Study of nuclear matter property in heavy-ion fusion reactions

Omid Naser Ghodsi, Fatemeh Torabi

[1]Department of Physics, Faculty of Science, University of Mazandaran, P. O. Box 47415-416, Babolsar, Iran

Presented by

Fatemeh Torabi

Interaction potential in Skyrme Energy Density Functional (SEDF)

Formalism

$$V(R) = E_T(R) - E_1 - E_2$$

$$E_T(R) = \int \varepsilon[\rho_{1p}(\vec{r}) + \rho_{2p}(\vec{r} - \vec{R}), \rho_{1n}(\vec{r}) + \rho_{2n}(\vec{r} - \vec{R})]d^3r,$$

$$E_1 = \int \varepsilon[\rho_{1p}(\vec{r}), \rho_{1n}(\vec{r})]d^3r\,,$$

$$E_2 = \int \varepsilon[\rho_{2p}(\vec{r}), \rho_{2n}(\vec{r})]d^3r.$$

ε → **The Skyrme energy density**

ρ_{1n} and ρ_{1p} → **The neutron and the proton density distributions of projectile**

ρ_{2n} and ρ_{2p} → **The neutron and the proton density distributions of target**

Skyrme energy density

Formalism

$$\varepsilon(\vec{r}) = \frac{\hbar^2}{2m}\tau + \frac{1}{2}t_0\left[\left(1+\frac{1}{2}x_0\right)\rho^2 \cdots\right.$$

$$+\frac{1}{12}t_3\rho^{\alpha}\left[\left(1 + \cdots\right.\right.$$

$$+\frac{1}{4}\left[t_1\left(1 + \cdots\right.\right.$$

$$-\frac{1}{4}\left[t_1\left(x_1 \cdots\right.\right.$$

$$+\frac{1}{16}\left[3t_1\left(1 + \cdots\right.\right.$$

$$-\frac{1}{16}\left[3t_1\left(x_1+\frac{1}{2}\right) \cdots\right.$$

$$+\frac{1}{2}W_0\left[\vec{J}.\vec{\nabla}\rho + \vec{J}_n.\vec{\nabla}\rho_n \cdots\right.$$

ETF

Here, t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, α, and W_0 are the Skyrme force parameters.

Kinetic-energy density

$$\tau_q(\vec{r}) = \frac{3}{5}(3\pi^2)^{\frac{2}{3}}\rho_q^{\frac{5}{3}} + \frac{1}{36}\frac{\left(\vec{\nabla}\rho_q\right)^2}{\rho_q} + \frac{1}{3}\Delta\rho_q + \frac{1}{6}\frac{\vec{\nabla}\rho_q.\vec{\nabla}f_q}{f_q} + \frac{1}{6}\rho_q\frac{\Delta f_q}{f_q} - \frac{1}{12}\rho_q\left(\frac{\vec{\nabla}f_q}{f_q}\right)^2 + \frac{1}{2}\rho_q\left(\frac{2m}{\hbar^2}\right)^2\left(\frac{W_0}{2}\frac{\vec{\nabla}(\rho+\rho_q)}{f_q}\right)^2$$

$$f_q(\vec{r}) = 1 + \frac{2m}{\hbar^2}\frac{1}{4}\left[t_1\left(1+\frac{x_1}{2}\right) + t_2\left(1+\frac{x_2}{2}\right)\right]\rho(\vec{r}) - \frac{2m}{\hbar^2}\frac{1}{4}\left[t_1\left(x_1+\frac{1}{2}\right) - t_2\left(x_2+\frac{1}{2}\right)\right]\rho_q(\vec{r})$$

Spin-orbit density

$$\vec{J}_q(\vec{r}) = -\frac{2m}{\hbar^2}\frac{1}{2}W_0\frac{1}{f_q}\rho_q\vec{\nabla}(\rho+\rho_q) \qquad q=n,p$$

Inputs for SEDF calculations

Formalism

Skyrme interaction → **Density distributions** → **$\varepsilon(r)$** → **$V(R)$**

Skyrme interactions with K values ranging from 234 to 370 MeV

Quantum mechanical HFB method

$^{16}O + ^{208}Pb$
$^{40}Ca + ^{48}Ca$

SkSC4 (K = 234.7 MeV), SkT7 (K = 235.64 MeV), Es (K = 247.9 MeV), SKXce (K = 270 MeV), Z (K = 329.4MeV), E (K = 332.6 MeV), and SI (K = 370 MeV)

Results

Potential barriers

$^{16}O + ^{208}Pb$

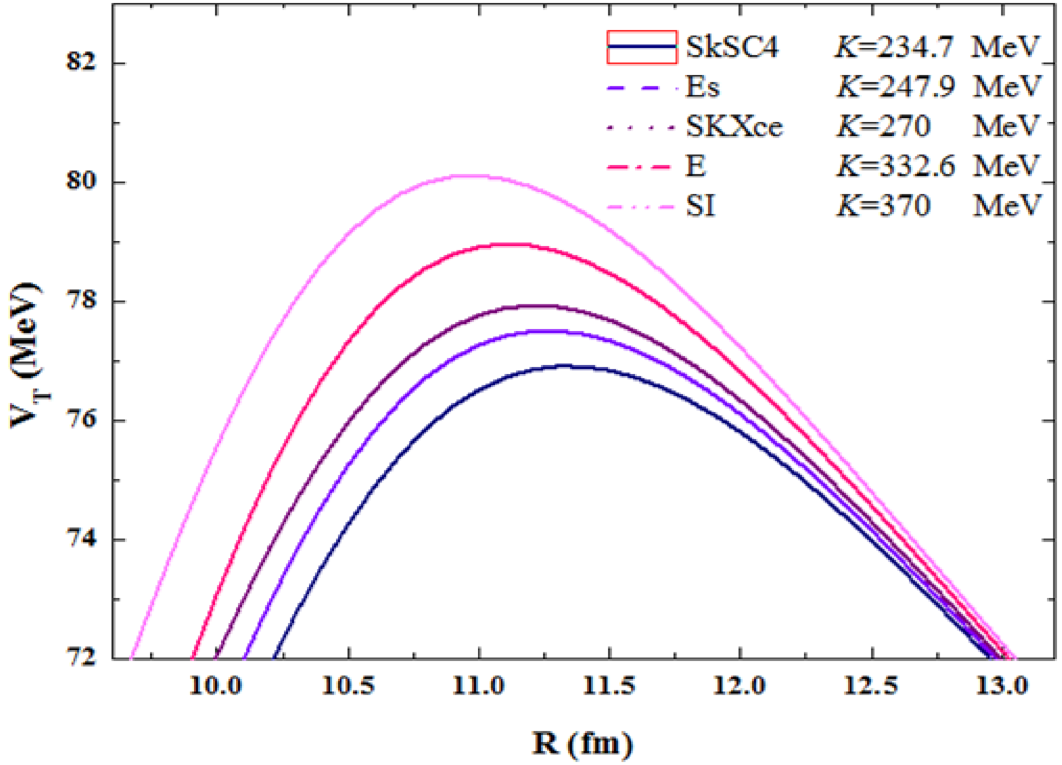


Fig. 1. The interaction potentials extracted from different Skyrme forces

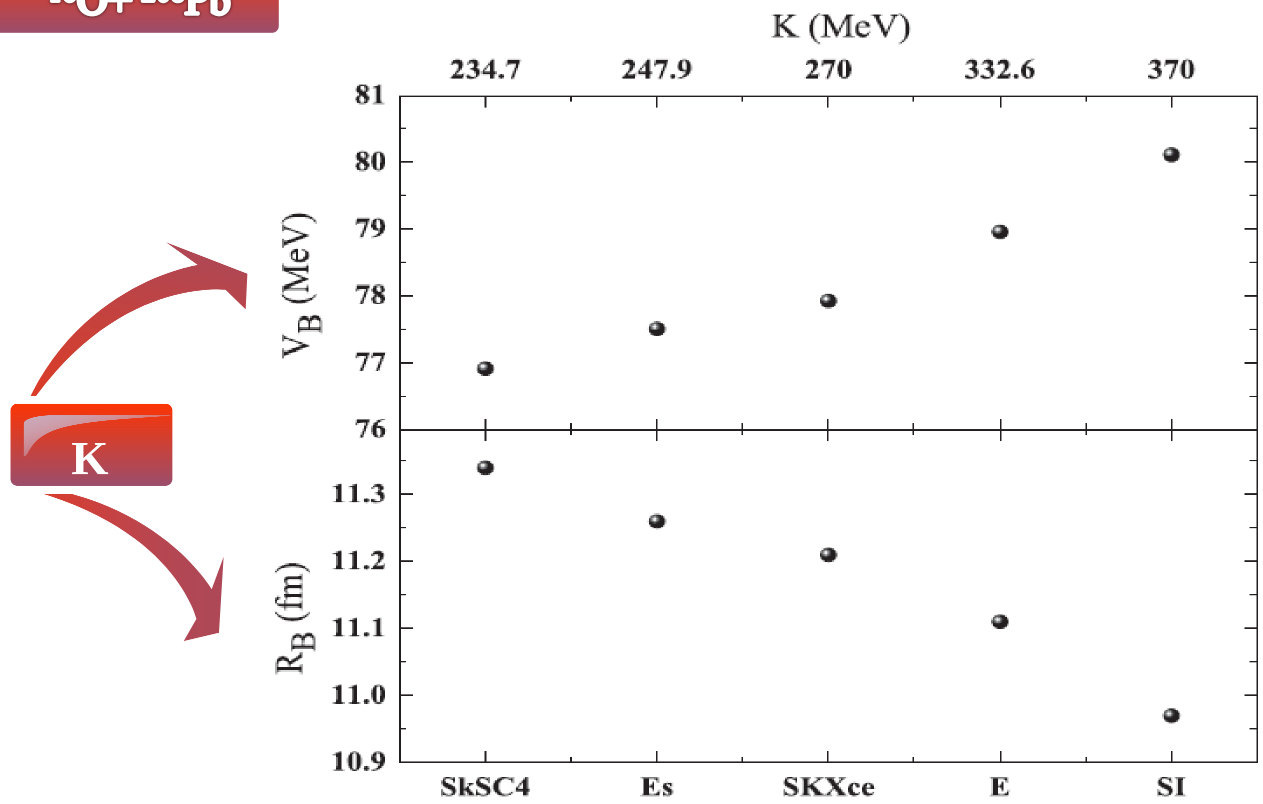
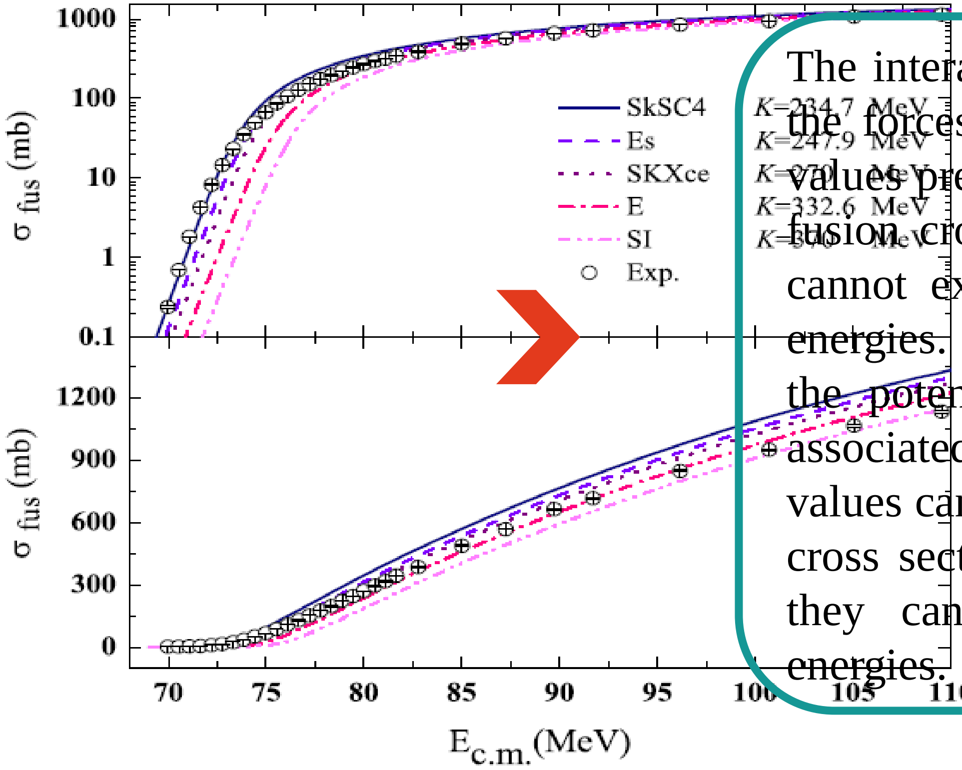


Fig. 2. The theoretical fusion barrier heights and positions

Fusion cross sections

Results

$^{16}O + ^{208}Pb$



The interaction potentials calculated from the forces with smaller incompressibility values precisely describe the experimental fusion cross sections at low energies but cannot explain the data at above-barrier energies. Furthermore, it is evident that the potentials obtained from the forces associated with higher incompressibility values can accurately reproduce the fusion cross sections at high energies; however, they cannot predict the data at low energies.

Fig. 3. Theoretical fusion cross sections compared with the experimental data taken from C. R. Morton, et al; Phys. Rev. C **60**, 044608 (1999).

Variation of the nuclear matter incompressibility

Results

$^{16}O + ^{208}Pb$

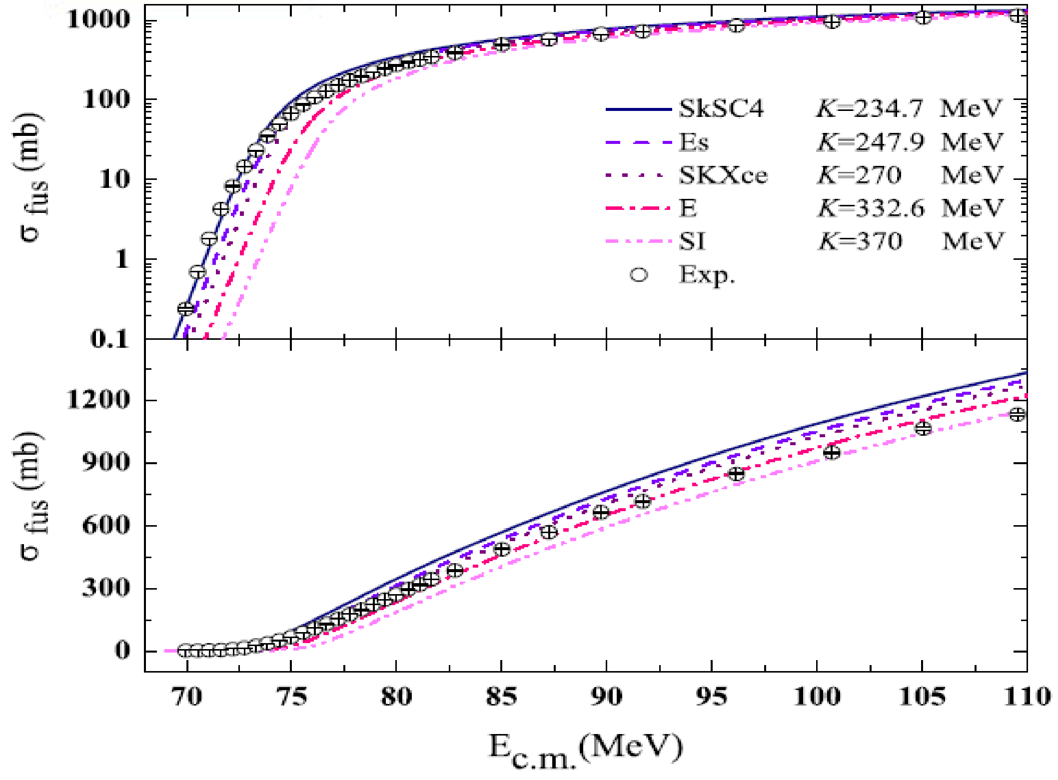


Fig. 3. Theoretical fusion data compared with the experimental data

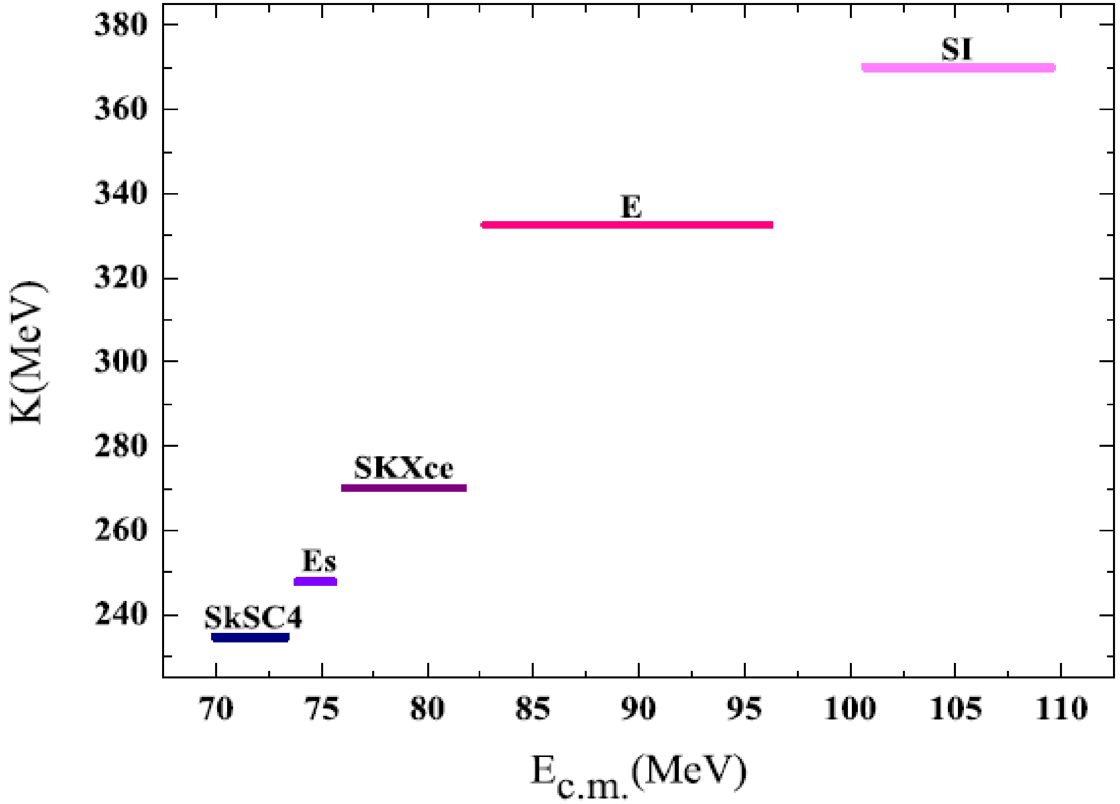


Fig. 4. The predicted values of the nuclear matter incompressibility

Variation of the nuclear matter incompressibility

Results

$^{40}Ca + ^{48}Ca$

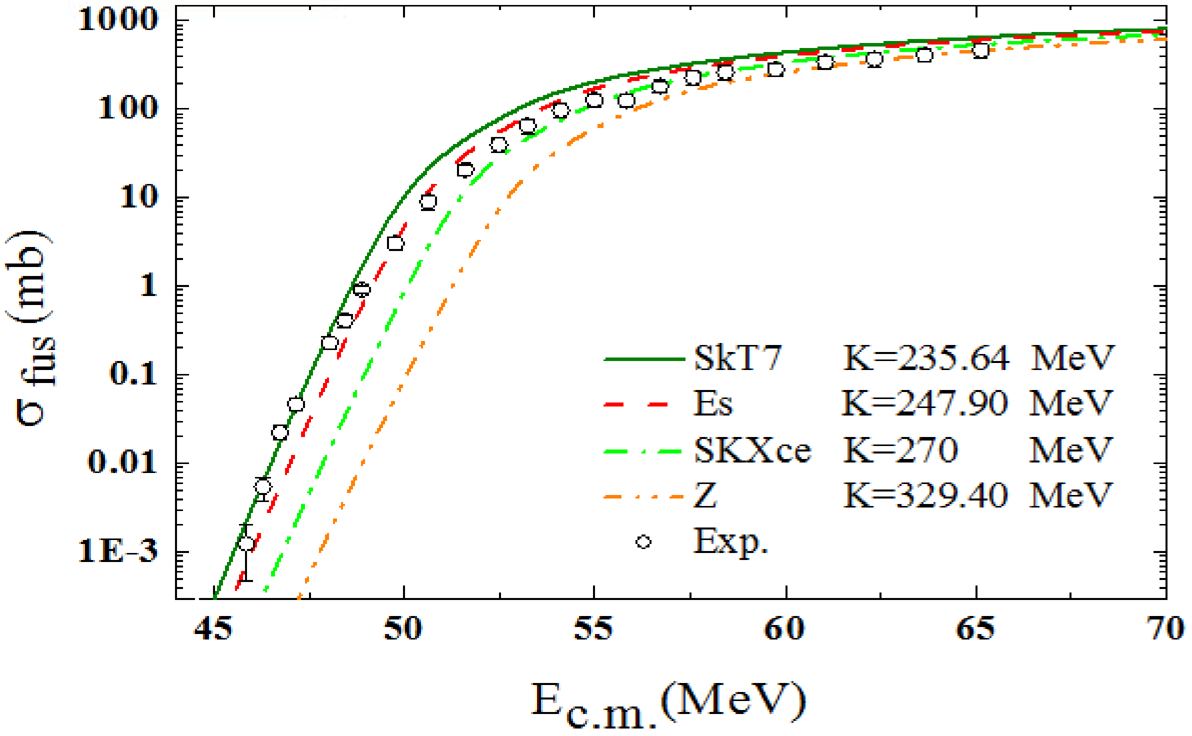


Fig. 5. Theoretical fusion data compared with the experimental data taken from C. L. Jiang, et al, Phys. Rev. C **82**, 041601(R) (2010).

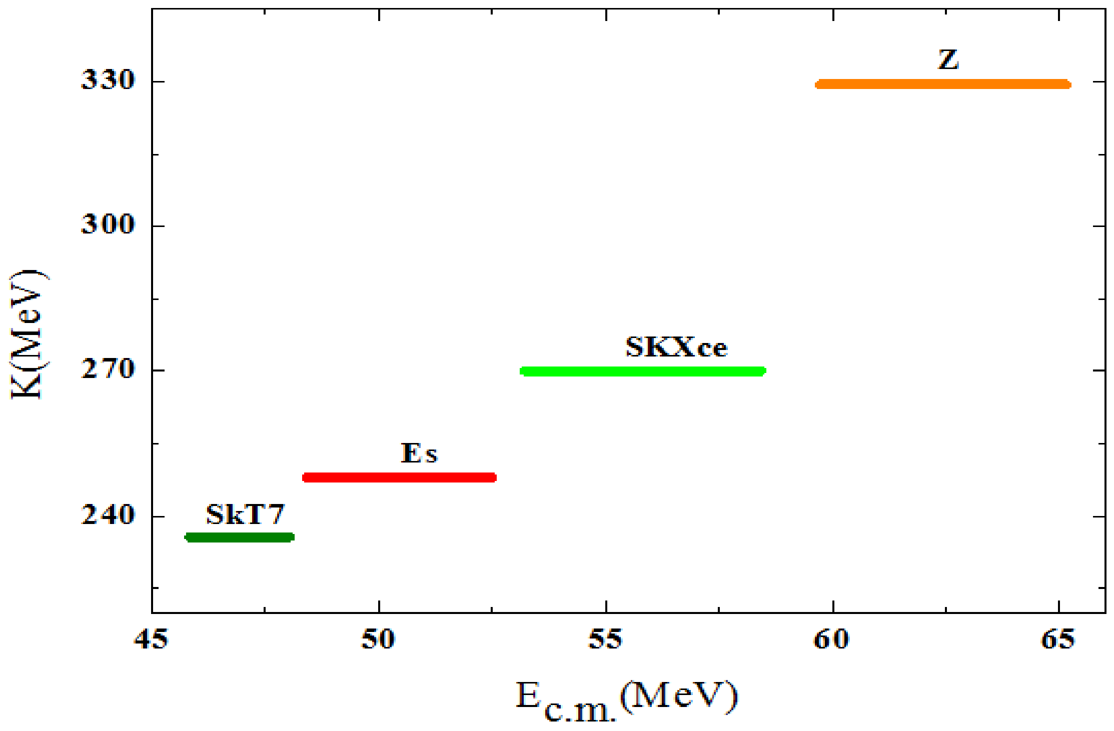


Fig. 6. The predicted values of the nuclear matter incompressibility

Summery and conclusion

The interaction potentials of different systems were calculated by using several Skyrme interactions associated with K values ranging from 234 to 370 MeV in the energy density formalism.

The fusion cross sections of the chosen systems were computed by using the ion-ion interaction potentials and the CCFULL code and compered to the experimental data.

The results revealed that the experimental cross sections at low energies can be accurately described by the potentials derived from the forces with smaller K values. On the other hand, the data at higher energies can be well explained by the potentials obtained from the forces associated with higher K values. This trend suggests that an exact fit to fusion cross-section data in different energy ranges can be achieved by using forces with different incompressibility values.

one can conclude that nuclear matter during the fusion process changes from less incompressible matter at low energies to more-incompressible matter at higher energies.


Thank
you