Eur. Phys. J. A **22**, 9–12 (2004)
DOI 10.1140/epja/i2004-10058-0

THE EUROPEAN PHYSICAL JOURNAL A

Letter

Predictions of the residue cross-sections for the elements Z = 113 and Z = 114

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Received: 16 June 2004 /
Published online: 19 October 2004 –
Communicated by W. Henning

Abstract. A good reproduction of experimental excitation functions is obtained for the $1n$ reactions producing the elements with $Z = 108$, 110, 111 and 112 by the combined usage of the two-step model for fusion and the statistical decay code KEWPIE. Furthermore, the model provides reliable predictions of productions of the elements with $Z = 113$ and $Z = 114$ which will be a useful guide for plannings of experiments.

PACS. 25.70.Jj Fusion and fusion-fission reactions – 24.60.-k Statistical theory and fluctuations – 25.60.Pj Fusion reactions – 27.90.+b $220 \leq A$

1 Introduction

The quests for the superheavy elements (SHE) originate from the establishment of the nuclear shell model [1]. Theoretical predictions on the location of the double magic nucleus next to ^{208}Pb have been made with various models of nuclear structure [2,3]. But the predictions are not unique up to now. Some predict 114 for the next magic number of protons, while others predict 120 and 124. That of neutrons is predicted to be mostly 184, but to be 172 in some calculations. However, it is commonly accepted that there exists the superheavy island, *i.e.*, the region of stability far away from the known elements and isotopes in the nuclear chart. In the meantime, enormous efforts have been devoted to the search for traces of their existence in nature as well as to their syntheses in laboratories. Nowadays, the elements with the atomic numbers up to 112 are synthesized and identified [4]. Furthermore, observations have been reported which strongly indicate the syntheses of the elements with $Z = 114$ and 116 [5]. Recent experimental progress is by the use of heavy-ion fusion reactions. But, unfortunately, the fusion mechanism of massive systems has not yet been understood well. Experimentally, it is well known that there exists a so-called fusion hindrance, which is typically described by the necessity of extra incident kinetic energy in addition to the Coulomb barrier height [6]. The extra energy rapidly increases as $Z_1 \times Z_2$ increases with Z_1 and Z_2 being the atomic numbers of projectile and target, respectively [7]. Thus, it is crucially important to understand the hindrance mechanism and to take it into account properly for theoretical predictions of fusion probabilities for SHE.

The present authors *et al.* have recently proposed the two-step model for the fusion of massive systems which has turned out to properly take into account the strong hindrance [8]. In the present paper, we apply it to the so-called cold-fusion path with target of ^{208}Pb or ^{209}Bi. According to the compound nucleus theory of reactions, the other important factor is survival probability against fission. Although the theory may not be valid for such unstable systems as the nuclei of SHE as discussed below, we presume the theory to be applicable, *i.e.*, we employ the following formula for residue cross-sections, as usual:

$$\sigma_{\rm res} = \pi\bar{\lambda}^2 \sum (2J+1) P^J_{\rm fusion}(E_{\rm c.m.}) \cdot P^J_{\rm surv}(E^*), \quad (1)$$

where J is the total spin of the system and $E_{\rm c.m.}$ the incident energy in the center-of-mass system. E^* is equal to $E_{\rm c.m.} + Q$ with the fusion Q-value. As usual, $P^J_{\rm fusion}$ and $P^J_{\rm surv}$ denote the fusion and the survival probabilities for the spin J, respectively. The latter is obtained by the use of the statistical disintegration code, which is newly developed by solving the time-dependent Bateman equation [9]. The former is the most unknown part, as mentioned above. There are several approaches for the description of the fusion process, such as quantum

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tunneling [10], mass transfer between two mass centers, etc. [11]. In the two-step model, the fusion process is divided into two phases: the approaching phase and the formation phase. They correspond, respectively, to the passing-over of the Coulomb barrier and to the shape evolution toward the spherical compound nucleus, starting from the pear-shaped sticking configuration of the incident system. The two steps proceed successively. Thus, $P^J_{\rm fusion} = P^J_{\rm sticking} \cdot P^J_{\rm formation}$, where $P^J_{\rm sticking}$ and $P^J_{\rm formation}$ denote probabilities for sticking and formation, respectively, corresponding to the steps. Each probability can be calculated by solving the dynamics of the process in each step.

We will first remind ourselves briefly of the two-step model. Then, we will check the ability of the model to reproduce known experimental data. Finally, we will present predictions for the residue cross-sections for the reactions ^{70}Zn + ^{209}Bi $\rightarrow$ $^{278}113 + 1n$, ^{71}Ga + ^{208}Pb $\rightarrow$ $^{278}113$ + $1n$ and ^{76}Ge + ^{208}Pb $\rightarrow$ $^{283}114 + 1n$ that have not yet been measured but will be in a near future.

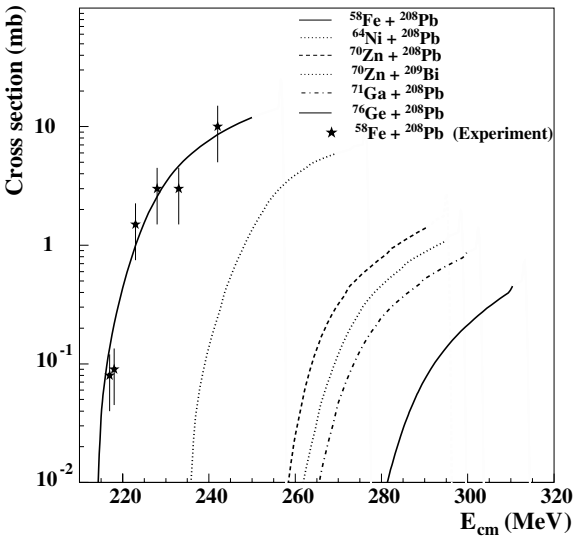

Fig. 1. Fusion cross-sections for several systems with ^{208}Pb target. The symbols represent experimental data for the ^{58}Fe + ^{208}Pb system The lines represent the results of the two-step model calculations.

2 Reminder of the important points of the two-step model

Since the two-step model is already explained elsewhere and successfully applied to the so-called hot-fusion path, *i.e.*, ^{48}Ca + actinide systems [8], here we would like to remind ourselves of the characteristic aspects of the model. The united system is supposed to be excited, which means that the incident kinetic energy has been converted into the thermal energy. This conversion is presumed to start around the top of the Coulomb barrier in view of the deep inelastic collisions (DIC). Thus, for the approaching phase, we adopt the surface friction model (SFM) [12], *i.e.*, we describe a two-body collision process up to the contact of the incident ions with classical trajectories under the Coulomb and the nuclear forces as well as the friction force, to which an associated fluctuation is supplemented in accord with the dissipation-fluctuation theorem. The temperature which controls the strength of the fluctuation force is time dependent, calculated with the energy transferred to the intrinsic excitation (the heat bath of nucleons) from the incident kinetic energy during the approaching phase. The formation phase of the spherical compound nucleus is described by a multi-dimensional Langevin equation for the shape evolution [13] with the friction of the one-body model (OBM) [14], *i.e.*, one-body wall-and-window formula and its associated random force, where a constant temperature is assumed for simplicity. And the minimum number of parameters are employed for the description of shapes of the united system, *i.e.*, the distance between two mass centers and the mass asymmetry. (Effects of the neck degree of freedom are being investigated [15].) The potential energy for the formation process is calculated with the liquid-drop model (LDM) [16] without shell correction energy, considering the amalgamated system to be well excited.

The two theoretical frameworks employed for the two steps, respectively, are not essentially new, but they are utilized not for the whole process, but for the proper parts of it. Of course, they might not be accurate enough, but for the moment, we keep their original values of the parameters in order to avoid introducing additional ambiguities.

A novel aspect of the present model, thus, is on how to connect the two phases, *i.e.*, how to connect two-body collision process and shape evolution of the amalgamated system. Actually, the SFM gives the results that the radial momentum at the contact point is of a Gaussian distribution [17]. The origin of this distribution comes from the Gaussian nature assumed for the fluctuation force. The width of this distribution is consistent with the temperature. The connection is made through this distribution at the contact point, which is the result of the two-body collision process and, at the same time, the distribution of the initial values for the shape evolution of the second phase. Therefore, the present model is a proposal of a new connection method, which is to be called "statistical connection method". It is worth emphasizing here that the method is new and completely different from the adiabatic or diabatic viewpoint.

3 Comparison with experiment

Firstly, we check the validity of the fusion probabilities calculated by the two-step model in the cold-fusion path. The fusion cross-sections are calculated with the usual expression as follows: $\sigma_{\rm fusion} = \pi\lambda^2 \sum (2J+1) P^J_{\rm fusion}$. Unfortunately, there are not many data available on fusion reactions in the cold-fusion path, except one set of data on the ^{58}Fe + ^{208}Pb system [18]. Figure 1 shows the comparison of the calculated results with the measured excitation function of the system, together with calculated results for the other systems.

It is readily seen that the calculation reproduces the experiment almost perfectly, which is remarkable, considering that there is no adjustable parameter used. This means that the present fusion model well takes into account the fusion hindrance, because it reproduces the data which apparently show the hindrance (the maximum value of order 10 mb is anomalously small, compared with the naively expected value of a few barn for such heavy systems). Thus, the fusion probabilities calculated by the present model are considered to be realistic.

Then, we calculate residue cross-sections according to eq. (1). Calculations of the survival probabilities are made for each partial wave with J by the code KEWPIE [9] which has only one free intrinsic parameter that is the reduced friction coefficient (β) used for the Kramers factor [19]. This value is set to $\beta = 5 \cdot 10^{20}$ s^{-1} consistently with OBM for all the results presented in this publication. Then, the essential ambiguities are the masses or shell correction energies of SHE, which are, of course, not known experimentally and predicted by various structure calculations, as mentioned in the introduction. To know their influence, we have made the calculations employing three different predictions of mass: Möller *et al.* [3], Koura [20], Myers and Swiatecki [21]. It should be noted here that the shell correction energy essentially determines the fission barrier in the SHE, because the LDM fission barrier height is nearly equal to zero, which is understood by the fact that the fissility is close to 1. Of course, the shell correction energies predicted by structure calculations are for the ground state, and are expected to decrease in absolute values as the excitation energy increases and finally to disappear in high excitation. This is crucially important for the survival probability of the compound nuclei. Therefore, it is taken into account with the prescription proposed by Ignatyuk *et al.* [22], where the level density parameter for the spherical shape is expressed as $a(E^*) = a_n \cdot (1 + f(E^*) \cdot \Delta E_{\rm shell}/E^*)$ with $f(E^*) = 1 - \exp(-E^*/E_{\rm d})$ and E^* being the excitation energy of the compound nucleus, as defined in the introduction. The shell damping energy $E_{\rm d}$ is taken to be 18 MeV, following ref. [22]. The parameter a_n (a_f for the saddle point shape as well) is calculated with the formula by Töke and Swiatecki [23].

Now it is in order to make comparisons of the present model with the experiments. As will be seen in fig. 2, the calculated peak positions in $E_{\rm c.m.}$ are not far from the data, though there are small differences among results with the different mass predictions. This is essentially due to the slight differences in the macroscopic part of the masses among the predictions, which is consistent with the qualitative explanation by Swiatecki *et al.* [24]. Absolute values of the calculated peak heights are always larger than the measured $1n$ cross-sections. How much they are depends on the mass predictions. For precise reproductions, refinements would be necessary somewhere in the present model. From the remarkable reproduction of the fusion excitation shown in fig. 1, they should be about the calculation of the survival probabilities. Since there are no commonly accepted values of the shell correction

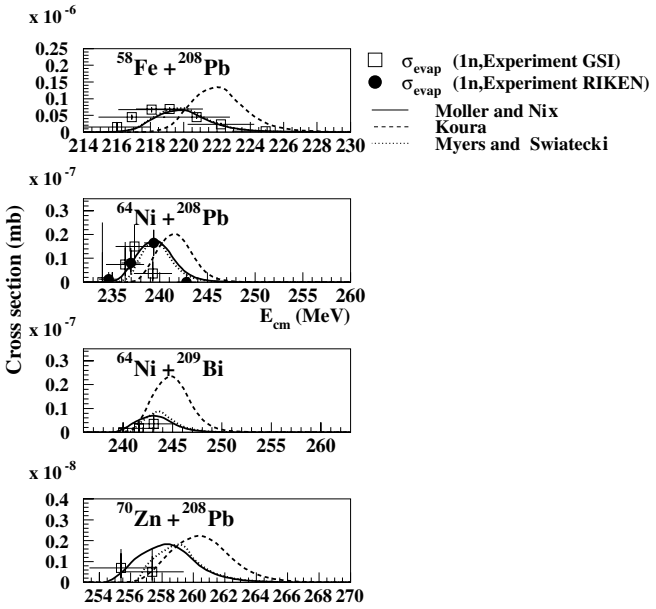

Fig. 2. Residue cross-sections for systems that have been already studied experimentally. The symbols represent experimental data with the error bar in energy (thickness of the target). The lines represent the results of the present calculations assuming different predictions of mass and shell correction energy.

energy, it would be allowed to introduce a phenomenological scaling factor for the predicted shell correction energies. Of course, scaled shell correction energies should not be outside the variety of the theoretical predictions. The factor is fixed for each model of mass predictions so as to reproduce well the peak height for the reaction ^{64}Ni + ^{208}Pb measured recently at RIKEN [25]. They are 0.4, 0.36 and 0.4 for Möller *et al.*, Koura, and Myers and Swiatecki, respectively. It is remarkable that the experiments on $Z = 108$, 110, 111, and 112 are extremely well reproduced by the calculations, especially with the mass predictions by Möller *et al.* and Myers and Swiatecki. It is worth noticing here that the positions and the widths of their peaks are calculated absolutely in $E_{\rm c.m.}$ without any adjustment, just simply by the use of $P_{\rm fusion}$ and $P_{\rm surv}$ calculated with the present model. Moreover, the global experimental trend of the decreasing peak heights as the atomic number Z increases is well reproduced (note that the scales of the ordinates in the panels are different).

4 Predictions of the residue cross-section for elements Z = 113 and Z = 114

As it has turned out that the present model is able to reproduce very well the residue cross-sections for the measured systems, it is natural and interesting to apply the present recipe to the systems where measurements are not yet made. We focus on the yet undiscovered element $Z = 113$ and a new isotope of the $Z = 114$ produced by the cold-fusion path.

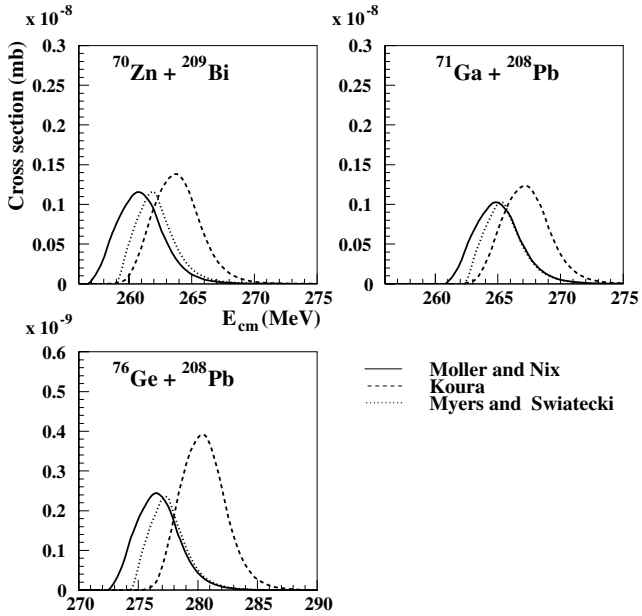

Fig. 3. $1n$ Residue cross-section for systems with $Z = 113$ and 114 that have not yet been measured. The lines represent the results of the present calculations assuming different predictions of mass and shell correction energy.

For the production of the $Z = 113$, the reaction $^{70}\mathrm{Zn} + {}^{209}\mathrm{Bi} \rightarrow {}^{278}113 + 1n$ or the reaction $^{71}\mathrm{Ga} + {}^{208}\mathrm{Pb} \rightarrow {}^{278}113 + 1n$ is under consideration among experimentalists. As we see in the upper panels of fig. 3, both reactions are predicted to lead to nearly the same absolute value of $1n$ residues for all the mass predictions employed, which comes from the fact that, on the one hand, the fusion barrier is unfavourable for the reaction $^{71}\mathrm{Ga} + {}^{208}\mathrm{Pb} \rightarrow {}^{271}113 + 1n$ but, on the other hand, the high Q-value of this reaction leads to lower excitation energy that is favourable for the emission of a neutron in the competition with fission.

The element $Z = 114$ has been already produced by the hot-fusion path [5], but the experiment with the reaction $^{76}\mathrm{Ge} + {}^{208}\mathrm{Pb} \rightarrow {}^{283}114 + 1n$ will be the first measurement of the production of $Z = 114$ by the cold-fusion path. The results by the present model are shown in the lower panel of fig. 3. The predicted value of the peak height is around a few tenths of pico-barn. The absolute values of the predicted peak heights could be even smaller, considering the possibility that the scaling factor would have a weak Z-dependence in view of the slight overestimations already seen in $Z = 111$ and 112. To measure residues with so low cross-sections is a challenge in experiment.

5 Conclusion

The two-step model, combined with the theory of statistical decay, has turned out to be successful in reproducing the positions, the shapes and the absolute values of the peak heights of the measured $1n$ residue cross-sections with only one scaling factor for the shell correction energies predicted by the structure calculations. Furthermore, the calculations are made on the reactions $^{70}\mathrm{Zn} + {}^{209}\mathrm{Bi} \rightarrow {}^{278}113 + 1n$ and $^{71}\mathrm{Ga} + {}^{208}\mathrm{Pb} \rightarrow {}^{278}113 + 1n$ as well as $^{76}\mathrm{Ge} + {}^{208}\mathrm{Pb} \rightarrow {}^{283}114 + 1n$ without any additional adjustment. Figure 3 shows the calculated excitation functions, which are the first predictions for the elements $Z = 113$ and 114 made with the dynamical model of reactions. The results are expected to be a reliable guide for ongoing or future experiments for the elements. More detailed analyses are now under way, including cases with another scaling factor for E_{d} (stiffness of the shell) instead of that for the shell correction energy, etc. In brief, it can be stated that the present model provides a realistic reaction mechanism for the production of the superheavy elements. The ultimate tests of the model are, of course, experiments on the above systems.

The authors thank W.J. Swiatecki for fruitful discussions and K. Morita for the access to the data before publication. One of us (B.B.) thanks the Yukawa Institute for its warm hospitality. The authors acknowledge JSPS for supports (contracts P-01741, 1340278).

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