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Excitation functions for the production of superheavy nuclei in cold fusion reactions

Robert Smolańczuk*

Nuclear Theory Department, Soltan Institute for Nuclear Studies,

Hoża 69, PL-00-681 Warszawa, Poland

and Nuclear Science Division, Lawrence Berkeley National Laboratory,

1 Cyclotron Road, Berkeley, CA 94720, USA

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Abstract

Excitation energy dependence of the cross sections of the reactions $^{208}\mathrm{Pb}_{126}(^{50}\mathrm{Ti}_{28},1n)^{257}\mathrm{Rf}_{153}$ and $^{208}\mathrm{Pb}_{126}(^{58}\mathrm{Fe}_{32},1n)^{265}\mathrm{Hs}_{157}$ is calculated and compared with the experimental data measured at GSI-Darmstadt. Such a dependence is also calculated for the reaction $^{208}\mathrm{Pb}_{126}(^{86}\mathrm{Kr}_{50},1n)^{293}118_{175}$ reported recently by the Berkeley group, and for reactions which may lead to the synthesis of element 119 and production of its odd-Z descendants. Recommendations for future experiments based on the present study are presented.
27.90.+b, 24.60.Dr

*Electronic address: smolan@fuw.edu.pl

In Ref. [1], we have developed a model describing the production mechanism of superheavy nuclei in fusion reactions of heavy ions with the doubly magic lead target nucleus. We considered cold reactions in which a final superheavy nuclear system is formed after the emission of only one neutron [2,3]. The proposed model [1] was based on the concepts of the quantal tunneling of the Coulomb barrier and the statistical description of the survival probability of the compound nucleus. Theoretical predictions for the formation cross sections made in Ref. [1], and also calculations of the nuclear properties performed in Ref. [4], have inspired an experiment on the production of superheavy nuclei in the bombardments of $^{208}Pb_{126}$ by the $^{86}Kr_{50}$ ions performed at Berkeley this year [5].

The aim of the present study is to extend our model [1] for the description of the excitation functions for the production of superheavy nuclei in the $1n$-emission channel of fusion reactions and, in particular, to predict the formation cross section of an isotope $^{294}119_{175}$. This isotope might initiate an α-decay chain of unobserved so far odd-Z elements, 119, 117, 115 and 113, with the predicted properties discussed in Ref. [4]. The objective of this paper is also the discussion of the possible uncertainties which may influence the probability of the formation of isotopes of the superheavy elements 118 and 119. Some of the discussed uncertainties arise from a shape and a position of the maximum of the calculated excitation functions.

Previously [1], we calculated the formation cross sections assuming that the maximum of the excitation function is at the excitation energy equal to the sum of the neutron separation energy for the compound nucleus S_n and the separation energy of the second neutron S_n^{ER} or the sum of S_n and the height of the static fission barrier for the $1n$-evaporation residue B_f^{ER} if $B_f^{ER} < S_n^{ER}$. In the latter case, the quantal tunneling through the fission barrier was disregarded. At the maximum of the excitation function, the probability of the emission of only one neutron $P_{1n,l}$ from the compound nucleus with the total excitation energy E^* and angular momentum l was assumed to be equal to the neutron-to-total width ratio Γ_n/Γ_{tot}, where Γ_n is the partial width for neutron emission and Γ_{tot} is the total decay width for the compound nucleus. The above simple rule for the maximum of the excitation function was proposed in Ref. [1] as a consequence of the expected drastic decrease of $P_{1n,l}$ for the intrinsic excitation energies exceeding slightly the threshold for the second neutron emission or fission following the first neutron emission.

In the present paper, in order to obtain the excitation functions, the excitation energy dependence of $P_{1n,l}$ is calculated by using simple analytical expressions. For the case of $B_f^{ER} < S_n^{ER}$, we calculate $P_{1n,l}$ by the formula

$$P_{1n,l} = \frac{\Gamma_n}{\Gamma_{tot}}\{1 - [1 + \exp(\frac{2\pi}{\hbar\omega}(S_n + B_f^{ER} - E^*_{int}(sd)))]^{-1}\}, \tag{1}$$

where $\hbar\omega$ is assumed to be equal to 1 MeV and $E^*_{int}(sd)$ is the intrinsic excitation energy at the saddle-point configuration of the compound nucleus. The latter quantity is the difference between the total excitation energy and the rotational energy calculated in the same way as in Ref. [1]. In Eq.(1), we assumed that the rotational energy at the saddle-point configuration of the $1n$-evaporation residue is the same as the one at the saddle-point configuration of the compound nucleus. The expression multiplying Γ_n/Γ_{tot}, i.e. the unity minus the Hill-Wheeler transmission coefficient through the fission barrier, describes the strong decrease of $P_{1n,l}$ for $E^*_{int}(sd)$ around $S_n + B_f^{ER}$ caused by the quantal tunneling effect. For $E^*_{int}(sd)$ about 1 MeV lower than $S_n + B_f^{ER}$, $P_{1n,l}$ is practically equal to the neutron-to-total width ratio and very close to zero for $E^*_{int}(sd)$ about 1 MeV higher than $S_n + B_f^{ER}$.

For the case of $S_n^{ER} < B_f^{ER}$ (i.e. for the reaction $^{208}Pb_{126}(^{50}Ti_{28},1n)^{257}Rf_{153}$), the excitation energy dependence of $P_{1n,l}$ is calculated as a product of the neutron-to-total width ratio and the Jackson function for the $1n$-emission channel. For the intrinsic excitation energy corresponding to the equilibrium deformation of the compound nucleus $E^*_{int}(eq)$ in the range $S_n < E^*_{int}(eq) \leq S_n + S_n^{ER}$, the Jackson function is equal to unity and, consequently, $P_{1n,l}$ is equal to the neutron-to-total width ratio. For $E^*_{int}(eq)$ larger than the threshold for the second neutron emission, $P_{1n,l}$ is given by the approximate formula

$$P_{1n,l} = \frac{\Gamma_n}{\Gamma_{tot}}[1 + \frac{E^*_{int}(eq) - (S_n + S_n^{ER})}{T}]\exp(-\frac{E^*_{int}(eq) - (S_n + S_n^{ER})}{T}). \tag{2}$$

To obtain the excitation function close to the measured function of $^{208}Pb_{126}(^{50}Ti_{28},1n)^{257}Rf_{153}$, a small value of the parameter T must be taken. We use the value of 0.1 MeV for T. This value is considerably smaller than the ones of about 1 MeV usually used in the calculations of the excitation functions for many-neutron-emission channels. The small value of T for the $1n$-emission channel is probably a consequence of a low level density (large shell effects) for the weakly excited compound nucleus $^{258}Rf_{154}$. Eq.(2) describes the decrease of $P_{1n,l}$ to zero for $E^*_{int}(eq)$ in the range of about 1 MeV above the threshold for the second neutron emission. In the energy range of 1 MeV just above this threshold, a change of the neutron-to-total width ratio is relatively small justifying the use of the simple approximate Eq.(2) instead of a more complicated convolution of Γ_n/Γ_f and the distribution of kinetic energy of the emitted neutrons.

The neutron-to-total width ratio Γ_n/Γ_{tot} is approximated by the neutron-to-fission width ratio Γ_n/Γ_f, where Γ_f ($\Gamma_f >> \Gamma_n$) is the partial width for fission. Partial widths for emission of charged particles are disregarded because they are considerably smaller than Γ_n. This is a consequence of larger thresholds for charged particle emission in comparison with the neutron separation energy for the compound nuclei in question. The partial width for γ-ray emission is also disregarded. The neutron-to-fission width ratio is calculated by means of the formulas given in Ref. [1]. The parameter E_D controlling the weakenning of the shell effects with increasing excitation energy is also taken the same as in Ref. [1]. The neutron-to-fission width ratio depends on the intrinsic excitation energy, the neutron separation energy and the height of the static fission barrier for the compound nucleus, as well as the microscopic energies for the saddle configuration of the compound nucleus and for the equilibrium configuration of the $1n$-evaporation residue. All neutron separation energies, fission barriers and microscopic energies are calculated by using the macroscopic-microscopic model [6,7]. For the case where one of the colliding nuclei is odd, Γ_n/Γ_f is calculated with the pre-factor $1/(2I+1)$ [8], where I is the measured ground-state spin of an odd reaction partner [9].

The formation cross section is calculated by using the formula

$$\sigma_{1n} = \pi \lambda\!\!\!^{-2} \sum_{l=0}^{l_{max}} (2l+1) T_l P_{1n,l}, \qquad (3)$$

where $\lambda\!\!\!^{-}$ is the reduced de Broglie wave length of the projectile calculated in the same way as in Ref. [1] and T_l is the transmission probability of the lth partial wave through the fusion barrier. For low $E^*_{int}(eq)$, l_{max} is the maximal value of l for which $E^*_{int}(eq)$ is still larger than S_n. For higher $E^*_{int}(eq)$, l_{max} is the value of l for which the contribution to σ_{1n} becomes smaller than 1%. As the fusion barrier, we use the cutoff Coulomb barrier with the cutoff distance dependent on the size and the electric charge of the colliding nuclei, as it was proposed in Ref. [1]. The parameter c controlling the cutoff distance is taken the same as in Ref. [1]. An important feature of our cutoff Coulomb barrier [1] is the relative isospin dependence of the size of the colliding nuclei which is described by the Nerlo-Pomorska and Pomorski formula [10]. Because of this dependence, which is not taken into account in the one-dimensional potentials discussed in Ref. [11], our fusion barrier is considerably higher in the region of spherical superheavy nuclei in comparison with the barriers obtained by means of the other models. The transmission probability is calculated by means of the WKB approximation with the action integral calculated accurately for each partial wave. This is because the approximate Eq.(4) from Ref. [1] cannot be used for larger excitation energies (in the tail of the excitation function) for which large l contribute to the cross section. For bombarding energies larger than the sum of the Coulomb and the centrifugal potentials at the cutoff distance, $T_l = 1/2$ is assumed. The parameters c, E_D (with the same values as in Ref. [1]) and $\hbar\omega$ (T for $^{257}\mathrm{Rf}_{153}$) have been effectively chosen to reproduce the measured excitation functions of $^{257}\mathrm{Rf}_{153}$ and $^{265}\mathrm{Hs}_{157}$.

The calculated excitation functions for five cold fusion reactions $^{208}\mathrm{Pb}_{126}(^{50}\mathrm{Ti}_{28},1n)^{257}\mathrm{Rf}_{153}$, $^{208}\mathrm{Pb}_{126}(^{58}\mathrm{Fe}_{32},1n)^{265}\mathrm{Hs}_{157}$, $^{208}\mathrm{Pb}_{126}(^{86}\mathrm{Kr}_{50},1n)^{293}118_{175}$, $^{208}\mathrm{Pb}_{126}(^{87}\mathrm{Rb}_{50},1n)^{294}119_{175}$ and $^{209}\mathrm{Bi}_{126}(^{86}\mathrm{Kr}_{50},1n)^{294}119_{175}$ are shown in the linear scale in Fig.1. For the first reaction, the excitation energy dependence of $P_{1n,l}$ is calculated by using Eq.(2) while for the other reactions by means of Eq.(1). The maxima of the excitation functions for the production of well deformed nuclei $^{257}\mathrm{Rf}_{153}$, $^{265}\mathrm{Hs}_{157}$ and an almost spherical nucleus $^{293}118_{175}$ are obtained for slightly larger excitation energies, by $0.3 - 0.4$ MeV, in comparison with the ones calculated in Ref. [1] by means of the simple rule for the optimal excitation energy, S_n+min(S_n^{ER}, B_f^{ER}). The calculated formation cross section has inreased by 30% for ^{257}Rf$_{153}$ and remained almost the same for ^{265}Hs$_{157}$ and $^{293}118_{175}$.

The calculated excitation functions of the reactions ^{208}Pb$_{126}$(^{50}Ti$_{28}$,1n)^{257}Rf$_{153}$ and ^{208}Pb$_{126}$(^{58}Fe$_{32}$,1n)^{265}Hs$_{157}$ are compared in Fig.1ab with the experimental data measured at GSI-Darmstadt [12]. The experimental points are shown with the statistical errors only [12]. For ^{257}Rf$_{153}$, the calculated optimal excitation energy corresponding to the maximum of the excitation function underestimates a measured value only by 0.8 MeV (1.0 MeV in the lab system) and the calculated cross section is larger than the measured one only by about 17%. For ^{265}Hs$_{157}$, we multiplied the theoretical curve by a factor of 2 to cover the experimental points. The experimental data are also accurate within a factor of 2 because of systematic uncertainties [12]. The calculated optimal excitation energy overestimates the measured one by 1.5 MeV (about 1.9 MeV in the lab system).

The formation cross section of $^{293}118_{175}$ measured by Ninov et al. [5] ($2.2^{+2.6}_{-0.8}$ pb) is smaller by a factor of about 300 in comparison with our prediction made in Ref. [1] (670 pb). The possible explanations of this fact might be as follows:

(1) An uncertainty in the bombarding energy used in the experiment, which in the center-of-mass system is $\pm$1.6 MeV ($\pm$2.3 MeV in the lab system [5]), cf. Fig.1c.

(2) A theoretical inacuracy in the optimal bombarding energy, which in the center-of-mas system is equal to $\pm$1.3 MeV ($\pm$1.8 MeV in the lab system). The theoretical uncertainty in the optimal bombarding energy in the center-of-mass system was evaluated as a sum of the uncertainties in the Q value, S_n and min(S_n^{ER}, B_f^{ER}).

(3) A strongly asymmetric shape of the excitation function of ^{208}Pb$_{126}$(^{86}Kr$_{50}$,1n)$^{293}118_{175}$ obtained in the present paper, cf. Fig.1c. For lower excitation energies, the theoretical curve is very steep decreasing by 1 order of magnitude with decreasing excitation energy by only 2.4 MeV (3.4 MeV in the lab system). A decrease of the excitation function with increasing excitation energy for higher energies is slower because higher l contribute to the formation cross section. In view of the experimental and the theoretical uncertainties in the bombarding energy given in points (1) and (2), the shape of the calculated excitation

function suggests that the use of a little higher bombarding energy in comparison with that suggested in Ref. [1] and used by the Berkeley group [5] might lead to larger production rates of $^{293}118_{175}$.

(4) An uncertainty in the calculated formation cross section of $^{293}118_{175}$ around the maximum of the excitation function, which, according to a pesimistic estimation, might lead to the smaller formation cross section by a factor of about 26. This factor was obtained by combining (in the pesimistic way) the uncertainties in the position of the fusion barrier, Q value, the optimal excitation energy and the damping constat E_D describing the weakening of the shell effects with increasing excitation energy.

All these effects may contribute to the discrepancy between our predicted value of the formation cross section of $^{293}118_{175}$ [1] and the measured one [5]. Moreover, Ćwiok et al. [13] have proposed recently an explanation of this discrepancy by the structurally forbidden α decays which might be responsible for measuring, via α decay, only a part of the formation cross section of $^{293}118_{175}$. It is worth noting that the measured formation cross section of $^{293}118_{175}$ [5] is pretty large in contrast to the previous common very pesimistic expectations, e.g. [3]. It is also worth mentioning that, very recently, Władek Świątecki suggested a qualitative explanation for the large formation cross section measured for $^{293}118_{175}$ by the idea of above-barrier fusion ("unshielded fusion") for heavy projectiles with the typical bombarding energy for the $1n$-deexcitation channel [14].

Especially interesting are the cold fusion reactions $^{208}\mathrm{Pb}_{126}(^{87}\mathrm{Rb}_{50},1n)^{294}119_{175}$ and $^{209}\mathrm{Bi}_{126}(^{86}\mathrm{Kr}_{50},1n)^{294}119_{175}$ which may lead to the production of element 119. A nucleus $^{294}119_{175}$, if produced, might initiate an α-decay chain of new odd-Z superheavy elements 119, 117, 115 and 113. The detailed discussion of the properties of nuclei constituting a predicted decay chain originating from a nucleus $^{294}119_{175}$ was performed in Ref. [4].

Our calculation indicates that the cross section of $^{208}\mathrm{Pb}_{126}(^{87}\mathrm{Rb}_{50},1n)^{294}119_{175}$ should be about 20% lower than that of $^{208}\mathrm{Pb}_{126}(^{86}\mathrm{Kr}_{50},1n)^{293}118_{175}$ and larger by a factor of about 2 in comparison with that of $^{209}\mathrm{Bi}_{126}(^{86}\mathrm{Kr}_{50},1n)^{294}119_{175}$. The calculated cross section and optimal bombarding energy in the lab system are 540 pb and 464.9 MeV ($E^* = 14.3$ MeV) for the formation of element 119 in the reaction of $^{87}Rb_{50}$ with $^{208}Pb_{126}$ and 260 pb and 455.9 MeV ($E^* = 14.3$ MeV) in the reaction of $^{86}Kr_{50}$ with $^{209}Bi_{126}$. Theoretical uncertainties in the calculated optimal bombarding energy and the calculated cross sections of $^{208}Pb_{126}(^{87}Rb_{50},1n)^{294}119_{175}$ and $^{209}Bi_{126}(^{86}Kr_{50},1n)^{294}119_{175}$ are the same as those of $^{208}Pb_{126}(^{86}Kr_{50},1n)^{293}118_{175}$ since the same procedure was used in determinig excitation functions of these reactions.

Because of the strong asymmetry of the predicted excitation functions of the reactions $^{208}Pb_{126}(^{86}Kr_{50},1n)^{293}118_{175}$, $^{208}Pb_{126}(^{87}Rb_{50},1n)^{294}119_{175}$ and $^{209}Bi_{126}(^{86}Kr_{50},1n)^{294}119_{175}$, (cf. Fig.1cd) and the discussed above theoretical and experimental uncertainties in the bombarding energy, the use of the bombarding energy a little higher than the calculated optimal one might be better for the synthesis of $^{293}118_{175}$ and $^{294}119_{175}$. On the other hand, even slightly underestimated bombarding energy may lead to the negative result of the experiment.

A measurement of the excitation function of $^{208}Pb_{126}(^{86}Kr_{50},1n)^{293}118_{175}$, or at least a part of this function around its maximum, would indicate the actual accuracy of our predictions for the optimal bombarding energies and the formation cross sections of spherical superheavy nuclei. In view of the discussed above possible factors which could have caused the significant decrease of the formation cross section of $^{293}118_{175}$, and which might also influence the formation cross section of $^{294}119_{175}$, the measurement of the excitation function of the reaction $^{208}Pb_{126}(^{86}Kr_{50},1n)^{293}118_{175}$ would be of a great help in setting up the best experimental conditions for the synthesis of element 119 and the production of its α-decay descendants.

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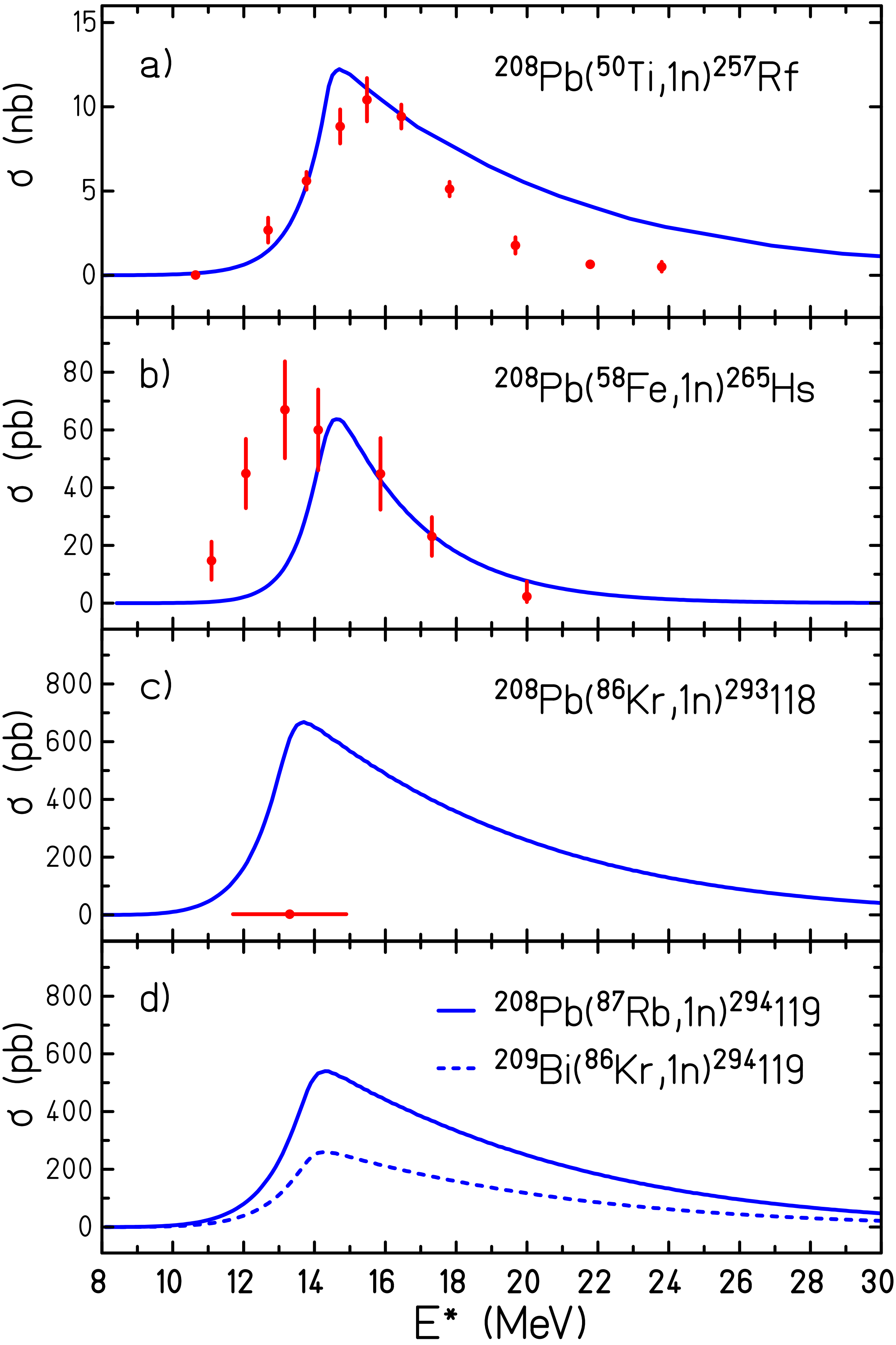
FIGURES

FIG. 1. a) Excitation function of $^{208}Pb_{126}(^{50}Ti_{28},1n)^{257}Rf_{153}$ measured at GSI-Darmstadt (experimental points) [12] and calculated in the present paper (solid curve). Experimental points with only statistical errors are shown [12].

b) Same as in Fig.1a) but for $^{208}Pb_{126}(^{58}Fe_{32},1n)^{265}Hs_{157}$. Theoretical curve has been multiplied by a factor of 2 to cover the experimental points which are also accurate within a factor of 2 because of systematic uncertainties [12]. A shift between the maxima of the experimental and the theoretical excitation function illustrates uncertainty in the calculated optimal bombarding energy.

c) Calculated excitation function of $^{208}Pb_{126}(^{86}Kr_{50},1n)^{293}118_{175}$. Experimental point is taken from the recent report by Ninov et al. [5]. The experimental uncertainty in the bombarding energy is indicated.

d) Calculated excitation function of $^{208}Pb_{126}(^{87}Rb_{50},1n)^{294}119_{175}$ (solid line) and $^{209}Bi_{126}(^{86}Kr_{50},1n)^{294}119_{175}$ (dashed line).



a)
$^{208}Pb(^{50}Ti,1n)^{257}Rf$
σ (nb)
b)
$^{208}Pb(^{58}Fe,1n)^{265}Hs$
σ (pb)
c)
$^{208}Pb(^{86}Kr,1n)^{293}118$
σ (pb)
d)
$^{208}Pb(^{87}Rb,1n)^{294}119$
$^{209}Bi(^{86}Kr,1n)^{294}119$
σ (pb)
E* (MeV)