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The role of various parameters used in proximity potential in heavy-ion fusion reactions: New extension

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Abstract. An attempt has been made to modify the original proximity potential using up-to-date knowledge of the universal function and surface energy coefficient available in the literature. A new radius formula has also been obtained using the recent data on charge distribution. The detailed investigation of over 395 reactions reveal that the new proximity potential reproduces the experimental data better than earlier versions.

Keywords. Nuclear reaction models and methods; fusion and fusion–fission reactions; fusion reactions; low and intermediate energy heavy-ion reactions.

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1. Introduction

A large number of theoretical and experimental efforts are under way to study the fusion of heavy nuclei leading to several new phenomena such as the formation of neutron-rich and superheavy elements [1–4]. The accurate determination of the interaction potential between two nuclei is a difficult task and continuous efforts are needed in this direction. This was the subject of very active research over the last three decades and remains one of the most widely studied subject in low-energy heavy-ion physics [2–13]. At intermediate energies, an accurate knowledge of the potential is necessary to study various phenomena such as multifragmentation [14], nuclear flow [15], subthreshold particle production [16], stopping [17] etc. The strength and form of nuclear potential are also very important in the study of cluster decay [6].

The total interaction potential is the sum of the long-range Coulomb repulsive force and short-range nuclear attractive force. The Coulomb part of the interaction potential is well known, whereas the nuclear part is not clearly understood. Many efforts have been put forward to give a simple and accurate form of the nuclear part of the interaction potential [2–13]. Among such efforts, proximity potential [7] is well known for its simplicity and numerous applications in different fields. It is based on the proximity force theorem [7,8], according to which the nuclear part of the interaction potential is a product of the geometrical factor depending on the mean curvature of the interaction surface and the universal function (depending on the separation distance) and is independent of the masses of the colliding nuclei [7].

As pointed out by various authors [10], the original form of the proximity potential 1977 overestimated the experimental data by 4% for fusion barrier heights. In a recent study involving the comparison of 16 proximity potentials, it was pointed out that the proximity potential 1977 overestimated the experimental data by 7% for symmetric colliding nuclei [2]. Similarly, large deviation was also observed for asymmetric colliding nuclei [3].

With the passage of time, several improvements/modifications were made over the original proximity potential 1977 to remove the discrepancy between theory and data. It included either the better form of the surface energy coefficient [9] or universal function and/or nuclear radius [10]. A careful look reveals that these modifications/improvements could not explain the experimental data [2,11]. A survey also pointed out that these parameters (i.e. surface energy coefficient, nuclear radius and universal function) were chosen quite arbitrarily in the literature. Among these, the surface energy coefficient is available in in a variety of forms from time to time [4]. It affects the fusion barrier heights and cross-sections significantly [4]. Nuclear radius is available in different forms [2–4]. These forms vary in terms of its coefficients, mass or isospin dependence. The third parameter, the universal function, is also parametrized in different improved forms by various authors [2,3,7,8,10]. But unfortunately, no systematic study is available in the literature, where one can explore the role of these parameters in fusion barrier heights and cross-sections. So, a new proximity potential, in terms of the best set of the above-stated parameters, is in demand.

In the present study, the main aim is to pin down the role of the above-stated parameters in fusion barriers and cross-sections by constructing a new proximity potential and also to compare the final outcome with huge experimental data and its earlier available versions. This will definitely give a direct check to test the accuracy of the new proximity potential. The present systematic study includes the reactions with combined mass between $A = 19$ and 294 units. Totally, 395 experimentally studied reactions with symmetric as well as asymmetric colliding partners are taken into consideration. Section 2 describes the model in brief, §3 depicts the results, and a brief summary is presented in §4.

2. The model

The nuclear part of the interaction potential $V_{\rm N}(r)$ is calculated within the framework of the proximity potential 1977 [7] as

$$V_{\rm N}(r) = 4\pi \bar{R}\gamma b\Phi\left(\frac{r - C_1 - C_2}{b}\right) \text{ MeV}, \tag{1}$$

where $\bar{R}$ is the reduced radius and has the form

$$\bar{R} = \frac{C_1 C_2}{C_1 + C_2}, \tag{2}$$

quite similar to the one used for reduced mass. Here C_i denotes the matter radius and is calculated using the relation [10]

$$C_i = c_i + \frac{N_i}{A_i} t_i, \quad i = 1, 2, \tag{3}$$

where c_i denotes the half-density radii of the charge distribution and t_i is the neutron skin of the nucleus. To calculate c_i, we used the relation given in ref. [10] as

$$c_i = R_{00i} \left(1 - \frac{7}{2} \frac{b^2}{R_{00i}^2} - \frac{49}{8} \frac{b^4}{R_{00i}^4} + \cdots \right), \quad i = 1, 2. \tag{4}$$

Here, R_{00i} is the nuclear charge radius which is given as

$$R_{00i}^{\text{fit}} = 1.171 A_i^{1/3} + 1.427 A_i^{-1/3} \text{ fm}, \quad i = 1, 2. \tag{5}$$

This form of the nuclear radius is similar to the one due to Bass and Winther [18]. This is obtained by fitting the measured rms values of the charge distribution $\langle r^2 \rangle^{1/2}$ given in ref. [19] and is marked as R_{00i}^{fit}. As a first step, the measured rms values are converted to equivalent rms radii using the relation $R_{00i}^{\text{expt}} = \sqrt{\frac{5}{3}} \langle r^2 \rangle^{1/2}$ suggested in ref. [10] and is labelled as R_{00i}^{expt}. After this, the least-squares fitting procedure is applied to obtain eq. (5) (shown in figure 1a). The neutron skin t_i used in eq. (3) is calculated as [10]

$$t_i = \frac{3}{2} r_0 \left[\frac{J I_i - \frac{1}{12} c_1 Z_i A_i^{-1/3}}{Q + \frac{9}{4} J A_i^{-1/3}} \right], \quad i = 1, 2. \tag{6}$$

Here $r_0 = 1.14$ fm, the nuclear symmetric energy coefficient $J = 32.65$ MeV and $c_1 = 3e^2/5r_0 = 0.757895$ MeV. The neutron skin stiffness coefficient Q was taken to be 35.4 MeV. These coefficients were taken from ref. [10].

The surface energy coefficient γ was taken from Myers and Świątecki [20] and has the form

$$\gamma = \gamma_0 \left[1 - k_s \left(\frac{N - Z}{A} \right)^2 \right], \tag{7}$$

where N, Z, and A refer to the neutron, proton and total mass of the two colliding nuclei. In eq. (7), γ_0 ($= a_2/4\pi r_0^2$; where a_2 is the usual liquid drop model surface energy coefficient and r_0 is the nuclear radius constant) is the surface energy constant and k_s is the surface-asymmetry constant. Both constants were first parametrized by Myers and Świątecki [20] by fitting the experimental binding energies. The first set of these constants yielded values for γ_0 and k_s as 1.01734 MeV/fm^2 and 1.79, respectively. In the original proximity version, γ_0 and k_s were taken to be 0.9517 MeV/fm^2 and 1.7826 [21], respectively. Later on, these values were revised depending on the advancement in the theories and in experiments [4]. Fourteen such coefficients are highlighted and listed in table 1 and the role of extreme 4 is analysed in depth in ref. [4]. Out of them, two best sets of surface energy coefficients are stressed. In the present study, we shall restrict to the latest set of γ values, i.e. $\gamma_0 = 1.25284$ MeV/fm^2 and $k_s = 2.345$ presented in ref. [4]. This particular set of values were obtained directly from a least-squares adjustment to the ground-state masses of 1654 nuclei ranging from ^{16}O to ^{263}106 and fission-barrier heights [26].

Table 1. The different surface energy coefficients available in the literature are displayed. The different references from where the corresponding values are taken are also listed.

a_2 (MeV)	r_0 (fm)	γ_0 (MeV fm^{-2})	k_s	Ref.
18.56	1.2049	1.01734	1.79	[20]
17.9439	1.2249	0.9517	1.7826	[21]
24.7	1.16	1.460734	4.0	[22]
21.7	1.18	1.2402	3.0	[23]
20.57	1.18	1.1756	2.2	[24]
21.53	1.16	1.27326	2.5	[24]
21.14	1.16	1.2502	2.4	[24]
21.13	1.16	1.2496	2.3	[24]
17.9439	1.2249	0.9517	2.6	[25]
21.18466	1.16	1.25284	2.345	[26]
19.3859	1.18995	1.08948	1.9830	[27]
17.0603	1.21610	0.9180	0.7546	[27]
16.9707	1.21725	0.911445	2.2938	[27]

The universal function $\Phi(\frac{r-C_1-C_2}{b})$ used in eq. (2) was derived by several authors in different forms [7,8,10]. In the present study, the modified form due to Blocki and Świątecki [8]

$$\Phi(\xi) = \begin{cases} -1.7817 + 0.9270\xi + 0.143\xi^2 - 0.09\xi^3, & \text{for } \xi \le 0.0, \\ -1.7817 + 0.9270\xi + 0.01696\xi^2 - 0.05148\xi^3, & \\ \qquad \text{for } 0.0 \le \xi \le 1.9475, & \\ -4.41 \exp\left(-\dfrac{\xi}{0.7176}\right), & \text{for } \xi \ge 1.9475, \end{cases} \tag{8}$$

with $\xi = (r - C_1 - C_2)/b$ will be used. The surface width b (i.e. $b = (\pi/\sqrt{3})a$ with $a = 0.55$ fm) has been evaluated close to unity. By using these parameters, a new proximity potential will be constructed. This potential is marked as Prox New. Along with this new form, the original proximity potential [7] and its recently modified form [10] will also be used to compare our results. These forms are denoted as Prox Old and Prox Mod, respectively.

The total ion–ion interaction potential $V_T(r)$ between the two colliding nuclei with charges Z_1 and Z_2, centre separation r and density distribution assumed spherical, and frozen, is approximated as [10]

$$V_T(r) = V_N(r) + V_C(r) = V_N(r) + \frac{Z_1 Z_2 e^2}{r}, \tag{9}$$

where e is the charge unit. The above form of the Coulomb potential is suitable when two approaching nuclei are well separated.

3. Results and discussion

As can be seen from the preceding section, three factors which govern the success of proximity potential are (i) the surface energy coefficient, (ii) the universal function and (iii) the nuclear radius. The literature is carefully scanned and it was found that the latest information on these three factors can reshape the old proximity potential. Recently, the role of surface energy coefficient was studied in detail in ref. [4]. As far as universal function is concerned, the modified form due to Blocki and Świątecki [8] for gap configuration will be used. It is noted that this universal function reduces the average deviation for fusion barriers by 1%. For nuclear radius new fitted formula (eq. (5)) from the measured rms values of the charge distribution [19] using least-squares procedure will be used and the results are displayed in figure 1a. This form is well known in ref. [18]. The accuracy of the

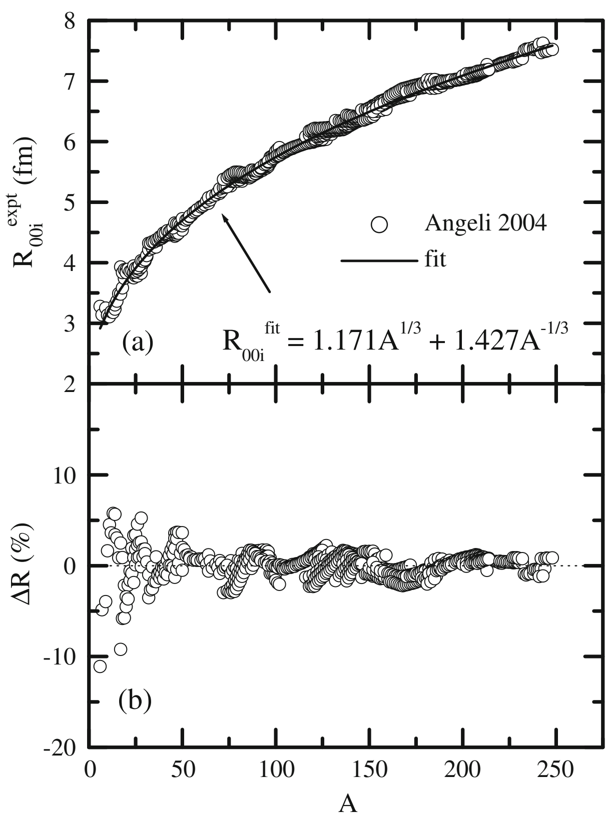

Figure 1. (**a**) The variation of equivalent rms nuclear radius R_{00i}^{expt} (in fm) (defined in text) as a function of the total mass of the nuclei A. The solid line represents the straight line least-squares fit made over the data points. The measured rms values of the charge distribution are taken from Angeli [19]. (**b**) The variation of ΔR (%) (defined in text) as a function of the total mass of the nuclei A.

fitted formula is checked in figure 1b, where the percentage difference between the fitted and experimental values defined as

$$\Delta R\ (\%) = \frac{R^{\rm fit} - R^{\rm expt}}{R^{\rm expt}} \times 100, \tag{10}$$

as a function of total mass of the nuclei A is displayed. Interestingly, the above-fitted radius formula (eq. (5)) reproduces the experimental values within ±5% on average. Slight scattering for lighter mass region is visible, whereas for heavy mass range the agreement is perfect. In the present analysis, the above new radius formula will be used.

A new form of the proximity potential is constructed using the above set of parameters. By using the new version of the proximity potential along with its old as well as its recently modified versions, fusion barriers are calculated for 395 reactions using the conditions

$$\left.\frac{{\rm d}V_{\rm T}(r)}{{\rm d}r}\right|_{r=R_{\rm B}} = 0 \ \text{ and } \ \left.\frac{{\rm d}^2 V_{\rm T}(r)}{{\rm d}r^2}\right|_{r=R_{\rm B}} \leq 0. \tag{11}$$

The height and position of the barrier are marked, respectively, as $V_{\rm B}$ and $R_{\rm B}$.

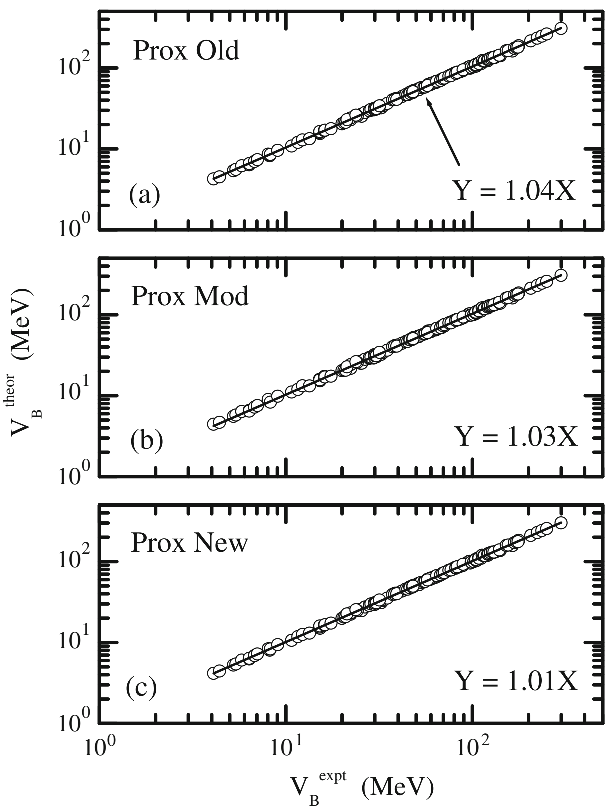

Figure 2. Comparison of theoretical fusion barrier heights $V_{\rm B}^{\rm theor}$ (MeV) calculated using the earlier versions of proximity potential (shown in (**a**) and (**b**)) along with new modification (shown in (**c**)) with the corresponding experimental values $V_{\rm B}^{\rm expt}$ (MeV). The solid lines represent the straight line least-squares fit made over different points. The experimental values are taken from refs [2–4,10,28].

In figure 2, the theoretical fusion barrier heights V_B^{theor} (MeV) calculated using different proximity versions vs. its corresponding experimental values are displayed. The experimental values are taken from refs [2–4,10,28]. Very encouragingly, Prox New reproduces the experimental fusion barrier heights within 1%, whereas its old and modified versions reproduce the same within 4% and 3%, respectively. However, the original form of the proximity potential presented in ref. [2] overestimates the data by 6.7% for symmetric colliding nuclei. Its recently modified version Prox Mod is also not good enough to explain data (within 5.3% for symmetric colliding nuclei [2]). This may be due to the improper use of the radius, surface energy coefficient and universal function values. Similar results were obtained for asymmetric colliding nuclei [3] also.

The final outcomes are quantified in figures 3a and 3b. In figure 3a, the percentage deviation between the theoretical and experimental values using different proximity potentials is presented. The original proximity potential along with its recently modified form are also displayed. The fusion barrier heights are reproduced within ±5% on average. In

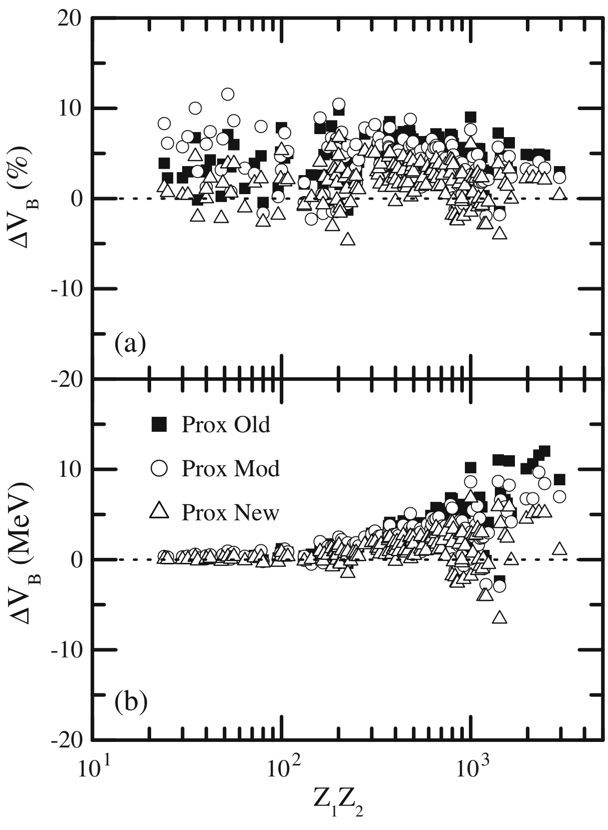

Figure 3. (**a**) The percentage deviation ΔV_B (%) (defined same as eq. (10)) as a function of the product of the charges of colliding nuclei $Z_1 Z_2$ using different versions of the proximity potential. (**b**) The variation of ΔV_B $(= V_B^{\text{theor}} - V_B^{\text{expt}})$ (in MeV) as a function of the product of the charges of the colliding nuclei $Z_1 Z_2$.

figures 2 and 3, only 155 reactions are displayed to maintain the clarity. The experimental data are taken from refs [2–4,10,28]. For more quantitative discussion, the total number of 395 reactions are divided into three different categories. Among them, the first category involves a set of 25 'light' reactions with both Z_1 and $Z_2 < 9$, second category involves a set of 123 'mixed' reactions with either Z_1 or $Z_2 < 9$, and third category involves a set of 247 'heavy' reactions with both Z_1 and $Z_2 > 8$. The average deviation for the fusion barrier heights over 395 reactions is 1.14% using our modified potential Prox New, whereas Prox Old and Prox Mod give 3.93% and 3.40%, respectively. For the three separate groups, from 'light' to 'heavy' the corresponding numbers are 1.87%, 5.33%, −0.52%; 4.48%, 4.60%, 1.86%; 3.87%, 2.60%, 0.95% for Prox Old, Prox Mod and Prox New, respectively. Separate categories of different reactions are not displayed in the figure to maintain clarity. This clearly shows that our modified proximity potential explains the experimental data nicely.

In figure 3b, the difference between the theoretical and experimentally extracted fusion barriers are displayed. It is clear from the figure that Prox New gives closer results. The mean deviation over 395 reactions are 2.56 MeV, 1.76 MeV and 0.30 MeV for Prox Old,

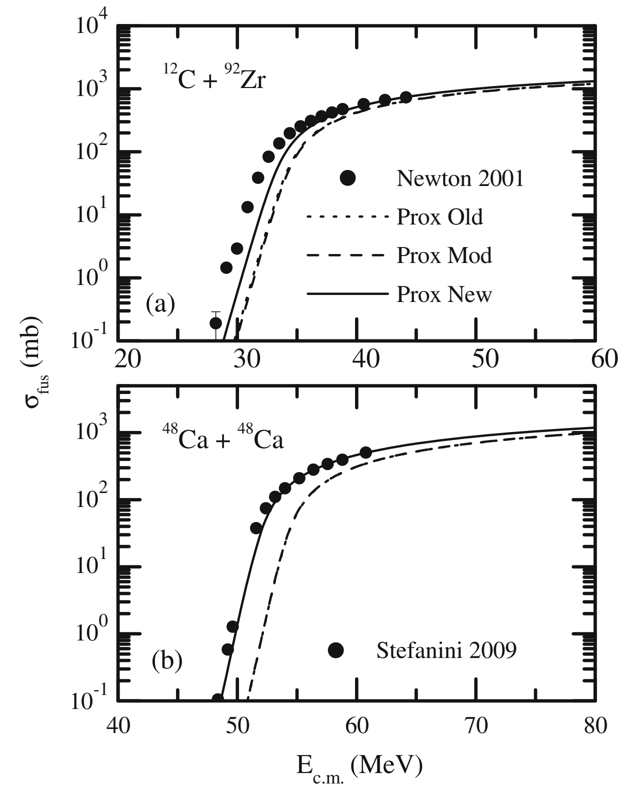

Figure 4. The fusion cross-sections σ_{fus} (mb) as a function of the centre-of-mass energy $E_{c.m.}$ (MeV) using the earlier versions of proximity potential (Prox Old and Prox Mod) along with the new version (Prox New). The experimental data are taken from Newton [29] and Stefanini *et al* [30].

Prox Mod and Prox New potentials, respectively. However, its value for the three separate groups from 'light' to 'heavy' are 0.12 MeV, 0.34 MeV, −0.04 MeV; 1.72 MeV, 1.75 MeV, 0.83 MeV and 3.23 MeV, 1.91 MeV, 0.08 MeV, respectively. The deviations especially for the heavy systems are significantly reduced. This was the problem with original as well as its recently modified form as pointed out by several authors [10,11]. It is clear from figures 3a and 3b, that Prox New is able to reproduce the experimental data nicely from low to heavy mass region. The small difference is not significant because of the uncertainties in the analysis of the experimental data.

Finally, the accuracy of new proximity potential is tested on fusion probabilities. In figure 4, the fusion cross-sections σ_{fus} (in mb) as a function of the centre-of-mass energy $E_{\text{c.m.}}$ (MeV) for the ^{12}C+^{92}Zr [29] and ^{48}Ca+^{48}Ca [30] reactions are displayed. The fusion cross-sections are calculated using the well-known Wong model [31]. The earlier versions, that is, Prox Old and Prox Mod are also displayed. It is clearly visible from the figure that Prox New is in good agreement, whereas the older forms are far from the experimental data. One can further note that Prox Old and Prox Mod show similar results. It means no improvement can be seen in Prox Mod potential as was claimed in [10].

4. Summary

By using up-to-date knowledge of the universal function, surface energy coefficient and nuclear radius, a new proximity potential is constructed. The newly constructed proximity potential Prox New reproduces the fusion barrier heights within ±5% on average. The average deviation of 4% reported in the literature is significantly reduced to 1.14% for fusion barrier heights. A comparison with experimental data reveals that the new proximity potential reproduces experimental data very accurately compared to earlier versions and can be used in further fusion studies.

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References

[1] J M B Shorto *et al*, *Phys. Rev.* **C81**, 044601 (2010)
[2] I Dutt and R K Puri, *Phys. Rev.* **C81**, 044615 (2010)
[3] I Dutt and R K Puri, *Phys. Rev.* **C81**, 064609 (2010)
[4] I Dutt and R K Puri, *Phys. Rev.* **C81**, 047601 (2010)
I Dutt and R Bansal, *Chin. Phys. Lett.* **27**, 112402 (2010)
[5] R K Puri *et al*, *Eur. Phys. J.* **A23**, 429 (2005)
R Arora *et al*, *ibid.* **8**, 103 (2000)
R K Puri *et al*, *ibid.* **3**, 277 (1998)
N K Dhiman *et al*, *Acta. Phys. Pol.* **B38**, 2133 (2007); **37**, 1855 (2006)
I Dutt and N K Dhiman, *Chin. Phys. Lett.* **27**, 112401 (2010)

[6] R K Gupta *et al*, *Phys. Rev.* **C47**, 561 (1993); *J. Phys. G: Nucl. Part. Phys.* **18**, 1533 (1992)
S S Malik *et al*, *Pramana – J. Phys.* **32**, 419 (1989)
R K Puri *et al*, *Europhys. Lett.* **9**, 767 (1989); *J. Phys. G: Nucl. Part. Phys.* **18**, 903 (1992)
[7] J Blocki, J Randrup, W J Świątecki and C F Tsang, *Ann. Phys. (N.Y.)* **105**, 427 (1977)
[8] J Blocki and W J Świątecki, *Ann. Phys. (N.Y.)* **132**, 53 (1981)
[9] W Reisdorf, *J. Phys. G: Nucl. Part. Phys.* **20**, 1297 (1994)
[10] W D Myers and W J Świątecki, *Phys. Rev.* **C62**, 044610 (2000), and earlier references therein
[11] K Siwek-Wilczyńska and J Wilczyński, *Phys. Rev.* **C69**, 024611 (2004)
[12] M Liu *et al*, *Nucl. Phys.* **A768,** 80 (2006)
A Dobrowolski *et al*, *ibid.* **729**, 713 (2003)
J Bartel *et al*, *Eur. Phys. J.* **A14**, 179 (2002)
[13] V Y Denisov, *Phys. Lett.* **B526**, 315 (2002)
V Y Denisov and V A Nesterov, *Phys. At. Nucl.* **69**, 1472 (2006)
[14] P B Gossiaux *et al*, *Nucl. Phys.* **A619**, 379 (1997)
R K Puri *et al*, *Phys. Rev.* **C54**, R28 (1996); *ibid. J. Comput. Phys.* **162**, 245 (2000)
Y K Vermani *et al*, *J. Phys. G: Nucl. Part. Phys.* **36**, 105103 (2010); *ibid.* **37**, 015105 (2010); *ibid. Europhys. Lett.* **85**, 62001 (2009); *ibid. Phys. Rev.* **C79**, 064613 (2009)
S Kumar *et al*, *ibid.* **78**, 064602 (2008)
R Chugh and R K Puri, *Phys. Rev.* **C82**, 014603 (2010)
[15] S Kumar *et al*, *Phys. Rev.* **C58**, 3494 (1998)
A D Sood *et al*, *Phys. Rev.* **C70**, 034611 (2004); *Phys. Rev.* **C79**, 064618 (2009); *Phys. Lett.* **B594**, 260 (2004)
E Lehmann *et al*, *Z. Phys.* **A355**, 55 (1996)
S Kumar *et al*, *Phys. Rev.* **C81**, 014601 (2010); *ibid.* **81**, 014611 (2010)
S Gautum *et al*, *J. Phys. G: Nucl. Part. Phys.* **37**, 085102 (2010)
[16] S W Huang *et al*, *Prog. Part. Nucl. Phys.* **30**, 105 (1993)
G Batko *et al*, *J. Phys. G: Nucl. Part. Phys.* **20**, 461 (1994)
[17] C Fuchs *et al*, *J. Phys. G: Nucl. Part. Phys.* **22**, 131 (1996)
[18] R Bass, *Phys. Rev. Lett.* **39**, 265 (1977)
P R Christensen and A Winther, *Phys. Lett.* **B65**, 19 (1976)
[19] I Angeli, *At. Data Nucl. Data Tables* **87**, 185 (2004)
G Fricke *et al*, *ibid.* **60**, 177 (1995)
E G Nadjakov, K P Marinova and Y P Gangrsky, *ibid.* **56**, 133 (1994)
[20] W D Myers and W J Świątecki, *Nucl. Phys.* **81**, 1 (1966)
[21] W D Myers and W J Świątecki, *Ark. Fys.* **36**, 343 (1967)
[22] P Möller and J R Nix, *Nucl. Phys.* **A272**, 502 (1976)
[23] H J Krappe, J R Nix and A J Sierk, *Phys. Rev.* **C20**, 992 (1979)
[24] P Möller and J R Nix, *Nucl. Phys.* **A361**, 117 (1981)
[25] G Royer and B Remaud, *J. Phys. G: Nucl. Phys.* **10**, 1057 (1984)
[26] P Möller, J R Nix, W D Myers and W J Świątecki, *At. Data Nucl. Data Tables* **59**, 185 (1995)
[27] K Pomorski and J Dudek, *Phys. Rev.* **C67**, 044316 (2003)
[28] A M Stefanini *et al*, *Phys. Rev.* **C82**, 014614 (2010)
C L Jiang *et al*, *ibid.* **82**, 041601(R) (2010)
V V Parkar *et al*, *ibid.* **82**, 054601 (2010)
R Rafiei *et al*, *ibid.* **81**, 024601 (2010)
M Dasgupta *et al*, *ibid.* **81**, 024608 (2010)
A M Stefanini *et al*, *ibid.* **81**, 037601 (2010)
H Kumawat *et al*, *ibid.* **81**, 054601 (2010)
S Nath *et al*, *ibid.* **81**, 064601 (2010)
D J Hinde and M Dasgupta, *ibid.* **81**, 064611 (2010)

M Ray *et al*, *ibid.* **78**, 064617 (2008)
V Tripathi *et al*, *Phys. Rev.* **C65**, 014614 (2001)
S Sinha, M R Pahlavani, R Varma, R K Choudhury, B K Nayak and A Saxena, *ibid.* **64**, 024607 (2001)
I Padron *et al*, *ibid.* **66**, 044608 (2002)
J O Newton *et al*, *ibid.* **70**, 024605 (2004)
J J Kolata *et al*, *ibid.* **69**, 047601 (2004)
Z H Liu *et al*, *Eur. Phys. J.* **A26**, 73 (2005)
S Mitsuoka, H Ikezoe, K Nishio, K Tsuruta, S C Jeong and Y Watanabe, *Phys. Rev. Lett.* **99**, 182701 (2007)
A M Stefanini *et al*, *Phys. Rev.* **C78**, 044607 (2008)
K Washiyama and D Lacroix, *ibid.* **78**, 024610 (2008)

[29] J O Newton *et al*, *Phys. Rev.* **C64**, 064608 (2001)

[30] A M Stefanini *et al*, *Phys. Lett.* **B679**, 95 (2009)

[31] C Y Wong, *Phys. Lett.* **B42**, 186 (1972); *Phys. Rev. Lett.* **31**, 766 (1973)