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PRODUCTION OF SUPERHEAVY ELEMENTS IN COLD FUSION REACTIONS*

V.Yu. Denisov[a,b] and S. Hofmann[a]

[a]GSI–Darmstadt, Planckstrasse 1, D-64291 Darmstadt, Germany
[b]Institute for Nuclear Research
Prospect Nauki 47, 252028 Kiev, Ukraine †

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In the presented work we make an attempt to describe the cold fusion reaction of the type X + (Pb,Bi) → SHE + 1n at subbarrier energies. The presented model describes well the available experimental cross-section data and allows for predicting cross-section values for the synthesis of so far unknown heavier elements.

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1. Introduction

The synthesis of superheavy elements (SHEs) was and still is an outstanding research object. In two series of experiments the heaviest elements from 107 to 109 and from 110 to 112 were synthesized at GSI in Darmstadt by using cold fusion [1]. In cold fusion, SHEs are synthesized by reactions of the type X + (Pb, Bi) → SHE + 1n at subbarrier energies. In the following section we shortly discuss the model for the description of the cold fusion reaction. In Section 3, the obtained results are discussed and compared with the available experimental data.

2. Model

Because the cold fusion is observed at energies below the barrier, we consider as a first step in our model the capture process and the penetration of the fusion barrier (part **1**). The formation of a compound nucleus of a near spherical equilibrium shape occurs after capture. A barrier develops on the way from the touching configuration of two spherical nuclei to the near spherical compound-nucleus shape. The shape evolution and

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† Permanent address.

the transmission through the barrier on the way to the spherical or near spherical configuration are discussed in part **2**. The last step of the reaction is determined by the evaporation of nucleons and the emission of γ quanta forming SHEs in the ground-state. These processes are in competition with fission (part **3**).

1. Various mechanisms were discussed to explain the phenomenon of subbarrier fusion: the excitation of low energy states in projectile and target nucleus, the transfer of nucleons and other phenomena [2,3]. It was shown that the fusion cross-section is strongly enhanced by the coupling to both the low-energy surface vibrations and the few-nucleon transfer channels [2,3].

The model which we apply here for the barrier penetration is discussed in more detail in [3]. In the following, we present the main features of the model. It describes well the experimental data of the fusion cross-sections $\sigma_{\rm fus}(E)$ as well as of the mean angular momenta $\langle L(E)\rangle$ in the case of lighter nuclei. The enhancement of subbarrier penetration due to the coupling to both the low-energy surface excitations and the neutron transfer is taken into account.

2. The shape of the fusing system after barrier penetration, *i.e.* at the inner turning point, is not much different from that of two spherical nuclei at the touching point. It is elongated, asymmetric and laced. From such a configuration the system develops further into the direction of a near spherical compound nucleus and later to the ground-state, which can be deformed or spherical. We propose that this shape evolution is described by smooth reduction of the parameters p and q used in the parametrization of the shape

$$R(\vartheta) = R(\{\beta\}) \left[1 + \sum_{l=2,\mathrm{even}}^{N} p\beta_l Y_{l0}(\vartheta) + \sum_{l=3,\mathrm{odd}}^{N} q\beta_l Y_{l0}(\vartheta)\right] . \qquad (1)$$

The values of p and q are equal to 1 at the touching point of two spherical colliding ions and the deformation parameters β_ℓ are fixed at the touching point. The values of the deformation parameters of SHEs in the ground-state are $p, q \approx 0$. The parameters p and q ($0 \le p \le 1$, $0 \le q \le 1$) are connected to the elongation and asymmetry degrees of freedom of the nuclear shape during the formation of the spherical compound nucleus, respectively.

The potential energy surfaces for the nuclei ^{266}Hs and ^{286}114 formed in reactions ^{58}Fe, ^{78}Ge + ^{208}Pb, respectively, are presented in Fig. 1. Although the shape parametrization (1) is rough at the touching point, it is possible to study the inner barrier, which has to be bypassed or crossed during the process of sphere formation, as shown in Fig. 1. The macroscopic energies plus shell correction energies as function of the parameters p and q in the deformation space $p\beta_2, q\beta_3, p\beta_4, q\beta_5, ..., q\beta_9$ are given.

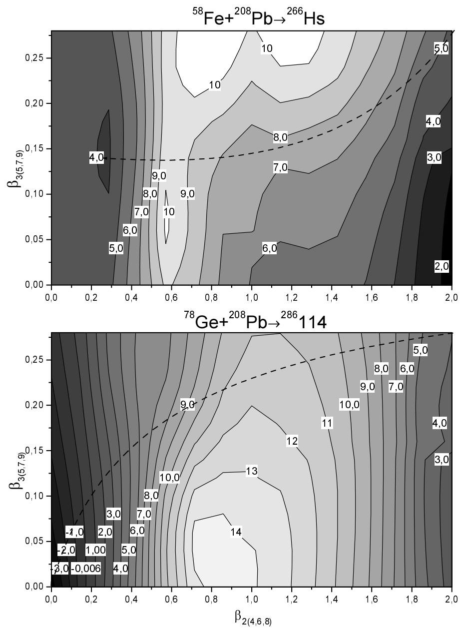

Fig. 1. Potential energy surfaces as function of the deformation parameters β_i for the cold fusion reactions ^{58}Fe+^{208}Pb→^{266}108 and ^{78}Ge+^{208}Pb→^{286}114. In each graph the touching configuration of the spherical projectile and target nucleus is close to the upper right corner and that of the ground-state close to bottom left. The dashed line is the tunneling trajectory which is drawn by eye and under assumption that all deformations are monotonously varying during the motion to the equilibrium compound nucleus shape.

The transmission coefficient for the barrier penetration during the shape evolution from the touching projectile and target nuclei to the near spherical shape of the compound nucleus were estimated in the Hill–Wheeler approximation for various collision energies E.

3. After the first two steps of the reaction, the transmission through the fusion and the inner barrier, a compound nucleus of atomic weight A is formed with equilibrium deformation near sphericity and excitation energy E^*. The dominant decay modes of a heavy compound nucleus at low excitation energy, as it is the case in cold fusion, are the evaporation of neutrons and the fission. The residue of mass $A-1$ after neutron emission may still be excited. Again, it may fission or cool down by emission of γ's. We take into account all these processes. In excited nuclei the fission barrier B^* is reduced due to both the washing out effect of the shell correction and the centrifugal potential. These two effects are very important for the correct description of SHE production cross sections.

3. Results and discussion

One of the heaviest systems studied experimentally over a wider range of excitation energy is ^{58}Fe+^{208}Pb $\rightarrow^{266}$Hs* [1], the data are shown in Fig. 2. 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 results strongly underestimate 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 by including in the calculations the low-energy 2^+ and 3^- surface vibrational excitations of both projectile and target. The best results are obtained by considering transfer and vibrations simultaneously.

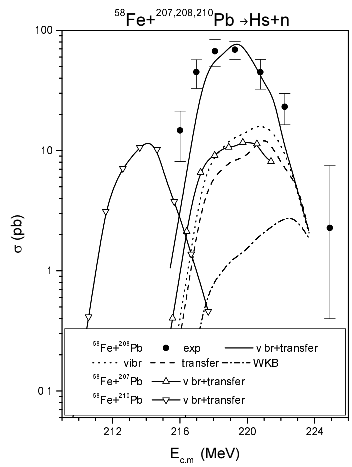

Fig. 2. Calculated excitation functions for the reactions ^{58}Fe + ^{207,208,210}Pb $\rightarrow^{264,265,267}$Hs + n. The continuous curve shows the results for the reaction ^{58}Fe + ^{208}Pb $\rightarrow^{265}$Hs + n taking into account both the low-energy 2^+ and 3^- vibrations and the neutrons transfer channels. The dotted and the dashed curve shows the results for considering solely the 2^+ and 3^- vibrations and the neutron transfer channels, respectively. The result of the one-dimensional WKB approach is shown by the dash-dotted curve. The data obtained for the reaction ^{58}Fe + ^{207}Pb $\rightarrow^{264}$Hs + n are represented by ($\triangle$) and those for ^{58}Fe + ^{210}Pb $\rightarrow^{267}$Hs + n by ($\bigtriangledown$). In both cases only the results including vibrations and transfer are shown. The relations taking into account the channels separately are similar as in the case of ^{58}Fe + ^{208}Pb. The experimental data shown here and in Figs. 3–4 are from [1].

The intrinsic barrier on the way from the touching configuration to the near spherical compound nucleus is close to 6 MeV for the reaction ^{58}Fe+^{208}Pb $\rightarrow^{265}$Hs+n, see Fig. 1. The intrinsic barrier is of minor importance for the reaction ^{58}Fe+^{208}Pb.

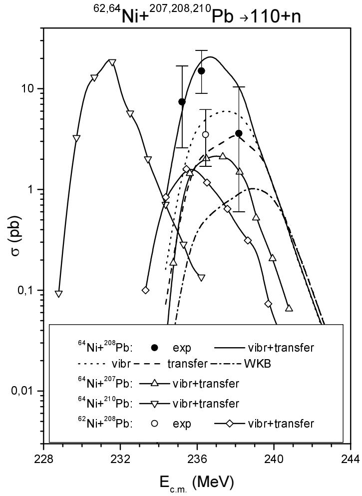

Fig. 3. Calculated excitation functions for the reactions ^{62,64}Ni + ^{207,208,210}Pb → 110 + n. The notation for the reactions ^{64}Ni + ^{207,208,210}Pb corresponds to ^{58}Fe + ^{207,208,210}Pb in Fig. 2. The insert explains the assignment of the reactions to the symbols.

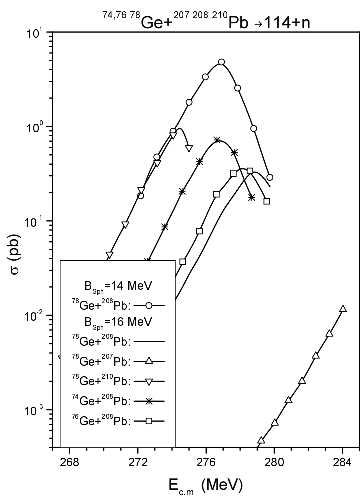

Fig. 4. Calculated excitation functions for the reactions ^{74,76,78}Ge + ^{207,208,210}Pb → 114 + n. The insert explains the assignment of the reactions to the symbols. All curves on the plot include both vibrations and transfer. For these reactions the subbarrier enhancement is small and, therefore, the values taking into account the individual contributions are only slightly lower. A reduction of the inner barrier by 2 MeV increases the cross-section considerably, as shown by the two curves for the reaction ^{78}Ge + ^{208}Pb →^{285}114 + n.

The results of the calculations for reactions between the projectiles ^{62,64}Ni, ^{74,76,78}Ge and a ^{208}Pb target are presented in Figs. 3–4. The high intrinsic barrier is very important for these reactions. The results of the calculations for reactions with the lighter and heavier target isotopes ^{207}Pb and ^{210}Pb are also drawn in Figs. 2–4.

In conclusion we note that the following reactions were analyzed in detail [4]: (^{58}Fe, ^{64}Ni, ^{70}Zn, ^{78}Ge) + ^{207}Pb, (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{59}Co, ^{62,64}Ni, ^{65}Cu, ^{66,68,70}Zn, ^{71}Ga, ^{74,76,78}Ge, ^{75}As, ^{80,82}Se) + ^{208}Pb, (^{58}Fe, ^{64}Ni, ^{70}Zn, ^{78}Ge) + ^{210}Pb and (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni, ^{70}Zn, ^{78}Ge) + ^{209}Bi. The measured cross-sections and the decrease by about a factor of 3 per element could be rather well reproduced.

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