STUDY OF FUSION CROSS-SECTIONS OF $^{16}O + {}^{208}Pb$ AND $^{28}Si + {}^{208}Pb$ REACTIONS BY EFFECTIVE SOFT-CORE NUCLEON-NUCLEON INTERACTION

by

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In this paper, the cross-sections of fusion reactions $^{16}O + {}^{208}Pb$, $^{28}Si + {}^{208}Pb$, $^{40}C +$ $+ {}^{40}Ca$, $^{40}Ca + {}^{48}Ca$, $^{58}Ni + {}^{58}Ni$, and $^{16}O + {}^{154}Sm$ at bombarding energies above and near the fusion barrier have been investigated. The fusion cross-sections have been studied by means of the Monte Carlo method and effective soft-core nucleon-nucleon interaction. One adjustable parameter was used in these calculations. This parameter can change the strength and repulsive parts of soft-core potential values. It has to be adjusted, so that the analytical results are in acceptable agreement with the experimental data.

In our calculations, we have taken the range of the nucleon-nucleon soft-core interaction to be constant and equal to that of the M3Y-Raid potential. Results show that the higher values for the diffusion parameter in the Woods-Saxon potential obtained from a careful analysis of $^{16}O + {}^{208}Pb$ and $^{28}Si + {}^{208}Pb$ reactions are due to the many particle effects on the nucleon-nucleon potential.

Key words: heavy-ion reaction, fusion cross-section, soft-core interaction, many particle effects

INTRODUCTION

The main issue when the interactions of heavy-ions are concerned is the nucleus-nucleus potential between the projectile and the target. This potential can be used in analytical studies of fusion cross-sections during heavy-ion reactions. One of the possible models used to this end is the single-barrier penetration model. In this model, the barrier formed by the Coulomb potential and the nuclear potential of the projectile-target system and the given nuclear potential is usually taken to be

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$$U_{ws} \quad \frac{v_{ws}}{1 \quad e^{\frac{R \quad r_{ws}(\sqrt[3]{A_p} \quad \sqrt[3]{A_t})}{a_{ws}}}} \qquad (1)$$

where R is the distance between the center of the mass of the projectile (atomic number A_p) and that of the target (atomic number A_t). The Woods-Saxon potential is specified by the radial r_{ws} , diffusion a_{ws}, and depth v_{ws} parameters. Studies of fusion cross-sections using this potential reveal that the calculated fusion cross-sections, for the most part, depend on the diffusion parameter a_{ws} [1, 2]. Recently, fusion cross-sections of heavy-ions at energies higher than the fusion barrier of $^{16}O + {}^{208}Pb$ and $^{28}Si + {}^{208}Pb$ reactions, using the Woods-Saxon potential and the Coupled-Channels Model, have been calculated and the diffusion parameter has been reported to be about 1 fm [1]. The results are higher than those obtained by elastic scattering. Since in the fusion process the surface nucleons play an important role, the higher values of the diffusion parameter might be associated with the variations of the range of the nucleon-nucleon potential. In this study, in order to ignore this effect, we have taken the range of the nucleon-nucleon interaction to be constant and equal to that of the M3Y-Reid potential [3, 4]. We have also chosen a semi-microscopic approach. By choosing an appropriate nucleon-nucleon interaction, while keeping the range fixed and varying the depth and the repulsive core of the nucleon-nucleon interaction simultaneously, by a single parameter, we will show that the variations in the diffusion parameter are due to the many particle effect corrections of the nucleon-nucleon potential. We have simulated the nucleus-nucleus potential using the Monte Carlo method instead of the commonly employed double folding approach. In this simulation method, the nucleus-nucleus potential has been evaluated for heavy-ion reactions by summing the effective interaction potentials between the individual nucleons belonging to each of interacting nuclei and by averaging them over various acceptable positions of nucleons inside each nucleus generated by the Monte Carlo method. Instead of the DDM3Y potential [2], we have taken the soft-core nucleon-nucleon interaction into consideration in our calculations. Using this potential, and taking into account a single adjustable parameter, we have studied the experimental fusion cross-sections for different reaction at different energies.

FUSION CROSS-SECTION

The total potential in the semi-classical model is defined by

$$V_l(R) = V_N(R) + V_C(R) + \frac{\hbar^2 l(l+1)}{2\mu R^2}$$

$$= V_o(R) + \frac{\hbar^2 l(l+1)}{2\mu R^2} \qquad (2)$$

where V_N, V_C, V_o, μ and l are the nuclear, Coulomb, total potential for S-wave, reduced mass and relative momentum between the nuclei of the projectile and the target, respectively. Using this potential, the total fusion cross-section in terms of the kinetic energy in the center of the mass form has been calculated to be [5]

$$\sigma(E) = \sum_{l=0}^{\infty} \frac{\pi\hbar^2}{2\mu E}(2l+1)T_l(E) \qquad (3)$$

where T_l is the penetration probability of the l-th partial wave which, for energies lower than the barrier, is approximately given by [5]

$$T_l(E) = \frac{1}{1 + \mathrm{e}^{\int_{R_{1l}}^{R_{2l}} \sqrt{\frac{8\mu}{\hbar^2}[V_l(R) - E]}\,\mathrm{d}R}} \qquad (4)$$

where R_{1l} and R_{2l} are the classical turning points of the l-th partial wave at energy E.

The calculated transmitting probability for the l-th partial wave at energies higher than the fusion barrier using Hill-Wheeler's formula is given by [6]

$$T_l(E) = \frac{1}{1 + \mathrm{e}^{\frac{2\pi(V_{Bl} - E)}{\hbar\omega_l}}} \qquad (5)$$

where

$$\hbar\omega_l = \sqrt{\left|\frac{\hbar}{\mu}\frac{\mathrm{d}^2 V_l}{\mathrm{d}R^2}\right|_{R_{Bl}}} \qquad (6)$$

and V_{Bl} is the height, R_{Bl} is the position and ω_l is the curvature of the barrier for the l-th partial wave.

EFFECTIVE SOFT-CORE NUCLEON-NUCLEON INTERACTION

The effective soft-core nucleon-nucleon interaction is strongly attractive, while at short distances it is repulsive. For hard-core potentials at short ranges, the repulsion is infinity. Unlike the soft-core potentials, these potentials do not explain the physical aspects of the problem. The form of the soft-core potential has been suggested to be [7, 8].

$$V(r) = v_o \frac{r^n - c^n}{r^n} V(r_{12}) \qquad (7)$$

where $V(r_{12})$ may have any of the following shapes:

Gaussian

$$V(r_{12}) = \mathrm{e}^{-\left(\frac{r}{r_o}\right)^2} \qquad (8)$$

Yukawa

$$V(r_{12}) = \frac{\mathrm{e}^{-\frac{r}{r_o}}}{\frac{r}{r_o}} \qquad (9)$$

and exponential

$$V(r_{12}) = \mathrm{e}^{-\frac{r}{r_o}} \qquad (10)$$

Suitably chosen values for v_o, c, n, and r_o yield a potential that plays an important role in the calculations of many body problems. This is not the case for hard-core potential. For $n \to \infty$ these potentials are infinitely repulsive in the range $r < c$, *i. e.* they become hard-core.

SIMULATION METHOD

In order to calculate the nuclear potential in the Monte Carlo method, this potential is taken to be the average sum of all the possible interactions between the nucleons of the target and the projectile. In this model, each of the nuclei of the projectile and the target is considered as a collection of points in which the nuclear matter is randomly distributed and each point represents a nucleon's position. The relation between this distribution and the nuclear charge distribution is given by $\rho_{p(t)A} \quad \rho_{p(t)Z} A/Z$, where ρ_{pA} and ρ_{tA} are the nucleon densities of the projectile and target nuclei, respectively. The two-parameter Fermi distribution (2PF) and three-parameter Fermi profiles (3PF) are used for the nuclear charge distribution, tab. 1. The random distribution of the positions of the nucleons, in general, provides an unstable state for the nucleons. To achieve a real nucleus in its ground state, the nucleons must move randomly under the static or dynamic processes [9]. The static process has been chosen for our studies. These nucleons move over very short distances, so that the sum of Coulomb and nuclear potentials between the nucleons inside the nucleus, considering the BDM3Y1-Paris potential [3], is equal to the total energy of the nucleus in its ground state and the $R_{\rm rms}$ parameter is also consistent with the experimental data. The results are given in tab. 1.

The Coulomb potential between two-point protons is given by

$$V_C(r) \quad \frac{e^2}{r} \quad \frac{1.44}{r} \quad [\text{MeV}] \tag{11}$$

Note that the radius of the proton is about 0.9 fm. When the distance between the two protons is less than this, the point-like assumption for protons fails. In that case, the effective Coulomb potential between the two protons has to be modified as [10]

$$V_C(r) \quad \frac{e^2}{r} \quad (1 \quad e^{\;s}) \quad \frac{se^{\;s}}{16} \quad 11 \quad 3s \quad \frac{s^2}{3} \tag{12}$$

where $s = \Lambda r$ and $\Lambda = 0.71^{1/2}$ GeV. This effect has been taken into account in our calculations and for the soft core nuclear potential between two protons, eqs. (7) and (9) are chosen. The nucleon-nucleon potential between the like particles is taken to be 20% weaker than that of the unlike particles [11].

RESULTS

In this paper, we have studied the fusion reactions of ^{16}O + ^{208}Pb and ^{28}Si + ^{208}Pb at energies above the fusion barrier. We have chosen the soft-core effective nucleon-nucleon interaction for our studies.

To choose the parameters representing the soft-core potential, we have fitted it to the M3Y-Reid potential, fig. 1. We have only considered the direct and exchange terms, $V_o^D(r)$ and $V_o^{Ex}(r)$, in the M3Y-Reid potential, where [3, 4]

$$V_o^D(r) \quad 7999\frac{e^{\;4r}}{4r} \quad 2134\frac{e^{\;2.5r}}{2.5r} \quad [\text{MeV}] \tag{13}$$

$$V_o^{Ex}(r) \quad 4631\frac{e^{\;4r}}{4r} \quad 1787\frac{e^{\;2.5r}}{2.5r}$$

$$7.847\frac{e^{\;0.7072r}}{0.7072r} \quad [\text{MeV}] \tag{14}$$

The obtained values for n, v_o, r_o, and c parameters are 1.5, 1080 MeV, 0.57 fm, and 0.45 fm, respectively.

In our calculations, we have taken parameter c to be an adjustable parameter and have chosen its values so that the analytical calculations of fusion cross-sections, using the potential obtained from the Monte Carlo method, are in agreement with experimental values. The reason for determining parameter c as an adjustable parameter is that this parameter could simultaneously vary the depth and radius of the repulsive core of the soft-core interaction. These variations for different reactions in different energies are shown in fig. 2. They indicate that the range of the soft-core potential is constant and close to the range of the M3Y-Reid potential. The values obtained for parameter c by regenerating the cross-sections of ^{16}O + ^{208}Pb and ^{28}Si + + ^{208}Pb reactions, using the soft-core potential and the Monte Carlo method, are shown in figs. 3 and 4. It can be seen that as energy increases, parameter c increases accordingly. In order to deepen our understanding of

Table 1. Binding energies (B) and root mean squares ($R_{\rm rms}$) of the nuclei under consideration. Experimental data and the parameters of two-parameter Fermi profiles (2PF) and three-parameter Fermi profiles (3PF) are taken from [12-17]

Nucleus	Charge distribution	c [fm]	a [fm]	ω	Experimental		Monte Carlo	
					$R_{\rm rms}$ [fm]	B [MeV]	$R_{\rm rms}$ [fm]	B [MeV]
^{16}O	3PF	2.608	0.513	0.051	2.730 ± 0.025	127.619 ± 0.893	2.72 ± 0.03	127.747 ± 0.986
^{28}Si	3PF	3.340	0.580	0.233	3.086 ± 0.018	236.537 ± 1.653	3.07 ± 0.03	236.682 ± 1.792
^{40}Ca	3PF	3.766	0.586	0.161	3.482 ± 0.025	342.052 ± 2.394	3.46 ± 0.04	342.184 ± 2.581
^{48}Ca	3PF	3.7444	0.5255	0.03	3.4762 ± 0.0254	415.991 ± 2.912	3.45 ± 0.04	416.086 ± 3.225
^{58}Ni	2PF	4.14	0.56		3.83 ± 0.03	506.454 ± 3.545	3.79 ± 0.05	506.592 ± 3.693
^{154}Sm	2PF	6.0226	0.4711	–	5.108 ± 0.036	1266.943 ± 8.868	5.05 ± 0.06	1267.213 ± 9.018
^{208}Pb	2PF	6.54	0.53	–	5.49 ± 0.04	1636.445 ± 11.455	5.43 ± 0.06	1636.576 ± 10.852

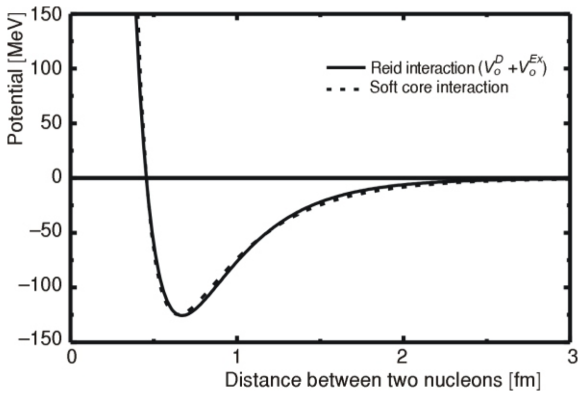

Figure 1. Soft-core nucleon-nucleon interaction for n = = 1.5, $_o$ = 1080 MeV, r_o = 0.57 fm, and c = 0.45 fm and the M3Y-Reid nucleon-nucleon interaction

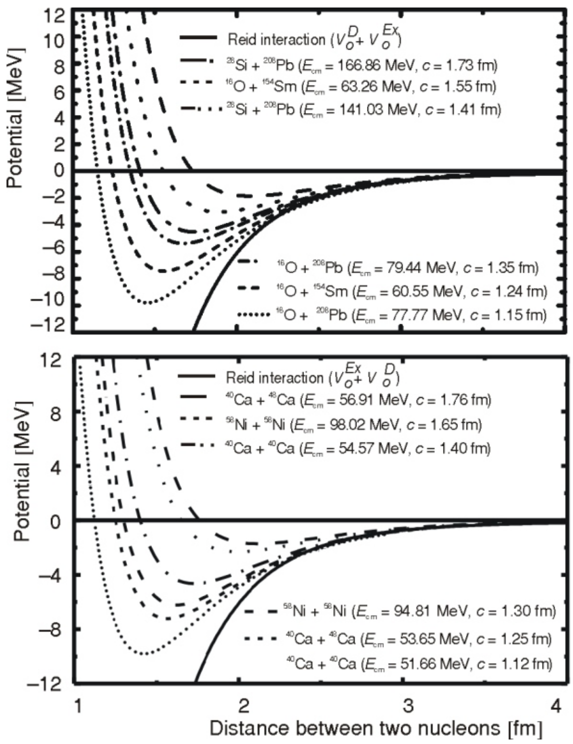

Figure 2. The depth and repulsive radius of the soft-core potential *vs.* parameter *c*. The calculated range of the soft-core nucleon-nucleon potential has also been compared with that of the M3Y-Reid potential for different reactions at different energies

the variations of parameter c, we have applied the same procedure to reactions ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, ^{58}Ni + ^{58}Ni, and ^{16}O + ^{154}Sm. In these calculations, we have used the spherical nuclei. The results are shown in figs. 5 to 7. Again, one could see that an increase in energy results in an increase of the parameter c, much in the same way as in the case of the analysis of ^{16}O + + ^{208}Pb and ^{28}Si + ^{208}Pb reactions. Figure 5 shows that,

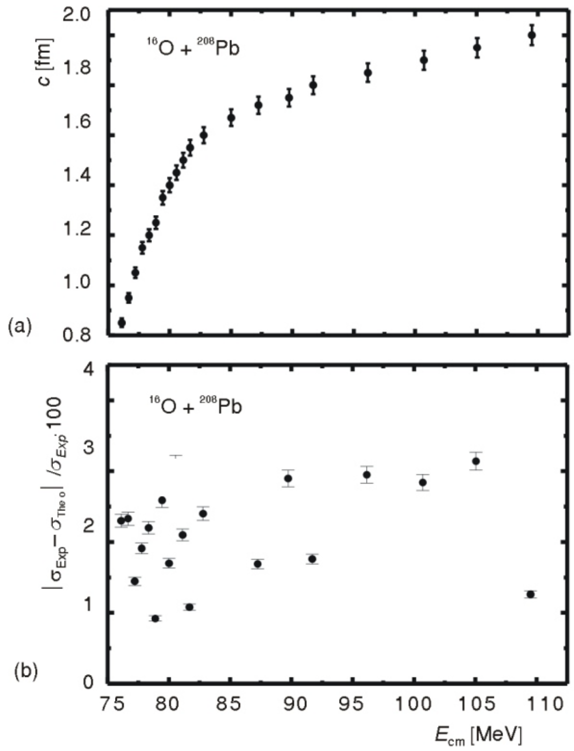

Figure 3. Parameter *c vs.* energy for the ^{16}O + ^{208}Pb reaction (a), and percentage difference between the experimental [18] and the theoretical fusion cross-sections (b)

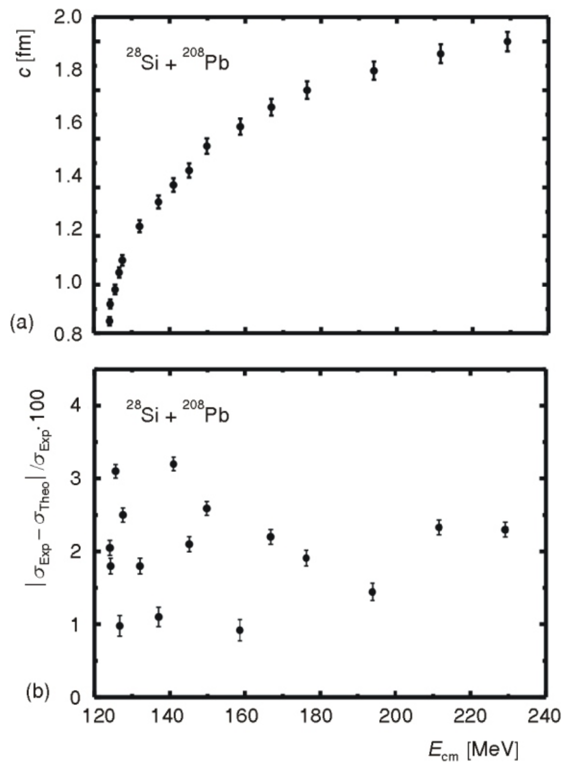

Figure 4. Parameter *c* vs. energy for the ^{28}Si + ^{208}Pb reaction (a), and percentage difference between the experimental [19, 20] and theoretical fusion cross-section (b)

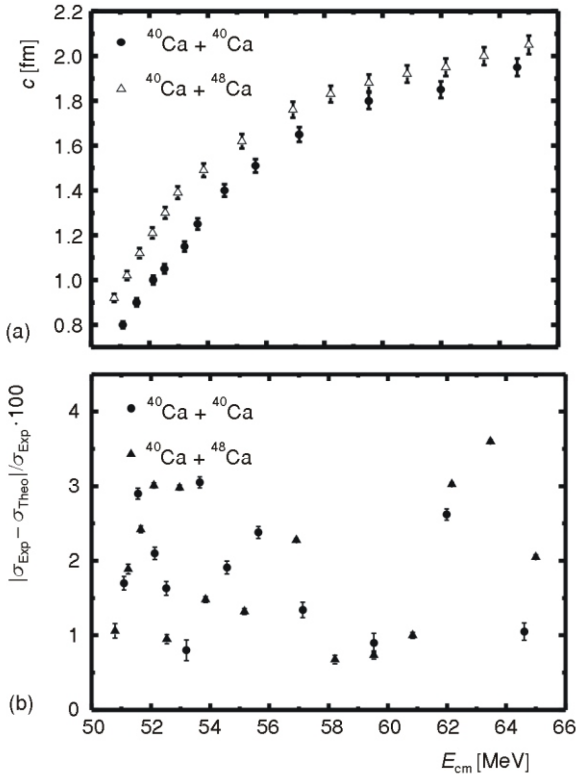

Figure 5. Parameter *c vs.* energy for $^{40}Ca + ^{40}Ca$ and $^{40}Ca + ^{48}Ca$ reactions (a), and percentage difference between the experimental [21, 22] and theoretical fusion cross-sections (b)

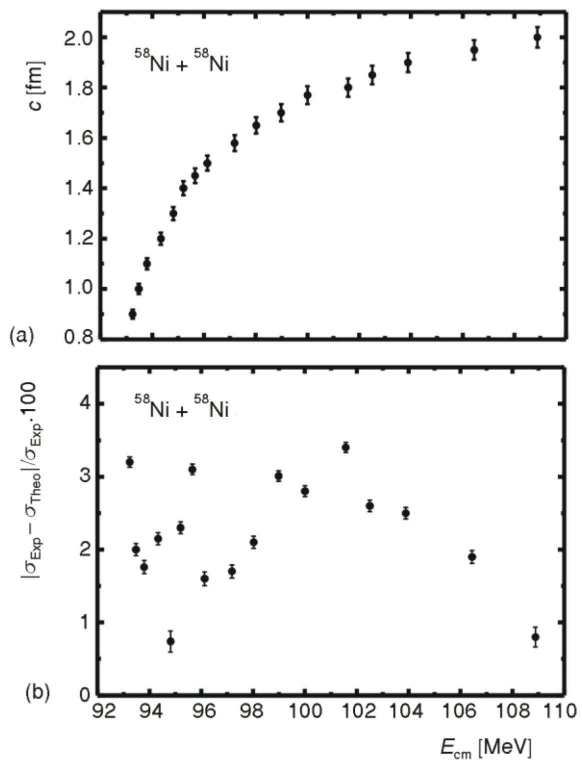

Figure 6. Parameter *c vs.* energy for the $^{58}Ni + ^{58}Ni$ reaction (a), and percentage difference between the experimental [23] and theoretical fusion cross-sections (b)

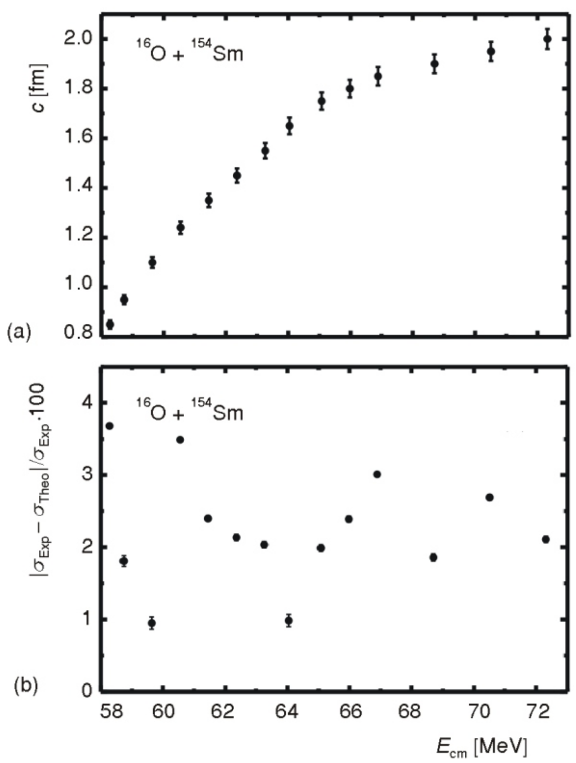

Figure 7. Parameter *c vs.* energy for the $^{16}O + ^{154}Sm$ reaction (a), and percentage difference between the experimental [24] and theoretical fusion cross-sections (b)

as the nuclear density of the target nucleus varies in the $^{40}Ca + ^{40}Ca$ and $^{40}Ca + ^{48}Ca$ reactions, parameter *c* increases. Since the increase in parameter *c* decreases the depth of the nucleon-nucleon potential (see fig. 2), it can be deduced that the increase in nuclear density decreases the nuclear attractive force. Also, the overall variation of parameter *c* is such that the increase in projectile energy increases this parameter (see figs. 3 to 7). In other words, as the energy of the projectile increases, the nuclear attractive force decreases. The two results just mentioned could be due to the effects of the many particles on the bare nucleon-nucleon potential. These results show the importance of the many particles effects on the calculation of the nuclear potential in $^{16}O + ^{208}Pb$ and $^{28}Si + ^{208}Pb$ reactions.

CONCLUSION

Instead of the commonly used double folding method, we have applied a semi-microscopic method in our studies and Monte Carlo simulation to calculate nuclear potential. Our results show that by choosing an appropriate nucleon-nucleon potential and using this method, one can calculate a nuclear potential so that the calculated cross-sections are in good agreement with experimentally obtained heavy-ion fusion cross-sections. Here a soft-core type nucleon-nucleon potential has been used. It has been shown that for a constant range nucleon-nucleon potential that is equal to the range of the M3Y-Reid potential and that, by covering the repulsive core and the depth of the potential by only one parameter, one can calculate the nuclear potential in ^{16}O + ^{208}Pb and ^{28}Si + ^{208}Pb reactions in such a manner that the calculated fusion cross-sections at energies higher and lower than the Coulomb barrier are in good agreement with experimental data.

The results obtained reveal that an increase in energy increases parameter *c*. This trend in the variation of the said parameter has been further confirmed by careful analysis of ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, ^{58}Ni + + ^{58}Ni, and ^{16}O + ^{154}Sm reactions.

The variations in parameter *c* indicate that an increase in energy and nuclear density decreases the depth of the nuclear potential. An increase in the parameter is also accompanied by an increase in the repulsive core and this increase in the repulsive core prevents the incoming projectile colliding with many of the nucleons in the target nucleus. This leads us to the conclusion that the higher values obtained for the diffusion parameter in reactions ^{16}O + ^{208}Pb and ^{28}Si + + ^{208}Pb are due to the effects of the many particles on nucleon-nucleon potential.

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ИСТРАЖИВАЊЕ ФУЗИОНИХ ПРЕСЕКА РЕАКЦИЈА ^{16}O + ^{208}Pb и ^{28}Si + ^{208}Pb ПОСРЕДСТВОМ НУКЛЕОН-НУКЛЕОН ИНТЕРАКЦИЈЕ ЕФЕКТИВНОГ МЕКОГ ЈЕЗГРА

У овом раду истраживани су пресеци за фузионе реакције ^{16}O + ^{208}Pb, ^{28}Si + ^{208}Pb, ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, ^{58}Ni + ^{58}Ni и ^{16}O + ^{154}Sm при енергијама бомбардовања непосредно изнад фузионог прага. Фузиони пресеци испитивани су Монте Карло методом и нуклеон-нуклеон интеракцијом ефективног меког језгра. У прорачунима је коришћен један усаглашавајући параметар којим се могу мењати јачина и репулзивни удео износа потенцијала меког језгра. Прилагођаван је тако да аналитички резултати буду у прихватљивој сагласности са експерименталним подацима.

У нашим рачунима изабрали смо да распон нуклеон-нуклеон интеракције меког језгра буде константан и једнак ономе код M3Y-Reid потенцијала. Резултати указују да више вредности дифузионог параметра у Вудс-Саксоновом потенцијалу, које су добијене пажљивом анализом ^{16}O + ^{208}Pb и ^{28}Si + ^{208}Pb реакција, потичу од вишечестичних ефеката на нуклеон-нуклеон потенцијал.

Кључне речи: реакција тешког јона, пресек за фузију, интеракција меког језгра, вишечестични ефекти