Systematic calculations of $\alpha$-decay half-lives with an improved empirical formula

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Based on the recent data in NUBASE2012, an improved empirical formula for evaluating the $\alpha$-decay half-lives is presented, in which the hindrance effect resulted from the change of the ground state spins and parities of parent and daughter nuclei is included, together with a new correction factor for nuclei near the shell closures. The calculated $\alpha$-decay half-lives are found to be in better agreements with the experimental data, and the corresponding root-mean-square (rms) deviation is reduced to 0.433 when the experimental $Q$-values are employed. Furthermore, the $Q$-values derived from different nuclear mass models are used to predict $\alpha$-decay half-lives with this improved formula. It is found that the calculated half-lives are very sensitive to the $Q$-values. Remarkably, when mass predictions are improved with the radial basis function (RBF), the resulting rms deviations can be significantly reduced. With the mass prediction from the latest version of Weizsäcker-Skyrme (WS4) model, the rms deviation of $\alpha$-decay half-lives with respect to the known data falls to 0.697.

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I. INTRODUCTION

$\alpha$-decay is a very important process in the field of nuclear physics. It was first observed as an unknown radiation by Becquerel in 1896 and further formulated empirically by Geiger and Nuttall in 1911 [1]. Afterwards, applying the theory of quantum mechanics in the field of nuclear physics, Gamow [2] and Condon and Gurney [3] independently described the spontaneous $\alpha$ decay as a quantum tunnelling effect through the potential barrier leading from the parent nucleus to the two emitted fragments: the $\alpha$ particle and the daughter nucleus. As a powerful tool, $\alpha$ decay can be used to investigate the low-energy structure of unstable nuclei, such as the ground-state energy, the ground-state half-life, the shell effects, and so on [4–12]. On the experimental side, the observation of $\alpha$-decay chains from unknown parent nuclei to known nuclei has been a reliable method used to identify different superheavy elements (SHEs) and isomeric states as well [13–16].

Up to now, on the basis of Gamow’s theory, the absolute $\alpha$-decay width has been estimated by many theoretical calculations [17, 18, 21, 25], which employ various approaches, such as the cluster model [17, 20], the density dependent M3Y (DDM3Y) effective interaction [21, 22], the generalized liquid drop model (GLDM) [23]. Different from the cluster model, also some other theoretical models have been proposed in the pursuit of a microscopic description of $\alpha$ decay, such as the shell model and the fission-like model [26–29].

Moreover, many simple empirical formulas were also exploited to analyze the $\alpha$ decay [30–45]. Among these studies, Viola and Seaborg proposed a semi-empirical formula to analyze $\alpha$-decay half-lives for the heavy elements ($A \geq 140$) [30], which has been often used up to the present day [37, 42]. In 2000, Royer developed other simple analytical formula by fitting on a completed set of 373 $\alpha$ emitters [31], which can well reproduce the experimental half-lives of the favored $\alpha$-decay. Based on the above two works, Sobiczewski and Parkhomenko [32] also presented a simple phenomenological formula for describing $\alpha$-decay half-lives of heavy (above $^{208}$Pb) and superheavy nuclei. In previous works, the ground state spins and parities of parent and daughter nuclei were conventionally ignored. However, when the spin and parity values of parent and daughter nuclei are different, then the emitted $\alpha$ particle carries out nonzero angular momentum $l$. Because of this, the orbital moment of emitted $\alpha$ particle should be taken into account in an accurate approach for $\alpha$ decay. In this way, Denisov and Khudenko [33] explored a carefully updated and selected partial $\alpha$-decay half-life data set of 344 ground-state-to-ground-state (g.s.-to-g.s.) $\alpha$ transitions, and presented sets of simple relations for evaluating the half-lives of $\alpha$ transitions. After that, Royer [34] proposed other sets of analytical formulas for $\log_{10}T_{1/2}$ depending or not on the angular momentum of the $\alpha$ particle from an adjustment on the similar experimental data set mentioned in Ref. [35]. Recently, Dong et al. [38] extended the Royer’s formula by taking into account the contribution of the centrifugal barrier, and then proposed a novel law, named the improved Royer’s formula, for calculating $\alpha$-decay half-lives, which was proved to work well [39, 40]. Very recently, Ren et al. [42] proposed a new Geiger-Nuttall law where the effects of the quantum numbers of $\alpha$-core relative motion as well as the possible effect of angular momentum and parity of $\alpha$ particle are naturally embedded in the law.

In the empirical formulas, the alpha-decay half-life is determined by the proton number $Z$, the number of nucleons in nucleus $A$, and the value of decay energy $Q$, which can be derived from the nuclear mass [9]. Half-life calculations are very sensitive to the choice of $Q$-
values, so reliable theoretical predictions of the nuclear mass, leading to precise $Q$-values, are essential to study $\alpha$ transitions when these nuclear masses can not be determined experimentally. In the past decades, many theoretical calculations were performed to extrapolate nuclear masses. One conventional method is the local mass relations, which have a high precision of prediction for nearby nuclei, such as the Garvey-Kelson relations [42], residual proton-neutron interactions [43, 44], Coulomb-energy displacement [45, 50], and systematics of $\alpha$-decay energies [51]. The other method relies on global mass models, which are usually believed to have a better ability of mass extrapolation for nuclei far from the known region, such as the macroscopic-microscopic finite-range droplet model (FRDM) [52], the Weizsäcker-Skyrme (WS) model [53], the microscopic Hartree-Fock-Bogoliubov (HFB) theory with a Skyrme force [54], and the relativistic mean-field (RMF) model [55].

In this paper, we synthetically consider the centrifugal effect and the hindrance of $\alpha$ emission with odd values of $l$, and then renovate the improved Royer’s formula by introducing two new empirical terms. The effect of angular momentum and parity of $\alpha$ particle is embedded remarkably, together with a new correction factor for nuclei near the shell closures. Comparisons about the root-mean-square (rms) deviation are performed, and the numerical results show that our formula can well reproduce the experimental half-lives of 341 $\alpha$ transitions between the ground states of nuclei. Moreover, we also consider different mass models to provide the $Q$-values for $\alpha$-decay half-lives. Especially, when the radial basis function (RBF) approach is canonically introduced to improve the precision of the mass models. A decrease of the rms deviations is obtained, which indicates that the calculated $\alpha$-decay half-lives after embedding the RBF approach agree better with the experimental data.

This paper is organized as follows. In section II, the theoretical method of calculating $\alpha$-decay half-lives is briefly described. In section III, the numerical results of $\alpha$-decay half-lives as well as some detailed discussions are given, including some comparisons between different empirical formulas and different mass models with (without) the RBF approach. Finally, we render a concise summary in section IV.

II. THE THEORETICAL METHOD

A. Input experimental data

In this paper, a recent $\alpha$-decay data of 341 nuclei is taken from NUBASE2012 [56], and then a fitting procedure on this data set leads to an improved empirical formula. Moreover, the following study is initially restricted to the g.s. to g.s. $\alpha$ transitions, which are known as partial $\alpha$ decay of the parent nucleus. In view of this, it is necessary to take into account experimental values of the branching ratio ($R$) for $\alpha$ transitions between the ground state of parent nuclei and various states of daughter nuclei for correct extracting of the half-lives for the g.s. to g.s. $\alpha$ decay.

According to the updated information of Audi et al. [56], there are totally about 700 nuclei for all possible $\alpha$ transitions with different $R$-values. The nuclei with well-defined experimental $R$-values are adopted in this paper. As a result, our data set contains 341 nuclei with their $R$-values being in the region of $1\% \leq R \leq 100\%$. These nuclei can be divided into four categories: 123 even $Z$-even $N$ (e-e), 93 even $Z$-odd $N$ (e-o), 79 odd $Z$-even $N$ (o-e), and 46 odd $Z$-odd $N$ (o-o) nuclei.

B. Spin and parity selection rule

In general, for e-e case, the spin and parity values of parent and daughter nuclei are usually ignored. However, for the other three cases, the transitions may occur with different spins and parities of the parent and daughter nuclei and, consequently, the $\alpha$ particle may take away an nonzero angular momentum $l$. Accordingly, the effect of the orbital moment of emitted $\alpha$ particle should be taken into account in an accurate approach for $\alpha$ decay. We select $l$ in accordance with the spin-parity selection rule, similar as that in Refs. [34, 35],

$$l_{\text{min}} = \begin{cases} \Delta_j & \text{for even } \Delta_j \text{ and } \pi_p = \pi_d, \\ \Delta_j + 1 & \text{for even } \Delta_j \text{ and } \pi_p \neq \pi_d, \\ \Delta_j & \text{for odd } \Delta_j \text{ and } \pi_p \neq \pi_d, \\ \Delta_j + 1 & \text{for odd } \Delta_j \text{ and } \pi_p = \pi_d, \end{cases}$$  \hspace{1cm} (1)

where $\Delta_j = |j_p - j_d|$, $j_p$, $\pi_p$, $j_d$ and $\pi_d$ are spin and parity values of the parent and daughter nuclei, respectively. It is worth noting that the orbital angular momentum of the emitted $\alpha$ particle can have several values according to the selection rule. However, for the sake of simplicity, in the following calculations, the angular momentum $l$ of the emitted $\alpha$-particle is endowed with a minimum value $l_{\text{min}}$. In addition, the values of spin and parity of parent and daughter nuclei in this paper are taken from Refs. [34, 54, 55].

C. Analytical formula for the $\alpha$ decay half-lives

In 2000, by fitting the experimental lifetimes of 373 emitters with $R$-values close to $100\%$, Royer gave an elementary analytical formula [32],

$$\log_{10}(T_{1/2}) = a + bA^{1/6}\sqrt{Z} + \frac{cZ}{\sqrt{Q_{\alpha}}}.$$  \hspace{1cm} (2)

Here $a$, $b$ and $c$ are the fitting parameters, $A$ and $Z$ are the mass number and charge of parent nucleus, respectively, $T_{1/2}$ is the half-life of $\alpha$ decay and given in seconds while $Q$ the corresponding decay energy and given in MeV. This formula can well reproduce the experimental half-lives of the favored $\alpha$-decay. However, it dose not
TABLE I: The parameters of our empirical formula found for e-e, e-o, o-e, and o-o ranges of nuclei, respectively.

|  | a   | b   | c   | d   |
|---|-----|-----|-----|-----|
| e-e | -29.432 | -1.146 | 1.577 |     |
| e-o | -26.591 | -1.171 | 1.639 | 1.123 |
| o-e | -27.747 | -1.093 | 1.620 | 0.829 |
| o-o | -28.460 | -0.984 | 1.573 | 0.970 |

consider the angular momentum in both unfavored and hindered $\alpha$ transitions. Just because of this, the above formula was reconsidered by Dong et al., and converted into a new version in terms of the centrifugal contribution to the $\alpha$-nucleus potential [38],

$$\log_{10}(T_{1/2}) = a + bA^{1/6}\sqrt{Z} + \frac{cZ}{\sqrt{Q_\alpha}} + \frac{d^{1-(-1)^l}l(l+1)}{\sqrt{(A-4)(Z-2)A^{-2/3}}} + S. \quad (3)$$

In this paper, after detailed investigation about the explicit dependence of the $\alpha$-decay half-lives, we propose a different formula,

$$\log_{10}(T_{1/2}) = a + bA^{1/6}\sqrt{Z} + \frac{cZ}{\sqrt{Q_\alpha}} + \frac{d^{1-(-1)^l}l(l+1)}{\sqrt{(A-4)(Z-2)A^{-2/3}}} + S. \quad (4)$$

The four parameters $a$, $b$, $c$, and $d$ can be obtained by fitting the new experimental data set, and then expressed in Tab. I. It is interesting that we find the coefficient $d^{1-(-1)^l}$ is a value less than 1 for odd $l$ in both o-e and o-o cases, so this may imply that the fourth term in the formula proposed in Eq. (3) may overestimate the centrifugal effects for these two cases.

In Eq. (4), the first three terms are the same as those in Refs. [32, 38], the fourth term is similar to the corresponding one in Ref. [38], which can be attributed to the distinct contribution of the centrifugal potential $\frac{d^2}{4\pi}\ell(l+1)$ to the total $\alpha$-nucleus potential at small distances between daughter nucleus and $\alpha$ particle while $l \neq 0$ [33]. The difference is that we have introduced an additional factor $d^{1-(-1)^l}$ into this term to account for the hindrance of the transition with the change of parity. It is such an exponential form that the formula can well reflect the changes of $\alpha$-decay half-lives originated from $l$ due to the rearrangement of single-particle orbits and of the nuclear spin orientation, the structure hindrance is relatively weak [34] and, consequently, will not be discussed here. The last empirical correction factor and defined as: $S = 0.5$ for $49 \leq Z \leq 51$, $81 \leq Z \leq 83$, $49 \leq N \leq 51$, $81 \leq N \leq 83$ or $125 \leq N \leq 127$. $S$ is introduced to mock up the systematic deviations of calculated $\alpha$-decay half-lives with respect to the experimental data near shell closures.

In addition, the rms deviation of the decimal logarithm of the $\alpha$-decay half-life, in this paper, is defined as

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N} [\log_{10}(T_{1/2i}^{\text{theo.}}) - \log_{10}(T_{1/2i}^{\text{expt.}})]^2}. \quad (5)$$

$N$ is the number of nuclei used for evaluation of the rms deviation. The $Q$-value for the $\alpha$-decay half-life can be calculated using experimental mass data as $Q = M_P - (M_d + M_{\alpha})$, $M_P$, $M_d$, and $M_{\alpha}$ are the masses of parent and daughter nuclei and $\alpha$ particle, respectively.

III. RESULT AND DISCUSSION

![FIG. 1: (Color online) Logarithms of the ratios between theoretical $\alpha$-decay half-lives calculated with different formulas and experimental ones versus the mass number $A$ of the parent nucleus. The red diamonds denote the results of this work, the blue circles and the olive squares correspond to the results calculated with two formulas proposed by Dong et al. and Royer, respectively.](image-url)

As proposed above, Royer’s formula works well in the favored $\alpha$-decay [32]. However, when it is used to evaluate the half-lives for nuclei with $Z$ and $N$ crossing the $Z = 82$ or $N = 126$ shell closures, respectively, a dramatic large deviation can be observed between calculated half-lives and experimental ones, which is drawn clearly in Fig. I with the squares corresponding to the results of Royer’s formula in Eq. (2). It can be seen in Fig. I that all squares are far away from the dotted line, the calculated values of $\alpha$-decay half-lives are always less than the experimental data for both $Z = 81 - 83$ isotopes and $N = 125 - 127$ isotones. There are about a half of the whole isotopes and isotones with the ratios between calculated values and experimental ones being beyond a factor of ten ($\log_{10}10 = 1$). The systematic deviation is very apparent.

Then after including the centrifugal effect, Royer’s formula was extended to the unfavored $\alpha$-decay with a new form proposed in Eq. (3) [38]. With this formula,
the same calculations are performed on both the isotopic chain of $Z = 81 - 83$ and the isotonic chain of $N = 125 - 127$, and we plotted the corresponding results with the filled circles in Fig. 1. It is obvious that the values of $\log_{10}(T_{1/2}^{\text{theo.}} / T_{1/2}^{\text{expt.}})$ for the most nuclei (denoted by filled circles) are in the range from $-1$ to $0$ and the whole points land close to the dotted line. It means the calculated $\alpha$-decay half-lives with Eq. (3) agree better than those deduced from Eq. (2) with the experimental data. However, the deviation is still systematic with the mean absolute value of $\log_{10}(T_{1/2}^{\text{theo.}} / T_{1/2}^{\text{expt.}})$ being about 0.5. Accordingly, the systematic behavior of deviation is decreased to some extent but not completely redressed. Then how to overcome the deviation error between the calculated half-lives and the experimental data?

As we know, accurate calculations of $\alpha$ transitions should take into account the spins and parities of parent and daughter nuclei and the angular momentum of the emitted $\alpha$ particle. Particularly for the transition with large change of spin and with the change of parity, the factor $d^{l - (l-1)/2}$ can well simulate the hindrance of $\alpha$ emission. Moreover, when $Z$ ($N$) goes across the shell closure at $Z = 82$ ($N = 126$), the effect of the closed shell results in a decrease of the $\alpha$-preformation factor, which has been shown in the experimental analysis [58], that may be the reason of the existence of the large deviations proposed above. In this way, we introduce two new empirical terms to remedy the systematic deviation, and a new analytical formula is proposed in Eq. (4). Applying our formula to both $Z = 81 - 83$ isotopes and $N = 125 - 127$ isotones leads to a desired effect, which can be seen in Fig. 1 with the red points. One can see that most of the red points float around the dotted line, the absolute values of $\log_{10}(T_{1/2}^{\text{theo.}} / T_{1/2}^{\text{expt.}})$ are generally less than 0.4 for almost all of the parent nuclei. Accordingly, the systematic behavior of deviation is decreased to a large extent.

For further insight of the dependence on $l$ and $S$, a comparison between the experimental $\alpha$-decay half-lives and the calculated ones for whole 341 nuclei with the three formulas proposed above is performed, and is drawn in Fig. 2 in which the results of the empirical formulas are calculated with the parameter values from the present work. In Fig. 2 Panel (a) denotes the decimal logarithm of $T_{1/2}^{\text{theo.}} / T_{1/2}^{\text{expt.}}$ for 341 nuclei with Royer’s formula proposed in Eq. (2). One can see that around the shell closures ($Z = 82$ and $N = 126$), the calculated half-lives are much shorter than the experimental ones, the ratios between calculated values and experimental ones are beyond a factor of ten ($\log_{10}(T_{1/2}^{\text{theo.}} / T_{1/2}^{\text{expt.}}) = -1$). The rms deviation for the full data set is 0.659. In panel (b), the formula proposed in Eq. (3) is applied. It is obvious that the agreements with the experimental data are visible around the shell closures. The amounts of discrepancy also decrease in other fields, and the rms deviation is reduced to 0.487, all of which indicate the extending of Royer’s formula by considering the centrifugal effect is successful. Panel (c) is designated the result obtained with our formula proposed in Eq. (4), respectively. Dotted lines denote the magic numbers.

FIG. 2: (Color online) Decimal logarithms of $T_{1/2}^{\text{theo.}} / T_{1/2}^{\text{expt.}}$ for 341 nuclei derived from the different formulas, for which calculations are performed with the present parameter set of this work. Panel (a) denotes the case with Royer’s formula proposed in Eq. (2), panel (b) corresponds to the case with the improved Royer’s formula proposed in Eq. (3), and panel (c) is designated the result obtained with our formula proposed in Eq. (4), respectively. Dotted lines denote the magic numbers.
Beyond a factor of ten for some isotopes or isotones and not decreased after introducing \( l \) and \( S \). The reason may be that the SHE experiments are very difficult and usually few decay events are observed. Hence the experimental error bar is relatively large in the measurement of both decay energies and half-lives.

The detailed numerical results for the full data set are listed in Tab. II as well as for e-e, e-o, o-e, and o-o subsets, respectively. Note that in order to study the effect of \( S \) and \( l \) on the accuracy of the formula, the parameters used in either Royer’s formula [32] or the improved Royer’s formula [38] have been recalculated by fitting the new experimental data set. After this, it is found that the corresponding rms deviations deduced from the above two formulas are 0.587 and 0.481, less than the old \( \sigma \) of 0.646 and 0.504 with the parameters taken from Refs. [32, 38], respectively. It means that the accuracies of these two formulas are improved apparently, but still lower than that of our formula with the standard \( \sigma \)-values being only 0.433. Moreover, a further comparison is performed between our formula with the well-known empirical formulas presented by Denisov and Khodenko [35] and Royer in 2010 [37], respectively. The calculations are also performed with the new parameters determined by fitting the updated experimental data set, and then lead to the corresponding \( \sigma \)-values of 0.536 and 0.561, respectively. The detailed \( \sigma \) deviations for both full data set and four subsets are displayed in Tab. II in the fourth and fifth lines, from which a similar conclusion is attained in comparison with our formula. That is our analytical formula has the smallest values of the \( \sigma \) deviations for both full data set and most of the subsets except for the e-o case, in which the \( \sigma \) deviations resulted from Refs. [35, 37] are smaller. All these indicate a higher accuracy in our formula than either one in Ref. [35] and Ref. [37].

To examine the predictive ability of nuclear mass model on \( \alpha \)-decay half-life, the improved formula expressed in Eq. (4) is employed to calculate \( \alpha \)-decay half-lives with the theoretical \( Q \)-values. In this work, eight nuclear mass models are taken into account, i.e., the FRDM model [52], the latest version of WS (WS4) model [53], the recent version of the HFB model (HFB-27) [54], the RMF model with TMA effective interaction [55], the Koura-Tachibana-Uno-Yamada (KTUY) model [61], the Duflo-Zuker formulas [59, 60] and the Bhagwat formula [62]. For simplicity, the deviations of \( \log_{10}(T_{1/2}^{\text{theo}}/T_{1/2}^{\text{expt.}}) \) for four mass models are drawn, and without loss of generality, FRDM, WS4, HFB-27 and RMF are taken as examples (see Fig. 3). The corresponding numerical results of \( \sigma \) errors for eight mass models are listed in Tab. III.
As can be seen in Tab. III, the descriptions of $\alpha$-decay half-lives for these mass models are generally within the same order of magnitude except for the RMF model. The smallest rms deviation of 1.163 is obtained from the WS4 model, which indicates the WS4 model has the best accuracy of $Q_\alpha$ prediction among mass models considered here. However, the RMF model significantly overestimates the $\alpha$-decay half-lives for nuclei around $N = 126$ and in some other fields (see panel (d1) in Fig. 39), so it is necessary to improve the mass precision of RMF model for reliably predicting $\alpha$-decay half-lives.

An efficient method to enhance the predictive power of mass models is the radial basis function (RBF) approach, which was first introduced into this field by Wang et al. 63. The basic formulas of the RBF approach have been detailed in our previous works 64, 65. So we will not repeat it anymore hereafter. For convenience, the mass model improved by the RBF approach is denoted with the Model+RBF henceforth, e.g. FRDM+RBF and RMF+RBF. After employing the RBF approach, the new $\alpha$-decay half-lives can be deduced with the optimized $Q$ values derived by the above mass equation, and subsequent comparisons between the new $\alpha$-decay half-lives and the experimental data are performed and exhibited in Tab. III. One can see from Tab. III that the systematic rms deviations decrease remarkably after using the RBF approach for all the eight mass models. Taking RMF model for an instance, the rms deviation is 5.822 before applying the RBF approach, and then significantly decreases to 1.511 with refinement by the RBF approach. From Fig. 3 one can also see that the calculated $\alpha$-decay half-lives with RBF approach result in better agreements with the experimental data. The precision in our formula is higher than that in the previous methods. Furthermore, we apply the improved formula to eight calculated mass tables. Using the $Q$-values resulted from these mass tables, the subsequent half-life outcomes indicate that WS4 model has the best accuracy of $Q_\alpha$ prediction. Then in order to improve the predictive ability of the mass model, the RBF approach is adopted. As a result, a rapid decrease of the rms deviation is obtained, which indicates the calculated $\alpha$-decay half-lives, after embedding the RBF approach, are in better agreements with the experimental data.

IV. SUMMARY

In summary, by fitting the new experimental data of 341 nuclei, we have proposed an empirical formula for systematically calculating the half-lives of $\alpha$ transitions between the ground states of parent and daughter nuclei. Within this new formula, we consider the hindrance effect resulted from the changes of spin and parity of parent and daughter nuclei and a phenomenological correction factor for the nuclei near the shell closure. The calculations of $\alpha$-decay half-lives with some other well-known empirical formulas are also performed. By comparing, it is found that our formula results in the smallest values of the rms deviation for both full data set and any subset. In other words, the precision in our formula is higher than that in the previous methods. Furthermore, we apply the improved formula to eight calculated mass tables. Using the $Q$-values resulted from these mass tables, the subsequent half-life outcomes indicate that WS4 model has the best accuracy of $Q_\alpha$ prediction. Then in order to improve the predictive ability of the mass model, the RBF approach is adopted. As a result, a rapid decrease of the rms deviation is obtained, which indicates the calculated $\alpha$-decay half-lives, after embedding the RBF approach, are in better agreements with the experimental data.

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Rev. C 75, 047306 (2007).

[23] H. F. Zhang, W. Zuo, J. Q. Li, and G. Royer, Phys. Rev. C 74, 017304 (2006).

[24] M. M. Sharma, A. R. Farhan, and G. M’unzenberg, Phys. Rev. C 71, 054310 (2005).

[25] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).

[26] K. Varga, R. Lovas, and R. Liotta, Phys. Rev. Lett. 99, 01 (1992).

[27] B. Buck, et al., At. Data Nucl. Data Tables 54, 53 (1993).

[28] N. Poenaru, M. Ivascu, A. Sandulescu, and W. Greiner, Phys. Rev. C 32, 572 (1985).

[29] N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C 71, 054310 (2005).

[30] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).

[31] K. Varga, R. Lovas, and R. Liotta, Phys. Rev. Lett. 99, 01 (1992).

[32] B. Buck, et al., At. Data Nucl. Data Tables 54, 53 (1993).

[33] N. Poenaru, M. Ivascu, A. Sandulescu, and W. Greiner, Phys. Rev. C 32, 572 (1985).

[34] N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C 71, 054310 (2005).

[35] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).

[36] K. Varga, R. Lovas, and R. Liotta, Phys. Rev. Lett. 99, 01 (1992).

[37] B. Buck, et al., At. Data Nucl. Data Tables 54, 53 (1993).

[38] N. Poenaru, M. Ivascu, A. Sandulescu, and W. Greiner, Phys. Rev. C 32, 572 (1985).

[39] N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C 71, 054310 (2005).

[40] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).

[41] K. Varga, R. Lovas, and R. Liotta, Phys. Rev. Lett. 99, 01 (1992).

[42] B. Buck, et al., At. Data Nucl. Data Tables 54, 53 (1993).

[43] N. Poenaru, M. Ivascu, A. Sandulescu, and W. Greiner, Phys. Rev. C 32, 572 (1985).

[44] N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C 71, 054310 (2005).

[45] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).

[46] K. Varga, R. Lovas, and R. Liotta, Phys. Rev. Lett. 99, 01 (1992).

[47] B. Buck, et al., At. Data Nucl. Data Tables 54, 53 (1993).

[48] N. Poenaru, M. Ivascu, A. Sandulescu, and W. Greiner, Phys. Rev. C 32, 572 (1985).

[49] N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C 71, 054310 (2005).

[50] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).

[51] K. Varga, R. Lovas, and R. Liotta, Phys. Rev. Lett. 99, 01 (1992).

[52] B. Buck, et al., At. Data Nucl. Data Tables 54, 53 (1993).

[53] N. Poenaru, M. Ivascu, A. Sandulescu, and W. Greiner, Phys. Rev. C 32, 572 (1985).

[54] N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C 71, 054310 (2005).

[55] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C 76, 044326 (2007).