Role of the saturation properties of hot nuclear matter in the proximity formalism

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Temperature dependence of the surface thickness parameter b in the original version of proximity formalism is investigated by including the modification effects of equation of state (EOS) at finite temperature on nuclear potential. Here, this modification is performed using the evaluation of the increasing of total energy in the overlapping region by the EOS extracted from the extended Thomas-Fermi approach for asymmetric nuclear matter at finite temperature. This EOS is also supplemented with the saturation effects of nuclear matter density. Our results show a different temperature dependence for surface thickness b of the excited compound nucleus, which is formed during the fusion process. The original version of Proximity 77 with this new form of $b(T)$ provides a reasonable result for theoretical values of the barrier characteristics and fusion cross section. Our obtained results are also compared with other theoretical approaches.

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I. INTRODUCTION

In recent decades, the equation of state (EOS) and analysis of its influence are interesting subjects in theoretical studies of nuclear physics, from astrophysics to nuclear fusion [1–6]. In general, an equation of state is a conceptual relationship of the various measurable properties of a physical system. In a nuclear system, the energy per particle of nuclear matter (NM) as a function of the nuclear density $\rho = \rho_n + \rho_p$ and relative neutron excess $\delta = (\rho_n - \rho_p)/\rho$ can be considered as the definition of NM equation of state, $\varepsilon(\rho, \delta)$. EOS of nuclear matter has been studied based on different approaches and models, both microscopic and phenomenological. Roughly speaking there are two basic approaches to microscopic calculations, Brueckner-type and variational-type calculations. The Brueckner-Hartree-Fock calculation and its relativistic versions [7–9] are of first type, and fermionic hypernetted chain [10] and lowest order constrained variational methods [9,11] are of the second type. Usually in microscopical calculations realistic N-N interactions are employed but such methods need many-body calculations and hence are more sophisticated. On the other hand, the phenomenological methods like Hartree-Fock [12], Thomas-Fermi [13,14], and Skyrme-type effective interactions [15] are much simpler, and by adjusting the parameters of the model one can achieve saturation properties of the system. The equation of state predicted by the Thomas-Fermi model is one of the most simple and popular types of nuclear equations of state [13,14]. The searches to determine the bulk nuclear and neutron star properties as well as the history of supernova explosion [4,5,16,17] are examples of the important uses of this type of EOS.

So far, many efforts have been carried out to investigate the modification effects of nuclear EOS in the fusion reactions using microscopic theories such as the double-folding model [3]. These studies consist of two different viewpoints. One is the cold NM approach, which analyzes the fusion excitation functions by ignoring the temperature effects of compound nucleus. The description of the unexpected behavior of fusion cross sections at deep sub-barrier energies is one of the most important applications of this approach [3,18–23]. Employing an EOS at finite temperature is more reasonable and useful when the excited energy of compound nucleus increases to the values greater than Fermi energy of the system [24].

One of the theoretical models which is extensively used to calculate the nuclear potential is proximity formalism [25]. So far, several thermal procedures have been applied to modify the different components of this nuclear potential [26–28]. In the present study, we focus on the temperature dependence of the surface thickness parameter b, which is a significant part of the proximity formalism. Using the thermal Hartree-Fock (THF) approach [29], Sauer and coworkers have analyzed the properties of finite nuclei at different temperatures [30]. It is shown that the nuclear distribution becomes more diffuse at higher temperatures. Therefore, one can expect that the surface thickness increases with energy or temperature of system. This behavior of the thickness parameter has been parameterized as a temperature-dependent form (second-order), i.e., $b(T) \approx 0.72(1 + 0.009T^2)$ fm [30]. Now, we are looking to analyze this dependence using the proposed extended Thomas-Fermi model (ETFM) [31], which is supplemented with the saturation effects during the overlapping of density distributions. Indeed, we focus on the modification effect of hot EOS on the proximity formalism using a systematic study over a wide energy range of fusion reactions to explore the thermal behavior of surface thickness parameter b.

In summary, our motivations in this work are as follows: (a) The temperature dependence of the thickness parameter b has been performed by analyzing the thermal properties of finite nuclei, whereas we have explored this behavior during a fusion process within the static framework. (b) It is noticeable that the extrapolation of proximity formalism to the shorter distances of Coulomb barrier has been performed to reach the following purposes:

(i) The saturation effects of nuclear matter as well as the temperature effects of compound nucleus have more importance at the complete overlapping region where the compound system is completely formed.

(ii) In comparison with the other proximity versions such as Bass 80, Bass73, and CW 76 models, the Prox. 77 potential provides an appropriate physical shape in the inner regions of the Coulomb barrier [25,32].

The paper is organized as follows: We discuss about the nucleon-nucleon interaction in the overlapping region of density distributions in Sec. II. This section also presents a brief discussion about ETFM. The description of the used nuclear proximity model is explained in Sec. III. Our predictions for total interacting potential and fusion cross sections of different colliding systems are described in Sec. IV. Some of our important conclusions are presented in Sec. V.

II. NUCLEON-NUCLEON INTERACTIONS IN THE OVERLAPPING REGION OF NUCLEAR DENSITIES

When two interacting nuclei approach each other based on the sudden approximation, it is assumed that the nuclei keep their original NM distribution in the overlapping region, and one can expect that the NM density in this region goes beyond the normal saturation density, namely $\rho \gg \rho_0 \simeq 0.16\ \mathrm{fm}^{-3}$. This effect can be modified in the calculation of nuclear potential in an static framework by adding an extra hard core potential to nucleon-nucleon interaction. The main physical aspect behind this extra interaction is the Pauli exclusion principle, which provides a repulsive interaction between nucleons in the overlapping region. On the other hand, one can expect an increase in the energy of system when the total density exceeds the saturation density of nuclear matter. In the current study, the estimation of this variation on the energy is performed by considering the thermal effects of the compound nucleus. Therefore, for evaluating the increasing energy of system as $\Delta U(T)$ one needs to know the form of the EOS for cold and hot nuclear matter [3,24]. It should be noted that we use the equation of state predicted by the original and the generalized forms of the Thomas-Fermi model for estimating the binding energy per nucleon of cold and hot NM, respectively [13,14,31]. Indeed, to predict the EOS at finite temperature we have employed a modern version of effective interaction proposed by Myers and Swiatcki (TF96) [14]. In this method, the motion of each nucleon in phase space is describe by a one-body Hamiltonian in the following form:

$$h(p) = \frac{p^2}{2B} + u(p), \tag{1}$$

where B is the effective mass and $u(p)$ is the effective single-particle potential that is both temperature and density dependent. At finite temperature the state of the nuclear system is governed by a phase-space single-particle Fermi-Dirac-type distribution function which determines the occupancy in phase space,

$$n(p) = \frac{1}{1 + e^{\beta(h(p)-\mu^*)}}, \tag{2}$$

where the lagrange multiplier μ^* as a flexible parameter is adjusted for a given temperature $T = \frac{1}{\beta}$ and nuclear density ρ. Finally, the functional minimization of free energy per nucleon with respect to the distribution function is an essential requirement for equilibrium situation. After doing all this, the appropriate effective mass and effective single-particle potential are obtained [31].

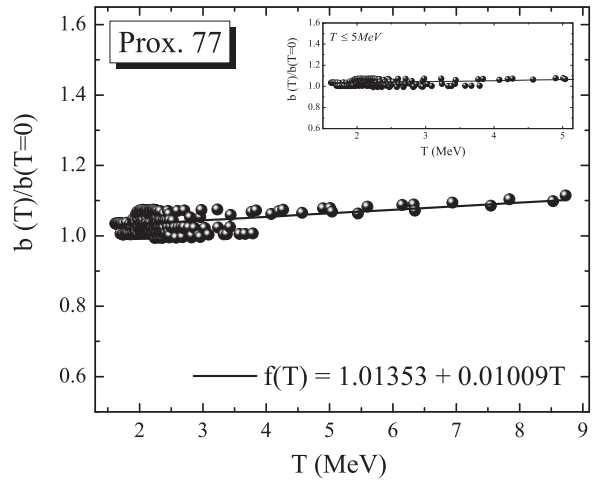

FIG. 1. Temperature dependence of the $b(T)/b(T=0)$ ratio of compound nucleus based on the Prox. 77 potential for our selected energy range. The solid line is applied to present the linear behavior of the calculated results.

III. A BRIEF DESCRIPTION OF PROXIMITY METHOD

The standard way to address the analysis of a fusion reaction is utilize the proper form of the nuclear part of total interacting potential. During the past four decades, many theoretical models have been provided to evaluate this part [33–35]. The proximity model is a favorable form of nuclear potential [25]. According to the proximity theorem [25], the shape and the geometry of the participant nuclei as well as the surface separation s are three important issues in this formalism. It should be mentioned that two functions are separately devoted to formulate these properties,

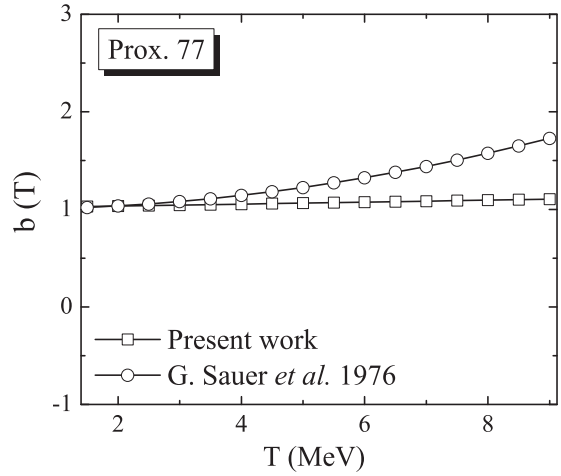

FIG. 2. Comparison of results of the present work and those reported by Sauer *et al.* [30] for temperature-dependent form of $b(T)$ at different temperatures.

$V_N(r) = f(\text{shp., geo.})\Phi(s)$, where $\Phi(s)$ is a universal function. Blocki *et al.* have introduced the original version of the proximity potential, which is marked as Prox. 77 [25]. Using their results, the nuclear part of the total potential $V_N(r)$ between two interacting surfaces can be written as

$$V_N(r) = 4\pi\gamma b\overline{R}\Phi\left(\frac{s}{b}\right)\text{MeV}, \tag{3}$$

where $\Phi(\xi = s/b)$ is a universal function,

$$\Phi(\xi) = \begin{cases} -\frac{1}{2}(\xi - 2.54)^2 - 0.0852(\xi - 2.54)^3 & \xi \leqslant 1.2511 \\ -3.437\exp(-\xi/0.75) & \xi \geqslant 1.2511 \end{cases} \tag{4}$$

and s is the separation distance between the half-density surfaces of the interacting nuclei, which given by

$$s = r - C_1 - C_2\,\text{fm}. \tag{5}$$

Moreover, b is the surface thickness parameter which is taken to be 1 fm in the above formula. In Eq. (3), the mean curvature radius $\overline{R}$ has the form

$$\overline{R} = \frac{C_1C_2}{C_1 + C_2}. \tag{6}$$

In this formalism, the $C_1(C_2)$ parameter denotes the radius of the spherical target (projectile), which is called Süssmann's central radius and reads as

$$C_i = R_i\left[1 - \left(\frac{b}{R_i}\right)^2 + \cdots\right]. \tag{7}$$

In the above relation, the effective sharp radius R_i can be written as

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}\,\text{fm} \quad (i = 1, 2). \tag{8}$$

The surface tension coefficient γ is defined as

$$\gamma = \gamma_0\left(1 - k_sA_s^2\right), \tag{9}$$

where γ_0 and k_s are the surface energy and surface-asymmetry constants, respectively. In this version, the value of the former is 0.9517 MeV/fm^2 and the latter is 1.7826. In the above formula, $A_s = (\frac{N-Z}{N+Z})$ is the asymmetry parameter, where N and Z denote the neutron and proton numbers of a compound system.

IV. RESULTS AND DISCUSSION

In the present study, the thermal effects of compound nucleus and the saturation properties of nuclear matter are taken into account to modify the original version of proximity formalism using a different physical approach. It is well known that such properties can be very important in a completely overlapping region of density distributions (i.e., $r = 0$) during a fusion process. Therefore, the knowledge of the nuclear potential and the variation of total energy at internuclear distance $r = 0$ is a key role to reach this purpose. Due to the intrinsic property of nuclear matter incompressibility, it is predictable that the proximity formalism provides an appropriate physical shape for interacting potential at shorter distances. It is proposed that the values of nuclear potential at this region can be estimated by [3]

$$V_N(r = 0) = \Delta U(T). \tag{10}$$

The values of the nuclear potential at each temperature T are calculated based on the Prox. 77 potential, which is modified using the temperature-dependent form of $b(T) = b(T = 0)$ $f(T)$, where $f(T)$ is an arbitrary temperature-dependent function. For evaluating this function we used Eq. (10). In addition to justifying this requirement, we consider the agreement between the theoretical and the experimental values of barrier characteristics to estimate the $f(T)$ function. It is noticeable that the temperature T is related to the excitation energy E^* of the compound nucleus or the energy of the projectile nucleus in the center-of-mass frame, $E_{\text{c.m.}}$, via the entrance channel Q_{in} value, as [36,37]

$$E^* = E_{\text{c.m.}} + Q_{\text{in}} = \frac{1}{a}AT^2 - T, \tag{11}$$

with $a = 9$ or 10 for intermediate mass or superheavy systems, respectively. To calculate the values of the temperature function $f(T)$, we have carried out a systematic analysis over a wide range of energy for different fusion reactions. Moreover, it is emphasized that the extended approach of the Thomas-Fermi method for NM has been proposed for different structures of baryonic matter, such as symmetric and asymmetric NM, at finite temperature [31]. In the present study, we assume that the excited compound nucleus for each fusion reaction to be a finite piece of a nuclear matter which

TABLE I. The calculated values of the R_B (in fm) and V_B (in MeV) using different considered potentials. They are carried out for fusion systems that the experimental data are reported for them.

	R_B (fm)				V_B (MeV)			
Reaction	a	b	c	Exp.	a	b	c	Exp.
^{16}O + ^{58}Ni [48]	8.86	8.9	8.90	9.3	33.32	33.05	33.08	31.67
^{28}Si + ^{58}Ni [39]	9.30	9.33	9.33	9.00	55.82	55.45	55.47	53.80
^{30}Si + ^{62}Ni [39]	9.55	9.6	9.59	9.7	54.45	54.00	54.08	52.20
^{30}Si + ^{64}Ni [39]	9.61	9.66	9.65	9.4	54.13	53.73	53.77	51.20
^{35}Cl + ^{60}Ni [41]	9.60	9.64	9.64	10.22	65.82	65.32	65.40	62.29
^{40}Ca + ^{62}Ni [42]	9.78	9.82	9.81	10.35	76.13	75.58	75.66	72.30
^{37}Cl + ^{73}Ge [43]	10.00	10.05	10.04	10.60	72.43	71.91	71.98	69.20

Notes. Column a: Based on Prox. 77 potential. Column b: Based on the modified Prox. 77 potential suggested in Ref. [30]. Column c: Based on the modified Prox. 77 potential suggested in the present work.

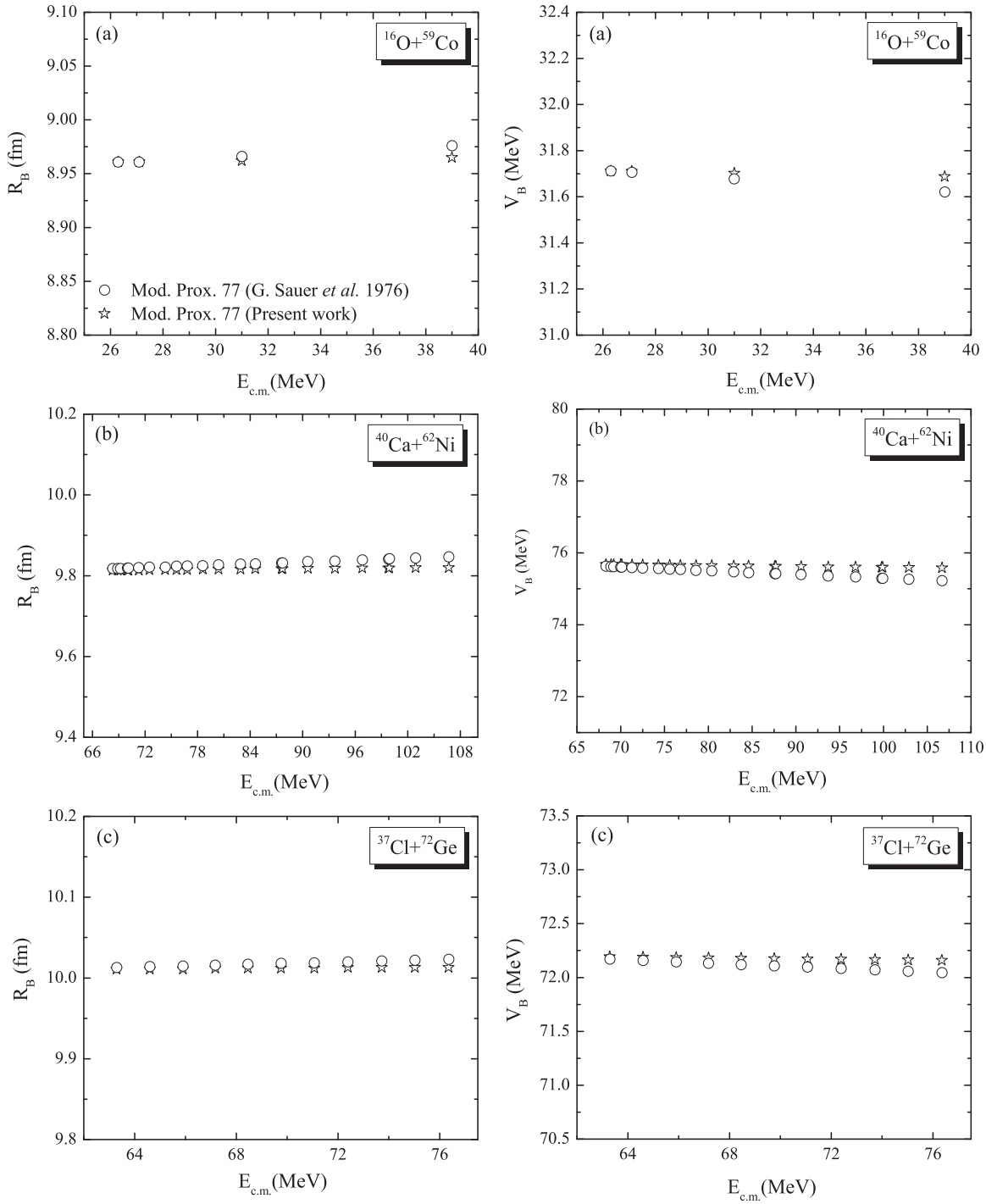

FIG. 3. The behavior of the barrier heights V_B (right panels) and its positions R_B (left panels) as a function of center-of-mass energy $E_{\text{c.m.}}$ (in MeV) for (a) ^{16}O + ^{59}Co, (b) ^{40}Ca + ^{62}Ni, and (c) ^{37}Cl + ^{72}Ge fusion reactions. The R_B and V_B values at each energy are calculated using our proposed form of $b(T)$ and that reported by Sauer *et al.* [30].

is asymmetric with respect to the number of the neutrons and protons. Such approximation is reasonable for a heavy compound system [38].

The obtained results for temperature function $f(T)$, or the ratio of $b(T)/b(T=0)$, at each bombarding energy are displayed in Fig. 1. As one can see from this figure, the compound nuclei which are formed during the fusion process of our selected colliding pairs are almost at a temperature range greater than 2 MeV. Moreover, it is clear that the ratio of $b(T)/b(T=0)$ has a regular systematic trend as a function of the temperature T. It can be formulated as follows:

$$\frac{b(T)}{b(T=0)} = f(T) = 1.013\,53 + 0.010\,09T. \qquad (12)$$

In comparison with the proposed form of Ref. [30], Eq. (12) reveals that the thermal corrections caused by the Thomas-Fermi (TF) model give rise to a linear temperature dependence for $b(T)$. It worth mentioning that the obtained function for $b(T)$ satisfies the asymptotic condition for temperature T, namely $b(T) \approx b(T = 0)$ when $T \to 0$.

Figure 2 shows a comparison between the obtained results of surface thickness b based on the ETFM and THF approaches for our selected energy range. One finds that the results of these two thermal approaches are consistent with each other at temperatures less than 4 MeV. For higher temperatures, the predictions of Ref. [30] are considerably larger. In other words, one may conclude that the ETFM and THF formalism exhibit similar predictions for thermal conditions of a hot nucleus at low temperatures.

The barrier height and its position are two important quantities to describe and understand the system. So, we calculate the theoretical values of the barrier height V_B and its position R_B using the Prox. 77 potential with and without the thermal modification effects of $b(T)$; see Table I. It is remarkable that the calculations of this table are performed for fusion reactions for which the experimental data of barrier characteristics are reported. Moreover, the values of R_B and V_B are evaluated at temperature T which corresponds to the bombarding energy near the Coulomb barrier position. Our predictions in Table I indicate that both proposed thermal procedures for the Prox. 77 potential improve the theoretical values of the barrier height in different fusion reactions.

The behaviors of the calculated values of R_B and V_B as a function of the center-of-mass energy $E_{\text{c.m.}}$ for $^{16}\text{O} + {}^{59}\text{Co}$, $^{40}\text{Ca} + {}^{62}\text{Ni}$, and $^{37}\text{Cl} + {}^{72}\text{Ge}$ colliding systems are indicated in Fig. 3. This figure shows that the barrier characteristics for each reaction have systematic decreasing (barrier height) and

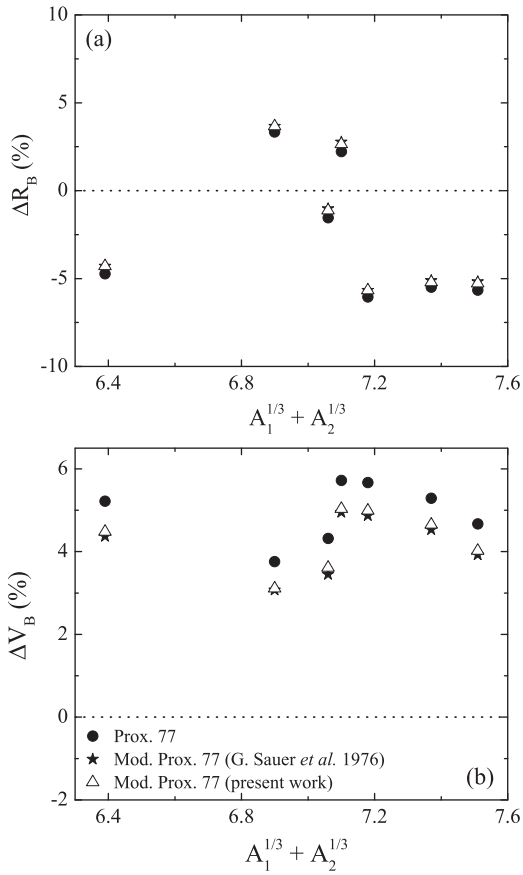

FIG. 4. The percentage difference of (a) barrier positions $\Delta R_B(\%)$ and (b) barrier heights $\Delta V_B(\%)$ based on the Prox. 77, modified Prox. 77 ([30]), and modified Prox. 77 (present work) potentials for fusion reactions, which are reported in Table. I.

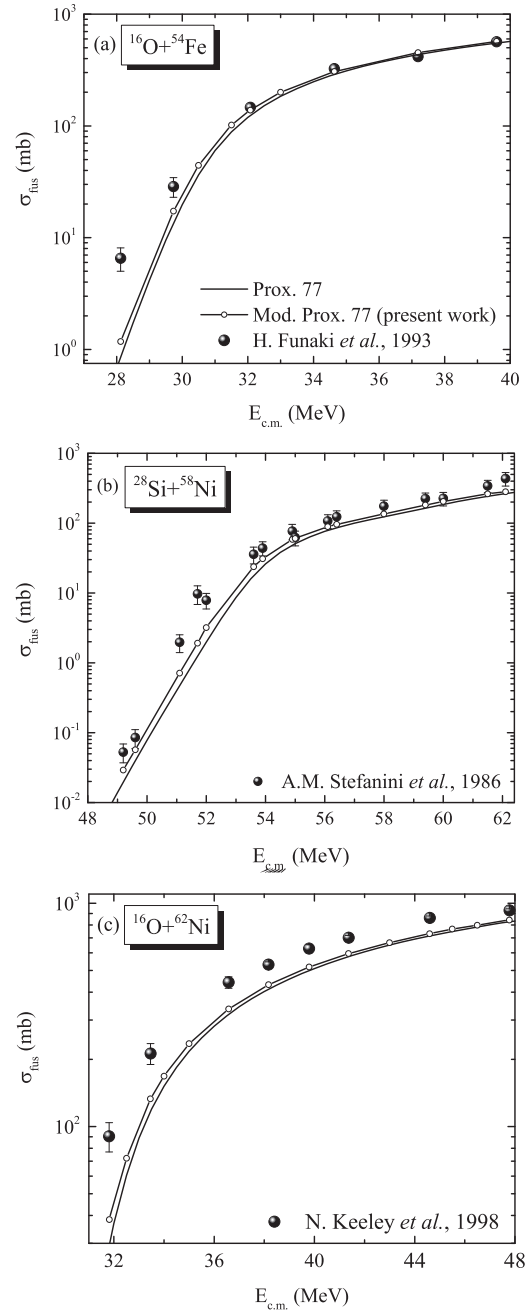

FIG. 5. Experimental fusion excitation functions for (a) $^{16}\text{O} + {}^{54}\text{Fe}$, (b) $^{28}\text{Si} + {}^{58}\text{Ni}$, and (c) $^{16}\text{O} + {}^{62}\text{Ni}$ colliding systems compared with the calculated results of our modified formalism for Prox. 77 potential. The experimental data are from Refs. [47] and [39,40].

increasing (barrier position) trends versus the center-of-mass energy. These calculations also emphasize the behavior of the $b(T)$ values presented in Fig. 2. Indeed, the discrepancy of two thermal methods enhances at higher energies.

To reach further understanding, the percentage relative error between the theoretical values of barrier characteristics and their corresponding experimental data are estimated by

$$\Delta X_B(\%) = \frac{X_B^{\text{Theor.}} - X_B^{\text{Exp.}}}{X_B^{\text{Exp.}}} \times 100, \tag{13}$$

where $X = R_B$ (V_B). The obtained results for $\Delta R_B(\%)$ and $\Delta V_B(\%)$, which are carried out for fusion reactions of Table I, are displayed in Fig. 4. It shows that both the modified proximity potentials based on our framework and those determined using Ref. [30] generate better results than the original version of Prox. 77.

To illustrate the influence of the temperature effects of compound nucleus on the fusion cross sections, we determine the theoretical values of σ_{fus} using the coupled channels (CC) calculations [44]. In this approach, the nuclear potential in the entrance channel is parameterized as the Woods-Saxon (WS) form. Therefore, for calculating the values of the fusion cross section, one should adjust the different parameters of this form of potential by fitting them to the considered potential model. Moreover, for nuclear structure input of target and projectile nuclei in the CC approach, we have considered the coupling between the low-lying excited states 2^+ and 3^- [45,46]. The behaviors of the calculated values of σ_{fus} versus the center-of-mass energy $E_{\text{c.m.}}$ are presented in Fig. 5 for ^{16}O + ^{54}Fe, ^{28}Si + ^{58}Ni, and ^{16}O + ^{62}Ni fusion reactions. It should point out that for these selected systems the fitting relative error of the WS potential to both potentials shown in Fig. 5 is less than 10^{-10}. As one can see from this figure, our modified potential reproduces the experimental fusion cross sections with more accuracy than the original version, i.e., the Prox. 77 model. Therefore, we can refer to the thermal effect of compound nucleus as a physical aspect which can improve the theoretical values of σ_{fus} in a fusion reaction. To compare the obtained results of fusion cross section based on the mentioned thermal approaches, we have calculated the ratio of the $\sigma_{\text{Exp.}}/\sigma_{\text{Theor.}}$ using these approaches for the ^{28}Si + ^{58}Ni colliding system; see Fig. 6. It is clear that they predict similar results for theoretical values of the fusion cross section.

In recent decades, one of the important challenges in theoretical investigations of nuclear physics is to justify the abnormally large diffuseness of WS potential a_{WS} for fusion reactions toward those reported by elastic and quasielastic scattering data [48–51]. In a static approach, nuclear matter incompressibility has been recently introduced as a reasonable explanation of this unknown behavior of a_{WS} parameter [52].

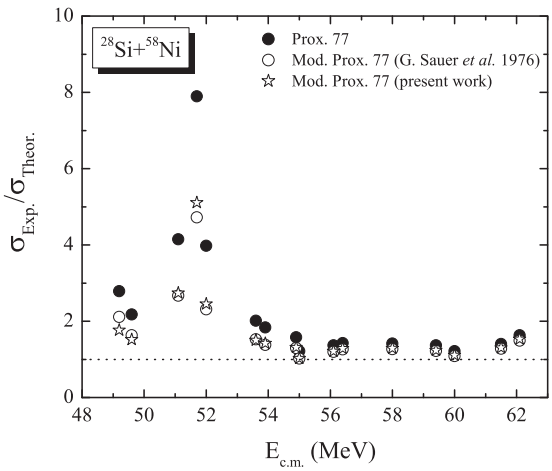

FIG. 6. The ratio of the the experimental [39] and the theoretical values of the fusion cross sections, $\sigma_{\text{Exp.}}/\sigma_{\text{Theor.}}$, based on the considered theoretical potentials for the ^{28}Si + ^{58}Ni colliding system.

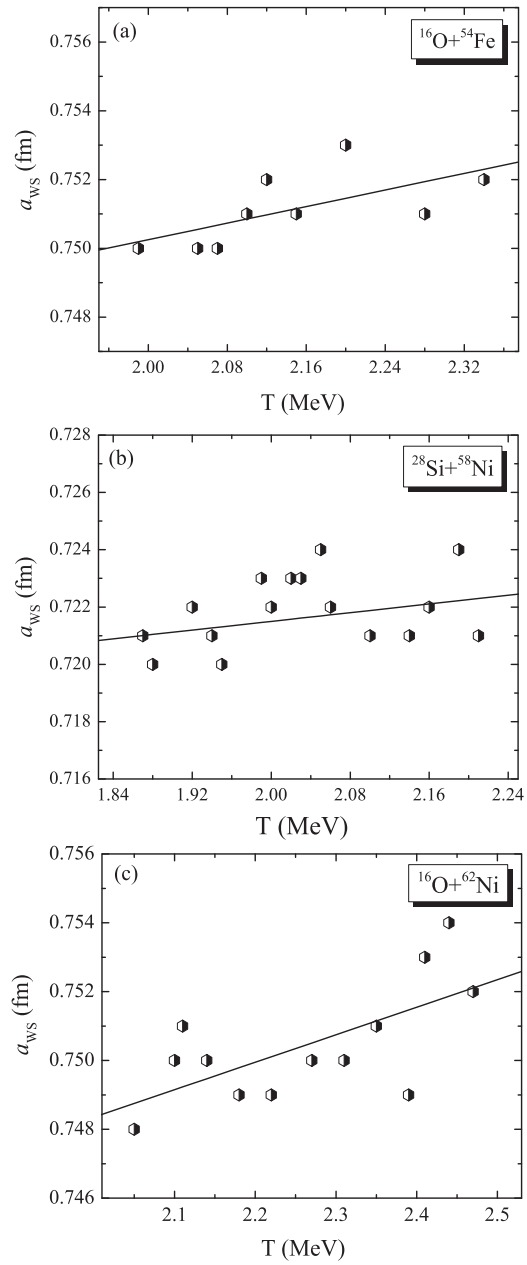

FIG. 7. Temperature trend of the diffuseness parameter of WS potential caused by fitting to our modified form of Prox. 77 potential at each bombarding energy for (a) ^{16}O + ^{54}Fe, (b) ^{28}Si + ^{58}Ni, and (c) ^{16}O + ^{62}Ni fusion reactions.

In Fig. 7, we have plotted the values of diffuseness parameter caused by fitting to our modified form for proximity potential versus the temperature of compound nucleus T. The calculations are carried out for those colliding systems introduced in previous figure. Using the Prox. 77 potential, the values of diffuseness parameters for $^{16}O + ^{54}Fe$, $^{28}Si + ^{58}Ni$ and $^{16}O + ^{62}Ni$ reactions are 0.726, 0.710, and 0.726 fm, respectively. It is clear that its thermal behavior reports larger values than those obtained by the original version of the proximity potential (see Fig. 7). Indeed, it seems that there is a systematic trend for diffuseness parameter to be a function of temperature T, namely $a_{WS}(T)$, which we leave for further study.

V. CONCLUSIONS

We investigated the influence of the suturation properties of NM density on the temperature-dependent form of surface thickness b. For this purpose, a systematic analysis with the medium- and heavy-ion fusion systems is applied using the original version of the proximity potential, which is supplemented with the ETFM for hot nuclear matter at finite temperature T. Our main results are as follows:

(i) The obtained results show that the saturation effects of hot nuclear matter using ETFM lead to a new temperature-dependent form (linear) for the surface thickness parameter b; see Fig. 1. It follows from the suggested formalism of Ref. [30] at lower temperatures; see Fig. 2.

(ii) It is demonstrated that imposing the modification effect of EOS at finite temperature in the proximity formalism causes the percentage difference between the theoretical and the experimental values of barrier height caused by the Prox. 77 model to be reduced by 1% on average; see Fig. 4.

(iii) Our calculations for theoretical values of the fusion cross sections exhibit that the modified proximity potential reproduces the corresponding experimental fusion data with more accuracy; see Fig. 5.

(iv) We examine the thermal behavior of diffuseness parameter of WS potential in Fig. 7. Using this figure, the temperature effects of the compound nucleus are a physical reason for the large values of this parameter in heavy-ion fusion reactions. It is an interesting subject that needs to more research and we are going to analyze it in future work.

Our research in this area has begun with the analysis of the saturation properties of NM in the temperature-dependent form of surface thickness $b(T)$. We can refer to the following subjects to investigate in further works: (i) It is remarkable that time-dependent Hartree-Fock calculations predict an adiabatic description for realistic overlap. Using this approach and mean field theory, it seems that the thermal behavior of the thickness parameter b follows a linear trend, which needs to a separate systematic study. (ii) Since the theoretical approaches such as the double folding model provide more accurate description for heavy-ion potential, it can be interesting to adjust the various parts of proximity formalism based on the suggested producer of Ref. [53]. (iii) Similar studies can be provided to examine these effects on the other parts of the proximity potential such as $R(T)$ and $\gamma(T)$. It may be a useful subject to introduce a new version of the proximity potential based on the temperature of the compound nucleus.

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