quantum dynamical shape evolution from two touching nuclei to the near spherical compound nucleus. Unfortunately such calculations are not available now. Therefore, we also made calculations for a higher value of the inner barrier $B_{\rm Sph} = 14$ MeV, which may simulate a stronger competition between SHE formation and quasi-

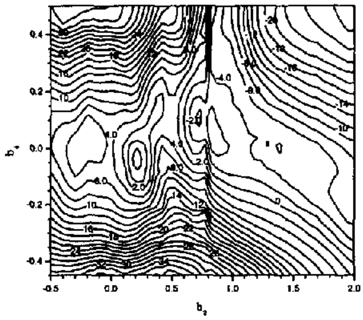

Figure 2: Potential energy surface as a function of the deformation parameters β_2 and β_4 for cold fusion reaction $^{130}Xe+^{136}Xe \rightarrow ^{266}Hs$. The touching configuration of the spherical projectile and target nucleus is close to the bottom right corner and that of the ground-state is close to $\beta_2 \approx 0.2$ and $\beta_4 \approx -0.05$. The ratio between deformation parameters β_2, β_3, β_5, β_6, β_7, β_8 and β_9 is fixed at the touching point. The contour lines are drawn every 2 MeV.

fission. Note that the SHE production cross sections for near symmetric reactions are mainly related to the shape evolution stage, because the height of the outer barrier (capture barrier) is relatively small.

3 Conclusion

Experimental studies of SHE formation in near symmetric collisions may be started by using the reaction $^{124}Sn+^{136}Xe \rightarrow ^{259}Rf+n$, because it is easy to substitute ^{208}Pb by ^{124}Sn as target. It would be interesting to check our estimates, because even for the inner barrier $B_{\rm Sph} = 14$ MeV the SHE formation cross section obtained in our model for near symmetric reactions is larger then for that for the cold fusion reaction leading to similar isotopes, see Fig. 1.

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