

## Theoretical study of the capture of stable $^{39}\text{K}$ and neutron-rich radioactive $^{46}\text{K}$ by $^{181}\text{Ta}$

Bing Wang (王兵),<sup>1</sup> Wei-Juan Zhao (赵维娟),<sup>1</sup> En-Guang Zhao (赵恩广),<sup>2,3</sup> and Shan-Gui Zhou (周善贵)<sup>2,3,4,5,\*</sup>

<sup>1</sup>*School of Physics and Engineering, Zhengzhou University, Zhengzhou 450001, China*

<sup>2</sup>*CSA Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

<sup>3</sup>*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

<sup>4</sup>*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*

<sup>5</sup>*Synergetic Innovation Center for Quantum Effects and Application, Hunan Normal University, Changsha, 410081, China*



(Received 8 May 2018; published 23 July 2018)

The empirical coupled-channel (ECC) model and the universal fusion function (UFF) prescription are used to analyze the data of capture cross sections for reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  reported recently by Wakhle *et al.* [*Phys. Rev. C* **97**, 021602(R) (2018)]. The results of the ECC model are in good agreement with the data of  $^{39}\text{K} + ^{181}\text{Ta}$ , while for  $^{46}\text{K} + ^{181}\text{Ta}$  the predictions of the ECC model overestimate the above-barrier capture cross sections. Comparing the reduced data of these two reactions, it is found that the above-barrier cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are consistent with the UFF and are larger than those of  $^{46}\text{K} + ^{181}\text{Ta}$ . This implies that the capture cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$  are suppressed at energies above the Coulomb barrier. Furthermore, at sub-barrier energies, the reduced calculated capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are a little larger than those of  $^{46}\text{K} + ^{181}\text{Ta}$ , which is owing to the coupling to the positive  $Q$ -value two-neutron transfer channel.

DOI: [10.1103/PhysRevC.98.014615](https://doi.org/10.1103/PhysRevC.98.014615)

### I. INTRODUCTION

The synthesis of superheavy nuclei (SHN) is at the frontier of research in nuclear physics [1]. Up to now, superheavy elements with charge number  $Z \leq 118$  have been produced via fusion reactions [2–5]. However, it is still an open question as to where the center of the island of stability is located because the SHN produced so far are neutron deficient and still far from the center of the predicted island of stability. To synthesize neutron-rich SHN, one possible way is to use neutron-rich radioactive beams, although the intensities of these beams are smaller than those of stable beams. In recent years, the synthesis of new heavy nuclei and SHN with radioactive beams has been studied a lot [6–12].

Recently, Wakhle *et al.* have measured the capture cross sections of the reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  [13], and the data of these two reactions were compared with the predictions of the time-dependent Hartree-Fock (TDHF) calculations and some models including the coupled-channel approach of Zagrebaev [14], the empirical model of Wang and Scheid [15], and the quantum diffusion approach [16–18]. It was found that the calculations of the quantum diffusion approach can do the best overall job of representing the capture excitation functions for the reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$ , although the calculations of the quantum diffusion approach underestimate the sub-barrier capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  and overestimate the above-barrier capture cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$ .

We have developed an empirical coupled-channel (ECC) model and performed a systematic study of capture excitation

functions of 217 reaction systems [19]. In this ECC model, the effects of couplings to inelastic excitations and neutron transfer channels are taken effectively into account by introducing an empirical barrier weight function [19–21]. The  $Q$  value of the two-neutron transfer channel for the reaction with stable beam  $^{39}\text{K}$  is positive while that for the reaction with neutron-rich radioactive beam  $^{46}\text{K}$  is negative. In the present work, we are interested in whether this ECC model can reproduce the data of the reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$ . In addition, to investigate the effect of the neutron-rich radioactive  $^{46}\text{K}$  relative to the stable  $^{39}\text{K}$  projectile, the data of these two reactions will be reduced and compared with each other through the reduction procedure of the universal fusion function (UFF) prescription.

The paper is organized as follows. In Sec. II, we briefly introduce the ECC model. In Sec. III, the ECC model and the UFF prescription are applied to analyze the capture excitation functions of  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$ . Finally, a summary is given in Sec. IV.

### II. METHOD

The evaporation residue (EvR) cross section for producing heavy nuclei via fusion reactions can be written as [22–25]

$$\sigma_{\text{EvR}}(E_{\text{c.m.}}) = \sum_J \sigma_{\text{capture}}(E_{\text{c.m.}}, J) P_{\text{CN}}(E_{\text{c.m.}}, J) \times W_{\text{sur}}(E_{\text{c.m.}}, J), \quad (1)$$

where  $\sigma_{\text{capture}}$  is the capture cross section for the transition of the colliding nuclei over the entrance channel Coulomb barrier,  $P_{\text{CN}}$  is the probability of the formation of a compound nucleus (CN) after the capture, and  $W_{\text{sur}}$  is the survival probability of

\*sgzhou@itp.ac.cn

the excited CN. It is very important to examine carefully these three steps in the study of the synthesis mechanism of heavy nuclei [19]. Especially when heavy nuclei are produced with radioactive ion beams, one should first examine whether the capture cross section can be described well by various models.

Theoretically, the capture process is treated as a barrier penetration problem. The capture cross section at a given center-of-mass energy  $E_{c.m.}$  can be written as the sum of the cross section for each partial wave  $J$ ,

$$\sigma_{\text{capture}}(E_{c.m.}) = \pi \lambda^2 \sum_{J=0}^{J_{\text{max}}} (2J+1) T(E_{c.m.}, J). \quad (2)$$

Here  $\lambda^2 = \hbar^2 / (2\mu E_{c.m.})$  is the reduced de Broglie wavelength,  $\mu$  is the reduced mass of the reaction system,  $J_{\text{max}}$  is the critical angular momentum, and  $T$  denotes the penetration probability of the Coulomb barrier.

Comparing with predictions of the single barrier penetration model (SBPM), sub-barrier capture cross sections are enhanced [26]. The enhancement is caused by the strong coupling between the relative motion and intrinsic degrees of freedom and the coupling to nucleon transfer channels [27–29]. The capture cross sections can be calculated by either the quantum coupled-channel models [30,31] or the empirical coupled-channel (ECC) models. In ECC models, the coupled-channel effects are treated effectively by introducing an empirical barrier weight function [15,19–21,32–37]. Besides coupled-channel approaches, the capture can also be described by microscopic dynamics models, such as the TDHF theory [38–44] and the quantum molecular dynamics (QMD) model [45–54]. As mentioned above, the quantum diffusion approach was developed to study the capture process as well [16–18].

Within the ECC model, the coupled-channel effects are taken into account by introducing an empirical barrier weight function  $f(B)$ . When the interaction potential around the Coulomb barrier is approximated by an “inverted” parabola,  $T$  can be calculated by the well-known Hill-Wheeler formula [55]. Then the penetration probability  $T$  in Eq. (2) is given as [19–21]

$$T(E_{c.m.}, J) = \int f(B) T_{\text{HW}}(E_{c.m.}, J, B) dB, \quad (3)$$

where  $B$  is the barrier height. Note that there is not a proof or mathematical derivation of Eq. (3) based on the coupled Schrödinger equations. Furthermore, for light systems at sub-barrier energies and heavy systems at deep sub-barrier energies, the parabolic approximation is not appropriate due to the omitting of the long tail of the Coulomb potential. Therefore, in these cases, the Hill-Wheeler formula does not describe properly the behavior of capture cross sections. In the present work, we are dealing with energies around and above the barrier, an energy region where the Hill-Wheeler formula can be applied. For the barrier penetration with incident energy much lower than the Coulomb barrier, a new barrier penetration formula proposed by Li *et al.* [56] can be used.

The empirical barrier weight function  $f(B)$  is taken to be an asymmetric Gaussian form

$$f(B) = \begin{cases} \frac{1}{N} \exp \left[ -\left( \frac{B-B_m}{\Delta_1} \right)^2 \right], & B < B_m, \\ \frac{1}{N} \exp \left[ -\left( \frac{B-B_m}{\Delta_2} \right)^2 \right], & B > B_m. \end{cases} \quad (4)$$

$f(B)$  satisfies the normalization condition  $\int f(B) dB = 1$ . Thus the normalization coefficient  $N = \sqrt{\pi} (\Delta_1 + \Delta_2) / 2$ .  $\Delta_1$  and  $\Delta_2$  denote the left width and the right width of the empirical barrier weight function. The  $B_m$  denotes the most probable barrier height, i.e., the peak of the empirical barrier weight function.

In our ECC model [19–21], the barrier distribution is related to the effects of couplings to low-lying collective states and positive  $Q$ -value neutron transfer (PQNT) channels. Considering the dynamical deformations due to the attractive nuclear force and the repulsive Coulomb force [57,58], a two-dimensional potential energy surface (PES) with respect to quadrupole deformation of the system and relative distance  $R$  can be obtained. To take into account the effects of the couplings to low-lying collective states, empirical formulas for calculating the parameters of the empirical barrier weight function were proposed based on the PES. Then the effect of the coupling to the PQNT channels is simulated by broadening the empirical barrier weight function. In the present model, only the two-neutron transfer channel is considered. When the  $Q$  value for two-neutron transfer is positive, the widths of the empirical barrier weight function are calculated as  $\Delta_i \rightarrow gQ(2n) + \Delta_i$  ( $i = 1, 2$ ), where  $Q(2n)$  is the  $Q$  value for two-neutron transfer.  $g$  is taken as 0.32 for all reactions with positive  $Q$  value for the two-neutron transfer channel. In addition, this ECC model was extended to describe the complete fusion cross sections for the reactions involving weakly bound nuclei at above-barrier energies [59,60]. More details for the ECC model can be found in Refs. [19,60].

### III. RESULTS AND DISCUSSIONS

Note that the parameters of the empirical barrier weight function are calculated by the empirical formulas which were proposed in Ref. [19] where the parameters of the deformed nuclear potential and the Coulomb potential were also fixed. Therefore, there is no free parameters in the following calculations.

We first focus on the reaction with stable beam  $^{39}\text{K}$ . The comparison of the calculated capture cross sections to the experimental values for  $^{39}\text{K} + ^{181}\text{Ta}$  is shown in Fig. 1. The arrow indicates the peak of the empirical barrier weight function  $B_m$  given in Eq. (4). The solid line denotes the results from the ECC calculations with all the couplings (to low-lying collective states and PQNT channels). The three parameters  $\Delta_1$ ,  $\Delta_2$ , and  $B_m$  of the empirical barrier weight function are 3.56, 23.46, and 146.78 MeV, respectively. One can see that the results of the ECC model are in good agreement with the data. The results of this ECC model are much closer to the data than those calculations shown in Ref. [13]. Note that, for  $^{39}\text{K} + ^{181}\text{Ta}$ , the  $Q$  value of two-neutron transfer channel is 3.67 MeV, and thus part of the enhancement of sub-barrier

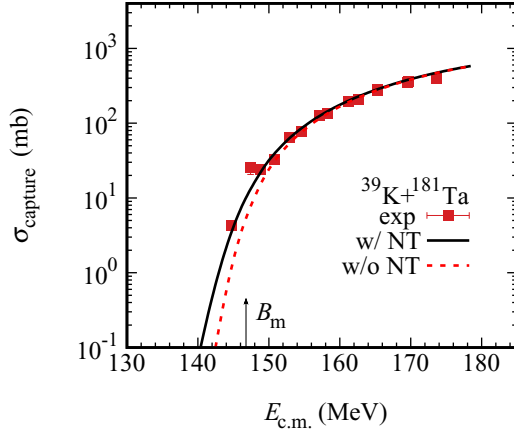


FIG. 1. The calculated and experimental capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$ . The dashed line denotes the results from the ECC calculations without the neutron transfer (NT) effect considered. The solid line denotes the results from the ECC calculations with the NT effect considered. The arrow indicates the peak of the empirical barrier weight function  $B_m$  given in Eq. (4). The data taken from Ref. [13] are represented by the solid squares.

capture cross sections comes from the coupling to the PQNT channel. To show this enhancement clearly, the results from the ECC calculations without the coupling to the neutron transfer channels considered are shown in Fig. 1 by the dashed line. Thus, the difference between the solid line and the dashed line shows the PQNT effect on capture cross sections.

For the reaction with neutron-rich radioactive beam  $^{46}\text{K}$ , the comparison of the calculated capture cross sections to the experimental values is shown in Fig. 2. For  $^{46}\text{K} + ^{181}\text{Ta}$ , the  $Q$  value of two-neutron transfer channel is negative; thus, in this case, the coupling to the PQNT channels does not affect the capture cross sections. Therefore, only the couplings to low-lying collective states are responsible for the enhancement of the sub-barrier capture cross sections. The three parameters,

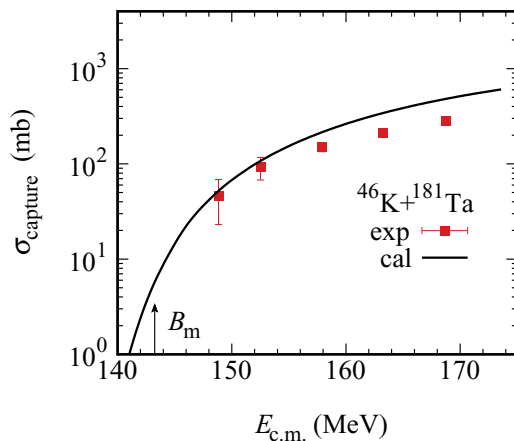


FIG. 2. The calculated and experimental capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$ . The solid line denotes the results from the ECC calculations. The arrow indicates the peak of the empirical barrier weight function  $B_m$  given in Eq. (4). The data taken from Ref. [13] are represented by the solid squares.

TABLE I. The barrier parameters calculated by the SPP and extracted from Ref. [13].

Reaction	SPP			Ref. [13]	
	$V_B$ (MeV)	$\hbar\omega$ (MeV)	$R_B$ (fm)	$V_B$ (MeV)	$R_B$ (fm)
$^{39}\text{K} + ^{181}\text{Ta}$	155.651	4.328	12.030	152.690	12.82
$^{46}\text{K} + ^{181}\text{Ta}$	152.141	4.029	12.333	146.484	10.16

i.e.,  $\Delta_1$ ,  $\Delta_2$ , and  $B_m$ , of the barrier weight function are 2.38, 22.20, and 143.25 MeV, respectively. The results from the ECC calculations are shown in Fig. 2 by the solid line. It can be seen that the calculated results overestimate the cross sections except the two lower energies or, in other words, the above-barrier capture cross sections are suppressed as compared with the ECC calculations. The results from the ECC calculations are similar to those from the quantum diffusion approach shown in Ref. [13].

The results from the ECC calculations are very interesting, as the data of the reaction with stable beam  $^{39}\text{K}$  are reproduced quite well while those of the reaction with neutron-rich radioactive beam  $^{46}\text{K}$  are not. Therefore, it is natural to ask what the effect of the neutron-rich radioactive  $^{46}\text{K}$  relative to the stable  $^{39}\text{K}$  projectile is. Actually, in Ref. [13], the capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  were reduced by the traditional reduction procedure, i.e.,  $E_{c.m.} \rightarrow E_{c.m.}/V_B$  and  $\sigma_{\text{capture}} \rightarrow \sigma_{\text{capture}}/R_B^2$ . The parameters  $V_B$  and  $R_B$  were extracted from the plot of the cross sections versus  $1/E_{c.m.}$ . It was found that the reduced excitation functions of these two reactions do not show any significant difference. In the present work, we adopt another reduction method proposed in Refs. [61,62] which can eliminate completely the geometrical factors and static effects of the potential between the two nuclei. In this case, the capture cross section and the collision energy are reduced to a dimensionless fusion function  $F(x)$  and a dimensionless variable  $x$ ,

$$F(x) = \frac{2E_{c.m.}}{R_B^2 \hbar\omega} \sigma_{\text{capture}}, \quad x = \frac{E_{c.m.} - V_B}{\hbar\omega}, \quad (5)$$

where  $V_B$ ,  $\hbar\omega$ , and  $R_B$  denote the height, curvature, and radius of the barrier which are calculated by the double folding and parameter-free São Paulo potential (SPP) [63–65]. The barrier parameters calculated by the SPP are shown in Table I.

The reduced capture excitation functions, i.e., fusion functions  $F(x)$ , for the reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  are shown in Fig. 3 by the solid squares and points, respectively. It can be seen that, at  $x > 0$  region, i.e., at above-barrier energies, the reduced capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are clearly larger than those of  $^{46}\text{K} + ^{181}\text{Ta}$ . Furthermore, the reduced above-barrier capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are close to the UFF (denoted by the solid line), which are the predictions of the Wong formula [66] reduced by Eq. (5), while the above-barrier capture cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$  lie below the UFF. This tells us that the above-barrier capture cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$  are suppressed as compared with those of  $^{39}\text{K} + ^{181}\text{Ta}$  and the UFF. This result is not

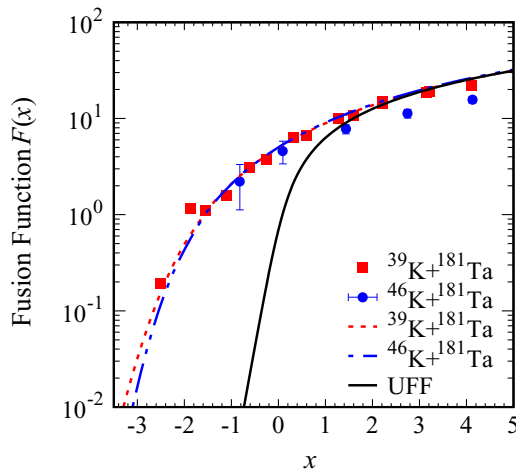


FIG. 3. The reduced capture excitation function  $F(x)$  for reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  as a function of  $x$ . The dashed and dash-dotted lines denote the reduced calculated capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$ , respectively. The solid line represents the UFF. The data taken from Ref. [13] are represented by the solid squares and points.

consistent with the conclusion drawn in Ref. [13], which might result from the different barrier parameters used in the reduction procedures. The parameters  $V_B$  and  $R_B$  extracted from Ref. [13] are also given in Table I. It can be found that the extracted parameter  $R_B$  of  $^{46}\text{K} + ^{181}\text{Ta}$  (10.16 fm) is obviously smaller than that of  $^{39}\text{K} + ^{181}\text{Ta}$  (12.82 fm), while from the SPP, the opposite is true, i.e.,  $R_B = 12.333$  fm for  $^{46}\text{K} + ^{181}\text{Ta}$  12.030 fm for  $^{39}\text{K} + ^{181}\text{Ta}$ . Actually, the barrier parameters extracted from the experimental excitation function already include part of the dynamical effects. For  $^{46}\text{K} + ^{181}\text{Ta}$ , the fact that  $R_B$  extracted from the experiment is small is a manifestation of the suppression effect on the above-barrier cross sections. In addition, from Fig. 3 in Ref. [13], it is shown that the models overestimate the above-barrier cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$ . The results shown in Ref. [13] strongly support the conclusion that the above-barrier cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$  are suppressed.

The calculated capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  are also reduced and shown in Fig. 3 by the dashed and dash-dotted lines. It can be seen that, at the sub-barrier energy region, the calculated cross sections are much larger than the UFF due to the coupled-channel effects. Furthermore, at sub-barrier energies, the reduced calculated capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are a little larger than those of  $^{46}\text{K} + ^{181}\text{Ta}$ , which is owing to the coupling to the positive  $Q$ -value two-neutron transfer channel. At energies above the Coulomb barrier, the predictions from the ECC

model of these two reactions are consistent with the UFF. This means that above the barrier, the measured capture cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$  are suppressed as compared with the predictions of the ECC model and the UFF. Therefore, for producing heavy and superheavy nuclei using the neutron-rich radioactive beams, it is necessary and important to consider this suppression. Further experimental and theoretical studies are expected.

#### IV. SUMMARY

In summary, the capture cross sections for reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  are investigated by using the empirical coupled-channel (ECC) model and the universal fusion function (UFF) prescription. For the reaction  $^{39}\text{K} + ^{181}\text{Ta}$ , the results of the ECC model are in good agreement with the data. While for the reaction with neutron-rich radioactive beam  $^{46}\text{K}$ , the predictions of the ECC model overestimate the above-barrier capture cross sections; in other words, the measured capture cross sections are suppressed as compared with the ECC calculations. Comparing the reduced data of these two reactions, it is found that the data of above-barrier cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are consistent with the UFF and are larger than those of  $^{46}\text{K} + ^{181}\text{Ta}$ . This implies that the capture cross sections of  $^{46}\text{K} + ^{181}\text{Ta}$  are suppressed at energies above the Coulomb barrier. Furthermore, at sub-barrier energies, the reduced calculated capture cross sections of  $^{39}\text{K} + ^{181}\text{Ta}$  are a little larger than those of  $^{46}\text{K} + ^{181}\text{Ta}$ , which is owing to the coupling to the positive  $Q$ -value two-neutron transfer channel.

#### ACKNOWLEDGMENTS

We thank Dr. A. Wakhle for providing us the data of the capture cross sections for reactions  $^{39}\text{K} + ^{181}\text{Ta}$  and  $^{46}\text{K} + ^{181}\text{Ta}$  and helpful discussions. The referee's suggestions on the expression of the empirical barrier weight function  $f(B)$  are appreciated gratefully. This work has been partly supported by the National Key R&D Program of China (Grant No. 2018YFA0404402), the National Natural Science Foundation of China (Grants No. 11525524, No. 11621131001, No. 11647601, No. 11747601, No. 11711540016, and No. 11705165), the Key Research Program of Frontier Sciences of Chinese Academy of Sciences (Grant No. QYZDB-SSWSYS013), the IAEA Coordinated Research Project "F41033," and the Physics Research and Development Program of Zhengzhou University (Grant No. 32410017). The computational results presented in this work have been obtained on the High-Performance Computing Cluster of KLTP/ITP-CAS and the ScGrid of the Supercomputing Center, Computer Network Information Center of the Chinese Academy of Sciences.

- [1] W. Nazarewicz, *Nat. Phys.* **14**, 537 (2018).  
 [2] S. Hofmann and G. Münzenberg, *Rev. Mod. Phys.* **72**, 733 (2000).  
 [3] K. Morita, K. Morimoto, D. Kaji, T. Akiyama, S. I. Goto, H. Haba, E. Ideguchi, R. Kanungo, K. Katori, H. Koura *et al.*, *J. Phys. Soc. Jpn.* **73**, 2593 (2004).

- [4] Y. Oganessian, *J. Phys. G: Nucl. Part. Phys.* **34**, R165 (2007).  
 [5] Y. T. Oganessian, F. S. Abdullin, P. D. Bailey, D. E. Benker, M. E. Bennett, S. N. Dmitriev, J. G. Ezold, J. H. Hamilton, R. A. Henderson, M. G. Itkis *et al.*, *Phys. Rev. Lett.* **104**, 142502 (2010).  
 [6] W. Loveland, *Phys. Rev. C* **76**, 014612 (2007).

- [7] V. Zagrebaev and W. Greiner, *Phys. Rev. C* **78**, 034610 (2008).
- [8] B.-A. Bian, F.-S. Zhang, and H.-Y. Zhou, *Nucl. Phys. A* **829**, 1 (2009).
- [9] V. V. Sargsyan, A. S. Zubov, G. G. Adamian, N. V. Antonenko, and S. Heinz, *Phys. Rev. C* **88**, 054609 (2013).
- [10] V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, and Z. Kohley, *Phys. Rev. C* **92**, 054613 (2015).
- [11] X. J. Bao, Y. Gao, J. Q. Li, and H. F. Zhang, *Phys. Rev. C* **91**, 064612 (2015).
- [12] X. J. Bao, Y. Gao, J. Q. Li, and H. F. Zhang, *Phys. Rev. C* **93**, 044615 (2016).
- [13] A. Wakhle, K. Hammerton, Z. Kohley, D. J. Morrissey, K. Stiefel, J. Yurkon, J. Walshe, K. J. Cook, M. Dasgupta, D. J. Hinde *et al.*, *Phys. Rev. C* **97**, 021602(R) (2018).
- [14] <http://nrv.jinr.ru/nrv/webnrv/fusion/>.
- [15] N. Wang and W. Scheid, *Phys. Rev. C* **78**, 014607 (2008).
- [16] V. V. Sargsyan, Z. Kanokov, G. G. Adamian, N. V. Antonenko, and W. Scheid, *Phys. Rev. C* **80**, 034606 (2009).
- [17] V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, and W. Scheid, *Eur. Phys. J. A* **45**, 125 (2010).
- [18] V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, *Phys. Rev. C* **84**, 064614 (2011).
- [19] B. Wang, K. Wen, W.-J. Zhao, E.-G. Zhao, and S.-G. Zhou, *At. Data Nucl. Data Tables* **114**, 281 (2017).
- [20] B. Wang, W. Zhao, E. Zhao, and S. Zhou, *Sci. China-Phys. Mech. Astron.* **59**, 642002 (2016).
- [21] B. Wang, W. Zhao, E. Zhao, and S. Zhou, *Nucl. Phys. Rev.* **34**, 539 (2017).
- [22] N. V. Antonenko, E. A. Cherepanov, A. K. Nasirov, V. P. Permjakov, and V. V. Volkov, *Phys. Lett. B* **319**, 425 (1993).
- [23] N. V. Antonenko, E. A. Cherepanov, A. K. Nasirov, V. P. Permjakov, and V. V. Volkov, *Phys. Rev. C* **51**, 2635 (1995).
- [24] E. A. Cherepanov, V. V. Volkov, N. V. Antonenko, V. P. Permjakov, and A. K. Nasirov, *Nucl. Phys. A* **583**, 165 (1995).
- [25] G. G. Adamian, N. V. Antonenko, W. Scheid, and V. V. Volkov, *Nucl. Phys. A* **627**, 361 (1997).
- [26] R. G. Stokstad, Y. Eisen, S. Kaplanis, D. Pelte, U. Smilansky, and I. Tserruya, *Phys. Rev. C* **21**, 2427 (1980).
- [27] C. H. Dasso, S. Landowne, and A. Winther, *Nucl. Phys. A* **405**, 381 (1983).
- [28] C. H. Dasso, S. Landowne, and A. Winther, *Nucl. Phys. A* **407**, 221 (1983).
- [29] R. A. Broglia, C. H. Dasso, S. Landowne, and A. Winther, *Phys. Rev. C* **27**, 2433 (1983).
- [30] I. J. Thompson, *Comput. Phys. Rep.* **7**, 167 (1988).
- [31] K. Hagino, N. Rowley, and A. L. Kruppa, *Comput. Phys. Commun.* **123**, 143 (1999).
- [32] K. Siwek-Wilczyńska, E. Sieniaszko, and J. Wilczyński, *Acta Phys. Pol. B* **33**, 451 (2002).
- [33] V. I. Zagrebaev, Y. Aritomo, M. G. Itkis, Y. T. Oganessian, and M. Ohta, *Phys. Rev. C* **65**, 014607 (2001).
- [34] M. Liu, N. Wang, Z. Li, X. Wu, and E. Zhao, *Nucl. Phys. A* **768**, 80 (2006).
- [35] L. Zhu, Z.-Q. Feng, C. Li, and F.-S. Zhang, *Phys. Rev. C* **90**, 014612 (2014).
- [36] P.-W. Wen, Z.-Q. Feng, F. Zhang, C. Li, C.-J. Lin, and F.-S. Zhang, *Chin. Phys. Lett.* **34**, 042501 (2017).
- [37] X. J. Bao, S. Q. Guo, H. F. Zhang, and J. Q. Li, *Phys. Rev. C* **96**, 024610 (2017).
- [38] A. S. Umar and V. E. Oberacker, *Phys. Rev. C* **74**, 021601(R) (2006).
- [39] A. S. Umar, V. E. Oberacker, J. A. Maruhn, and P.-G. Reinhard, *Phys. Rev. C* **85**, 017602 (2012).
- [40] V. E. Oberacker and A. S. Umar, *Phys. Rev. C* **87**, 034611 (2013).
- [41] G.-F. Dai, L. Guo, E.-G. Zhao, and S.-G. Zhou, *Sci. China-Phys. Mech. Astron.* **57**, 1618 (2014).
- [42] G.-F. Dai, L. Guo, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* **90**, 044609 (2014).
- [43] X. Jiang, J. A. Maruhn, and S. Yan, *Phys. Rev. C* **90**, 064618 (2014).
- [44] D. Bourgin, C. Simenel, S. Courtin, and F. Haas, *Phys. Rev. C* **93**, 034604 (2016).
- [45] J. Aichelin, *Phys. Rep.* **202**, 233 (1991).
- [46] N. Wang, Z. Li, and X. Wu, *Phys. Rev. C* **65**, 064608 (2002).
- [47] N. Wang, Z. Li, X. Wu, J. Tian, Y. X. Zhang, and M. Liu, *Phys. Rev. C* **69**, 034608 (2004).
- [48] Z.-Q. Feng, G.-M. Jin, and F.-S. Zhang, *Nucl. Phys. A* **802**, 91 (2008).
- [49] K. Wen, F. Sakata, Z.-X. Li, X.-Z. Wu, Y.-X. Zhang, and S.-G. Zhou, *Phys. Rev. Lett.* **111**, 012501 (2013).
- [50] L. Zhu, J. Su, W.-J. Xie, and F.-S. Zhang, *Nucl. Phys. A* **915**, 90 (2013).
- [51] K. Wen, F. Sakata, Z.-X. Li, X.-Z. Wu, Y.-X. Zhang, and S.-G. Zhou, *Phys. Rev. C* **90**, 054613 (2014).
- [52] N. Wang, K. Zhao, and Z. Li, *Phys. Rev. C* **90**, 054610 (2014).
- [53] V. Zanganeh, R. Gharaei, and N. Wang, *Phys. Rev. C* **95**, 034620 (2017).
- [54] H. Yao and N. Wang, *Phys. Rev. C* **95**, 014607 (2017).
- [55] D. L. Hill and J. A. Wheeler, *Phys. Rev.* **89**, 1102 (1953).
- [56] L.-L. Li, S.-G. Zhou, E.-G. Zhao, and W. Scheid, *Int. J. Mod. Phys. E* **19**, 359 (2010).
- [57] V. I. Zagrebaev, *Phys. Rev. C* **67**, 061601(R) (2003).
- [58] N. Wang, E.-G. Zhao, W. Scheid, and S.-G. Zhou, *Phys. Rev. C* **85**, 041601(R) (2012).
- [59] B. Wang, W.-J. Zhao, P. R. S. Gomes, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* **90**, 034612 (2014).
- [60] B. Wang, W.-J. Zhao, A. Diaz-Torres, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* **93**, 014615 (2016).
- [61] L. F. Canto, P. R. S. Gomes, J. Lubian, L. C. Chamon, and E. Crema, *J. Phys. G: Nucl. Phys.* **36**, 015109 (2009).
- [62] L. F. Canto, P. R. S. Gomes, J. Lubian, L. C. Chamon, and E. Crema, *Nucl. Phys. A* **821**, 51 (2009).
- [63] M. A. Cândido Ribeiro, L. C. Chamon, D. Pereira, M. S. Hussein, and D. Galetti, *Phys. Rev. Lett.* **78**, 3270 (1997).
- [64] L. C. Chamon, D. Pereira, M. S. Hussein, M. A. Cândido Ribeiro, and D. Galetti, *Phys. Rev. Lett.* **79**, 5218 (1997).
- [65] L. C. Chamon, B. V. Carlson, L. R. Gasques, D. Pereira, C. De Conti, M. A. G. Alvarez, M. S. Hussein, M. A. Cândido Ribeiro, E. S. Rossi, and C. P. Silva, *Phys. Rev. C* **66**, 014610 (2002).
- [66] C. Y. Wong, *Phys. Rev. Lett.* **31**, 766 (1973).