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INVESTIGATION OF $^{6}Li + {}^{12}C$ ELASTIC SCATTERING

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1. INTRODUCTION

Recently, the elastic scattering of ^{6}Li ions by ^{12}C nuclei has been investigated in a series of experimental and theoretical works [1-5] where the first interpretations have been given on the basis of a phenomenological nucleus-nucleus interaction potential. In refs. [1-3] the parameters for such potentials have been determined by fits to the cross sections of $^{6}Li + ^{12}C$ elastic scattering in a wide energy range. The theoretical analysis [4,5] has been performed in the framework of the folding-model using density distributions of the nuclei ^{6}Li and ^{12}C, which have been calculated in two microscopic ways - in the shell-model [4] and in the method of hyperspherical functions [5]. But the descriptions of the experimental values given by these approaches differ essentially from each other.

The aim of the present paper is the interpretation of the elastic scattering of ^{6}Li by ^{12}C at various energies of the projectile where the nuclear part of the ion-ion interaction potential is chosen as folding-potential with finite-range forces characterizing the nucleon-nucleon interaction [6]. The density distributions of the nuclei entering into the calculation have been obtained by the method of hyperspherical functions [7]. This calculational method is described briefly in Sec.2. In Sec. 3 the results of the computations are discussed and compared with those obtained by using zero-range forces for the NN-interaction. Some conclusions are drawn in Sec.4.

2. CALCULATIONAL METHOD

a) Nuclear Density Distribution in the Method of Hyperspherical Functions

In this approach [7] the wave function Ψ of a nucleus with mass number A is expanded in standard hyperspherical polynominals $|AK[f]\epsilon LST>$ according to

$$\Psi = \sum_{K \geq K_{min}} \phi_K^{K[f]\epsilon LST}(\rho)\,|AK[f]\epsilon LST> \qquad (1)$$

with the normalization condition $\int \phi_K^2(\rho)\rho^{3A-4}d\rho = 1$, where the collective variable ρ corresponds to the hyperradius. The radial part of the wave function (1) is given by the eigenfunctions of the following operator equation

$$\{-\frac{\hbar^2}{2m}\frac{d^2}{d\rho^2}+\frac{\hbar^2 L_K(L_K+1)}{2m\rho^2}-E\}\chi_K^{\overline{K[f]\epsilon LST}}(\rho)+\sum_{\overline{K\epsilon LST}} W_{K[f]\epsilon LST}^{\overline{K[f]\epsilon LST}}(\rho)\chi_{\overline{K[f]\epsilon LST}}(\rho)=0 \qquad (2)$$

with E being the eigenvalues. The matrix elements of the potential energy of the nucleon-nucleon interaction are denoted by $W_{K[f]\epsilon LST}^{\overline{K[f]\epsilon LST}}(\rho)$, the value of the angular momentum L_K is determined by the relation $L_K = K+\frac{1}{2}(3A-6)$, where K is the so-called global momentum. The calculated eigenvectors $\chi_K(\rho)$ are connected with the functions $\phi_K(\rho)$ according to $\chi_K(\rho)=\rho^{(3A-4)/2}\phi_K(\rho)$. Finally, the radial density distribution of nuclei takes the form

$$n_{ij}(r)=\frac{16}{\sqrt{\pi}}\frac{\Gamma(\frac{5A-11}{2})}{\Gamma(\frac{5A-14}{2})}\int_r^\infty\frac{(\rho^2-r^2)^{\frac{5A-16}{2}}}{\rho^{5A-13}}\chi_i(\rho)\chi_j(\rho)d\rho + \frac{8}{3}\frac{(A-4)}{\sqrt{\pi}}\frac{\Gamma(\frac{5A-11}{2})}{\Gamma(\frac{5A-16}{2})}\int_r^\infty\frac{r^2(\rho^2-r^2)^{\frac{5A-18}{2}}}{\rho^{5A-13}}\chi_i(\rho)\chi_j(\rho)d\rho \qquad (3)$$

and the diagonal matrix elements of the density operator are normalized as follows $4\pi\int n_{ii}(r)r^2dr = A$.

b) Folding-Potential with Finite-Range Forces

In the folding-model the interaction potential of two colliding nuclei A_1 and A_2 is calculated as the value of an effective nucleon-nucleon interaction averaged over the densities of these nuclei [4]

$$U_{A_1A_2}(\vec{R})=\iint\rho_{A_1}(\vec{r}_1)\rho_{A_2}(\vec{r}_2)V_{eff}(|\vec{r}_1+\vec{R}-\vec{r}_2|)d\vec{r}_1 d\vec{r}_2, \qquad (4)$$

where the central part of the effective NN-interaction consists of four terms

$$V(\vec{r}_{12})=V_{00}(\vec{r}_{12})+V_{01}(\vec{r}_{12})\vec{r}_1\vec{r}_2+V_{10}(\vec{r}_{12})\vec{\sigma}_1\vec{\sigma}_2+V_{11}(\vec{r}_{12})\vec{\sigma}_1\vec{\sigma}_2\vec{r}_1\vec{r}_2 \qquad (5)$$

with $\vec{\sigma}_1$ and $\vec{\sigma}_2$ being the spin operators.

In the case of finite-range forces the nucleon-nucleon potential is chosen to be of a Gaussian form allowing for a soft core in the effective interaction at small distances [6]

$$V_{eff}(r)=\sum_K V_K\exp(-\frac{r^2}{a_K^2})+d(E/A)\delta(r), \quad r=|\vec{r}_1+\vec{R}-\vec{r}_2|, \; k=1,2. \qquad (6)$$

The second term of formula (6) simulates the inclusion of the antisymmetrization effect due to the Pauli principle which depends on the relation of the incident energy E to the mass number A. In the same ref. the analytical expressions for the corresponding folding-potential have been derived assuming also a Gaussian form of the nuclear density distributions. Besides, the folding-potential (4) was constructed by using Skyrme interaction with δ-forces for the nucleon-nucleon interaction.

c) Cross Sections of Elastic Scattering

The folding-potentials described above are employed as real part of the optical potential in order to calculate cross sections for the elastic scattering of $^6Li+^{12}C$. In the present paper it is assumed that the forms of the real and imaginary part of the potential are the same. Consequently, one gets $U_{opt}(\vec{R}) = U_{A_1A_2}(\vec{R})(1+i\beta)$ with β being the only free parameter in this method.

3. RESULTS OF THE CALCULATION AND DISCUSSION

a) In Sec.1 it has been already remarked that the folding-potential with finite-range forces is calculated by using an analytical form of the nuclear density distributions according to refs. [6,8]

$$\rho(r)=\rho_0\{\exp(-\frac{r^2}{b_0^2})+C_2\frac{r^2}{b_2^2}\exp(-\frac{r^2}{b_2^2})\}. \qquad (7)$$

The parameters of formula (7) are summarized in table 1:

Table 1

A	ρ_0 [fm^{-3}]	b_0 [fm]	b_2 [fm]	C_2
6	0.133	1.98	1.38	0.08
12	0.127	2.04	1.75	1.06

They have been extracted from an approximation of the numerical density distributions which have been computed according to eqs. (2) and (3). It should be noted that the introduction of several "oscillator frequencies" b_0 and b_2 into the parametrization of the density distribution means in the language of the shell-model an effective allowance for mixing of configurations from different shells. This leads to a more realistic description of the density distributions in comparison with the results of the harmonic oscillator model.

b) In order to analyse the influence of the chosen variant of the nucleon-nucleon interaction on the calculated cross sections for the $^6Li + ^{12}C$ elastic scattering, zero-range forces according to Skyrme /9/ and finite-range forces proposed by Satchler and Love /4/ have been employed. The results obtained by the various methods have been compared with each other and with experimental data.

Figure 1 shows the cross sections for the elastic scattering of ^6Li by ^{12}C at the incident energy $E_{Li} = 90$ MeV. The dashed line refers to the calculation with Skyrme forces ($\beta = 0.9$), the solid curve represents the result given by the use of finite-range forces ($\beta = 0.7$). At last, there is demonstrated the angular distribution which follows from a semiphenomenological computation. The corresponding dash-dotted line shows the cross sections calculated so that a Woods-Saxon potential has been chosen as imaginary part of the optical potential, while the real one is the same as in the first case (comp. dashed line). That means that three free parameters enter into this computation. They are given together with the parameters of the nucleon-nucleon interaction by table 2.

Table 2

Interaction type	Parameters	
Skyrme	$t_0 = -1057.3$ MeV fm^{-3}	$t_3 = 14463.5$ MeV fm^{-3}
Satchler/Love	$V_1 = 601.99$ MeV	$V_2 = 2256.4$ MeV
	$a_1 = 0.8$ fm	$a_2 = 0.5$ fm
	$d = -276(1-0.005\ E/A)$	
Woods-Saxon (imaginary part)	$W = -45$ MeV	$r_W = 0.89$ fm, $a_W = 0.8$ fm

In general, the results of the three calculations utilizing various forms of the optical potential describe the measured data satisfactorily up to 40°, and the difference between them is small. At large angles the theoretical angular distribution

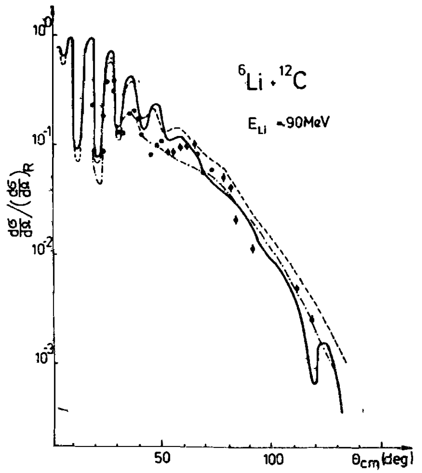

Fig.1. Angular distribution of the elastic scattering of $^6Li + ^{12}C$ at $E_{Li} = 90$ MeV in comparison with experimental data. The meaning of the various lines is explained in the text.

computed on the basis of zero-range forces underestimates the experimental values, while the curve calculated by the use of finite-range forces lies higher than the experimental one. In that angular range from 70° to 120° the semiphenomenological calculation leads to the best reproduction of the measured cross sections in comparison with the other results.

Figure 2 gives the elastic cross sections at various energies of the projectile, in particular $E_{Li} = 30.6$, 90, 99, 156 MeV. The points represent the experimental data, the theoretical results calculated by employing finite-range forces /4/ are demonstrated by solid lines.

It is seen that it is possible to reproduce the angular distributions of elastic scattering in this system at higher incident energies in qualitative agreement with experiment by choosing the parameter β equal to 0.7. To get at least a rough description of the cross sections at $E_{Li} = 30.6$ MeV it is necessary to enlarge the value of β up to 0.9. But also in this case the reproduction of the measured curve is not satisfactory. That is why a renormalization factor α has been introduced for the real part of the optical potential too. The use of the optical potential in the form $U_{opt}(\vec{R}) = U_{A_1A_2}(\vec{R})(\alpha + i\beta)$ allows the interpretation of the experimental data in the angular range up to 50° where the parameters α and β take the value 0.6. However, the theoretical cross sections computed in this way slope very rapidly at large scattering angles, while the curve corresponding to $\alpha = 1$ increases, which is in better accordance with the tendency of the measured data.

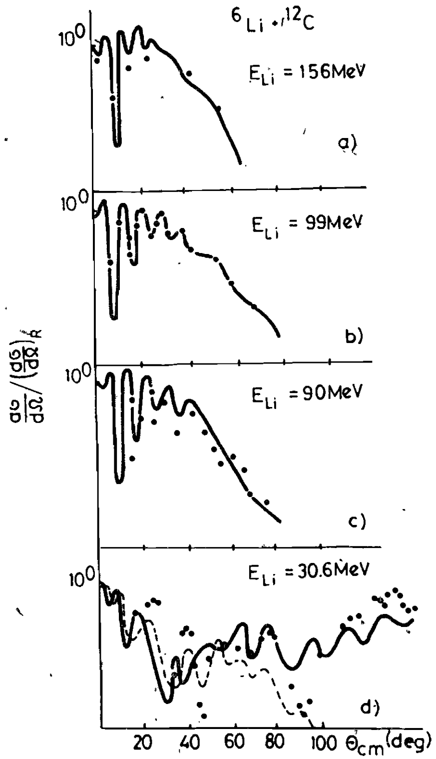

Fig.2. Angular distribution of the elastic scattering of $^6Li+^{12}C$ *at the incident energies* E_{Li}= *30.6, 90, 99, 156 MeV. The points are the experimental cross sections. Figure 2d represents the results for* E_{Li}= *30.6 MeV in the cases* $a = 1$ *(solid line) and* $a = 0.6$ *(dashed line).*

4. CONCLUSIONS

The comparison of the theoretical results describing the cross sections of the elastic scattering in the system $^6Li+^{12}C$ at four energies of the projectile with the experimental values shows that it is possible to interpret the angular distribution of such processes at higher incident energies in the framework of the hyperspherical-function method employing zero-range Skyrme forces as well as finite-range forces according to ref. /4/ and introducing only one free parameter of the optical potential.

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Исследование упругого рассеяния ^{6}Li + ^{12}C

Исследуется упругое рассеяние в системе $^{6}Li + ^{12}C$ при различных энергиях падающих частиц в области 30,6-156 МэВ. Рассчитаны сечения для этих процессов в формализме двойной свертки на основе радиального распределения плотности этих ядер, полученного методом гиперсферических функций, с помощью δ-силы Скирма и силы конечного радиуса действия. Результаты, достигаемые при энергиях E_{Li} = 90,99, 156 МэВ, удовлетворительно описывают экспериментальные данные, несмотря на то, что только один свободный параметр /множитель перенормировки мнимой части оптического потенциала/ вводится в схему расчета. При энергии E_{Li} = 30,6 МэВ возможно качественное описание эксперимента при малых углах до 50°, если обе части оптического потенциала перенормируются.

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Investigation of $^{6}Li + ^{12}C$ Elastic Scattering

The elastic scattering of $^{6}Li + ^{12}C$ is investigated at various incident energies in the range from 30.6 MeV to 156 MeV. The cross sections for these processes are calculated in the framework of the folding-model by using of the density distributions obtained in the hyperspherical-function method and Skyrme interaction with δ-forces as well as finite-range forces according to Satchler and Love. For the energies of the projectile E_{Li} = 90, 99, 156 MeV the results are in reasonable agreement with experimental data, although only one free parameter (renormalization factor of the imaginary part of the optical potential) has been introduced into the calculation. A qualitative description of the experiment at the incident energy E_{Li} = 30.6 MeV is possible only for the smallest angles up to 50°, but in this case both the parts of the optical potential must be renormalized.

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