

AN ANALYSIS OF ELASTIC AND INELASTIC CHANNELS OF ^3He IONS AND α -PARTICLES SCATTERINGS ON ^7Li , ^9Be AND ^{11}B NUCLEI AT THE ENERGIES OF (10-20) MeV/NUC

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INTRODUCTION

A measurement of inelastic scattering of nucleons, ^3He ions and α -particles at the low energies on nuclei is very important source of information regarding the parameters of deformation, mass distribution in nucleus and transient densities.

At the present time there are many indications regarding that this channels are essential for the description of the inelastic scattering on nuclei, and these channels are formed through the excitations of collective states of nucleus-target. In this case the channels coupling can be considered in the framework of adiabatic approximation of formalism of coupled channels method (MCC).

Isotopes of lithium, beryllium and boron among the nuclei of 1p- shell relate to the most deformed nuclei. Moreover, there are a significant spread in the parameters values of deformation β_2 , obtained from different experimental data /1-3/. In this connection, since some of low-lying levels of these nuclei have the pronounced collective nature, by this reason we have performed an analysis of experimental data on scattering of ^3He ions and α -particles on ^7Li , ^9Be and ^{11}B nuclei, measured at the energies of $E_\alpha = 40$ and 50.5 MeV /4,5/ and $E_h = 42$ and 60 MeV /6/ by the method of coupled channels.

1. Techniques of experiments and results of measurements

The experimental angular distributions of elastic and inelastic scattering of ^3He ions and α -particles on ^7Li , ^9Be and ^{11}B nuclei were measured in the extracted beams of U-150M isochronous cyclotron at "INP NNC RK" at the energies of (10-20) MeV/nuc.

The metallic foils from corresponding isotopes of lithium, beryllium and boron were used as targets. The working thickness of the targets was varied within the limits of 0.1 to 1.0 mg/cm² depending on the projectiles energy. The registration and the identification of scattered particles were carried out by means of the standard ΔE -E - technique, realized on the base of PC/AT personal computer. Silicon semiconductor detectors produced by ORTEC firm were

used as counters. The value of current on target has been varied depending on angle within the several units up to 200 nA.

Angular distributions of elastic and inelastic scattering were measured over the range of angles, $\theta_{lab} = (10 - 170)^\circ$ with the step $(1-2)^\circ$ for forward hemisphere and $(3-5)^\circ$ for backward one. The solid angle of registration system was 4.22×10^{-5} sr. The energetic resolution of E detector at small and large angles was within the limits of (300-400) keV and (400-500) keV, respectively, and was determined, mainly, by an energy spread in cyclotron beam and a target thickness.

The behavior of angular distributions of differential cross sections of scattered α -particles at these energies on the observed nuclei is almost the same. Therefore, let's consider in detail the scattering procedure only on ^{11}B . The differential cross sections of α -particles elastic and inelastic scatterings on ^{11}B at the energies of 40, and 50.5 MeV, are presented in Fig.1a,1b. The manifestation of a diffraction structure over the all angular range and significant section raise in the field of angles more than 120° are typical for them. With the incident α -particles energy increase the destruction of diffraction picture in the range of the intermediate angles as well as the gradual decrease of anomalous large value of $d\sigma/d\sigma_R$ at the backward angles take place. Such behavior of α -particles scattering cross sections is typical also for other nuclei (Fig.2).

There were suggested some mechanisms [7] for explanation of anomalous backwards scattering, peculiar to light, cluster nuclei. But there are not yet a commonly approved approach.

As regards to elastic scattering of ^3He ions, so with the energy increase of projectile in the angular distributions the effect of nuclear rainbow (Fig.3-4) evidently occurs. It is well known, that analysis of such data on the optical model allows to restrict discrete ambiguity of optical potential parameters [8].

2. Analysis of experimental data on the elastic scattering.

Data on the elastic scattering were analyzed within the framework of the standard optical model (OM) of nucleus. In this model the influence of inelastic channels is accounted with introducing of the imaginary absorbing part into phenomenological potential of interaction. By this model the elastic scattering is described by complex potential of interaction with radial dependence in Woods-Saxson form.

$$U(r) = -Vf(x_v) - i \left[Wf(x_w) - 4W_D a_D \frac{df}{dr}(x_d) \right] + V_C(r), \quad (1)$$

where $f(x_i) = (1 + \exp(x_i))^{-1}$, $x_i = (r - R_i)/a_i$, $R_i = r_i A^{1/3}$, $V_C(r)$ - Coulomb potential of uniformly charged sphere with radius of $R = 1.28 A^{1/3}$ fm.

Parameters of optical potentials (OP) were selected in order to achieve the best agreement between theoretical and experimental angular distributions. Theoretical calculations were performed under SPI-GENOA program /9/, realized by means of personal computer. An automatic search of optimal parameters OP was conducted by χ^2 / N value minimization. For restriction of discrete ambiguity in the parameters OP there were used recommendations, presented in the work /10/ for the α -particle scattering. There were fixed the values of radial parameters of interaction potential, obtained from global dependence of parameters OP, $r_v = 1.245$ fm and $r_w = 1.57$ fm and the theory fitting to experiment was realized by varying other 4 parameters OP (V_0 , W_v , a_R and a_W).

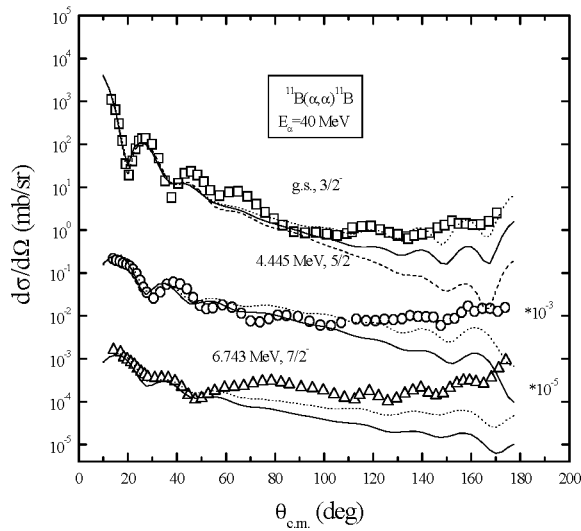


Fig.1a. Differential cross sections of α -particles scattering on the ^{11}B nucleus. Solid curve - calculation under coupled channels method (set A); dashed curve - calculation under optical model; dotted curve - calculation under coupled channels method (set B).

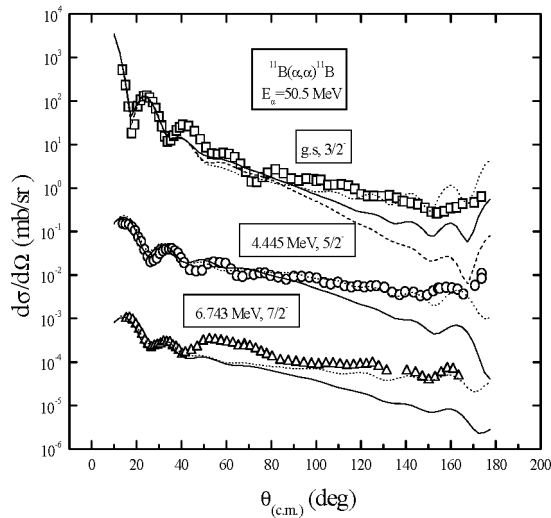


Fig.1b. Differential cross sections of α -particles scattering on the ^{11}B nucleus. Solid curve - calculation under coupled channels method (set A); dashed curve - calculation under optical model; dotted curve - calculation under coupled channels method (set B).

For influence decrease of other mechanisms contributions in to parameters OP, participating in the formation of elastic scattering sections along with «pure» potential mechanisms, the fitting of experimental data was realized using experimental ones, measured in forward hemisphere (set OP “A”). In addition, for comparison of different variants of potentials, there was calculated the experiment fitting on ^9Be and ^{11}B nuclei, inclusive the data over the all angular range.(set B).

As it is obvious from Figures, the set “A” describes the section of elastic scattering only in the field of forward angles, where a contribution of pure potential mechanisms dominates. At the same time, by using the set “B” it is possible to reproduce an experimental angular distribution over the total angular range, at that some overstating of absolute values of theoretical section at the largest angles are occurred.

The last fact, as well as a reproduction of experimental cross sections in the range of intermediate and large angles, indicates that the set “B” both with potential mechanism, accounts implicitly the contribution from others mechanisms into elastic scattering cross section formation. Consequently, using of such potential at the evaluation of other mechanisms contribution, such as heavy stripping, channels coupling etc., one may lead it to repeated account in the total section of elastic scattering.

An analysis of elastic scattering of ^3He ions by OM was conducted by using an absorption of the surface type. The presence of the nuclear rainbow effect in ^3He elastic scattering at the energy of $E_h=60$ MeV has allowed to restrict a discrete ambiguity of OP for ^7Li and ^9Be nuclei at the fixed values: $r_0 = 1.15$ fm $a_w = 0.80$ fm. These values of radius and diffusion were determined in Trost work [11]. Optimal values of OP for ^3He ions on nuclei ^7Li and ^9Be are presented in Table 1.

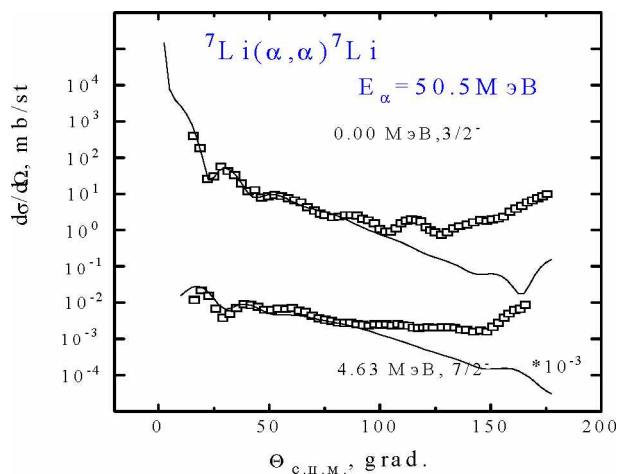


Fig.2a.Differential cross sections of α -particles scattering on the ^7Li nucleus. Solid curve - calculation under coupled channels method (set A).

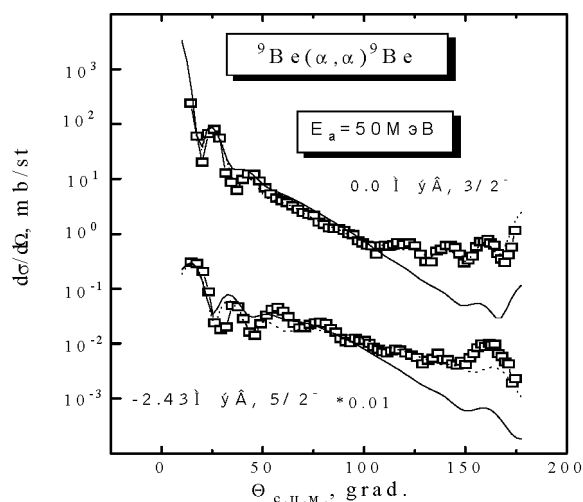


Fig.2b.Differential cross sections of α -particles scattering on the ${}^9\text{Be}$ nucleus. Solid curve - calculation under coupled channels method (set A); dotted curve - calculation under coupled channels method (set B).

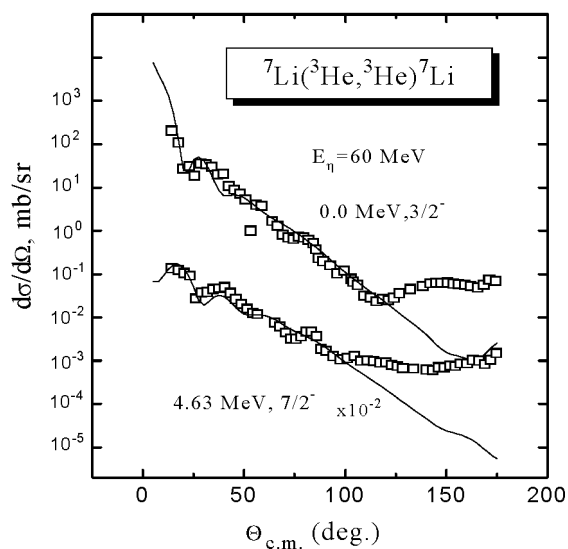


Fig.3a.Differential cross sections of ${}^3\text{He}$ ions scattering on the ${}^7\text{Li}$ nucleus. Solid curve - calculation under coupled channels method (set A).

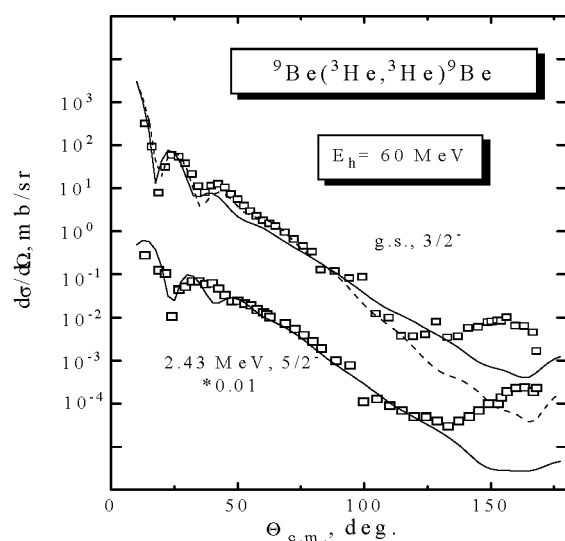


Fig.3b.Differential cross sections of ${}^3\text{He}$ ions scattering on the ${}^9\text{Be}$ nucleus. Solid curve - calculation under coupled channels method (set A); dotted curve - calculation under OM

Table 1. Parameters of optical potentials of α -particles and ^3He ions on ^7Li , ^9Be , ^{11}B nuclei.

Energy (MeV)	Target	Set	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_v (MeV)	r_w (fm)	a_w (fm)	J_R $\text{MeV} \cdot \text{Fm}^3$	χ^2/N
$E_\alpha=40$	^7Li	A	94.43	1.245	0.77	19.58	1.57	0.74	392	23.3
$E_\alpha=50$	^7Li	A	97.33	1.245	0.776	21.76	1.57	0.69	403	6.7
$E_\alpha=40$	^9Be	A	95.50	1.245	0.791	16.79	1.57	0.91	371	7.8
$E_\alpha=50$	^9Be	A	96.02	1.24	0.79	18.35	1.57	0.91	373	6.5
		B	101.12	1.39	0.73	33.4	1.05	1.08	371	4.7
$E_h=42$	^7Li	A	105.1	1.15	0.87	16.2	1.12	0.80	388	8.12
$E_h=60$	^7Li	A	100.3	1.15	0.73	15.3	1.12	0.80	387	9.98
$E_h=50$	^9Be	A	93.43	1.15	0.72	11.9	1.50	0.80	399	12.6
$E_h=60$	^9Be	A	114.0	1.15	0.87	13.7	1.59	0.80	392	23.3
$E_\alpha=40$	^{11}B	A	99.35	1.24	0.83	24.3	1.57	0.64	380	25.0
		B	102.48	1.24	0.79	18.69	1.57	0.68	375.5	18.1
$E_\alpha=50$	^{11}B	A	104.0	1.24	0.79	23.07	1.57	0.69	380.8	24.2
		B	120.8	1.24	0.74	17.7	1.57	0.77	417.8	12.4

As it is seen from Figure 3, these potentials well reproduce the sections of elastic scattering over the angles range, which completely capture the angle of rainbow scattering.

An sharp raise of section after its exponential incidence beyond the angle of rainbow scattering, in all probability, is occurred due to contribution to elastic channel of other mechanisms, differing from potential ones, for example exchange mechanisms /6/.

3. An analysis of α -particle scattering by method of coupled channels.

For data analysis on scattering on strongly deformed nuclei, the first excited levels of which have collective nature, it is expedient to use MCC version, where the real part of optical potential will be in form of:

$$V(\vec{r}) = V_0 \frac{1}{1 + \exp\left(\frac{r - R(\theta, \varphi)}{a_0}\right)}, \quad (2)$$

Thus, by the rotation model, the excited nucleus probably is constantly deformed, and the radius of half decrease of potential is determined as:

$$V(\vec{r}) = V_0 \frac{1}{1 + \exp\left(\frac{r - R(\theta, \varphi)}{a_0}\right)}, \quad (3)$$

where β_1 - deformation parameters.

In formula (2) the spherically -symmetrical part of potential describes elastic scattering, and the following members, corresponding to potential deflection from spherically -symmetrical one, describe inelastic transitions.

Calculations of angular distributions for first two or three states of $K = 3/2^-$ band of nuclei ${}^7\text{Li}$, ${}^9\text{Be}$ and ${}^{11}\text{B}$ were conducted at the two values of energy by using OP sets from the table according to coupling scheme $3/2^- + 5/2^- + 7/2^-$ (ECIS88 program /12/). An optimal agreement of calculations results with the experiment was obtained by varying of W , β_2 and β_4 parameters. The value $\chi^2_{\text{пол}}$ serves as quantitative assessment of agreement, which is determined by formula:

$$\chi^2_{\text{пол}} = \sum_i^n \chi_i^2 \quad (4)$$

where n is a number of angular distributions, being subject to fitting. The deformed imaginary and coulomb potentials were used in the calculations by MCC.

Results of description of alpha-particles scattering angular distributions on ${}^{11}\text{B}$ nuclei at the energies of 40 and 50 MeV are showed in Fig.1.

Account of channels coupling influence by using the set A has significantly allowed to improve an agreement of experimental results with theoretical calculations in the field of large angles up to 30% for elastic channels of scattering (see Table 1), as well as for inelastic ones. The last is confirmed by the fact, that if data on inelastic scattering fit without account of channels coupling (calculation by method of distorted channels), then β_2 values will be higher for (10-20) % of its value, obtained from MCC. An analogous assessment was fulfilled for β_4 parameter. A neglect of this parameter contribution has lead to increase of β_2 value up to 10% in calculations by MCC. Optimal description of experiment at 50 MeV was obtained when $\beta_2 = 0.45$ and $\beta_4 = 0.1$. The some overrated value $\beta_2 = 0.50$, at the energy of 40 MeV is most probably due to an increase the role of channels coupling at the energy decrease. Therefore, at the lower energies it is necessary to account a lot of channels coupling. The parameter of quadruple deformation $\beta_2 = 0.45$ (see table 2), obtained from description of scattering angular distributions at $E = 50$ MeV agrees with its value, determined from analysis of ${}^3\text{He}$ ions scattering.

In the work /5/ the parameters of quadruple deformation of ${}^6\text{Li}$, ${}^7\text{Li}$ nuclei were obtained from an analysis of α -particles inelastic scattering on lithium isotopes by the method of distorted waves. Using of the direct single-stage mechanism one can describe the sections of inelastic scattering only for angles of forward hemisphere. Description of the sections anomalous raise at the large angles was achieved with the account of heavy stripping mechanism contribution to formation of total section of inelastic scattering. However, due to using of these two mechanisms it was not possible to describe a section in the field of mean angles.

Angular distributions of elastic and inelastic scattering (4,64 MeV, $7/2^-$) of α -particles and ${}^3\text{He}$ ions on ${}^7\text{Li}$ nuclei were analyzed by MCC method according to coupling scheme $3/2^- + 7/2^-$.

The account of channels coupling influence by using the set “A” has significantly allowed to improve an agreement of experimental results with the theoretical calculations in the range of large angles - up to 30% for elastic channels of α -particles scattering, as well as for inelastic ones. The last is confirmed by fact, that if data on inelastic scattering fit without account of channels coupling (calculation by method of distorted channels), then β_2 values will be higher for (5-10)% of its value, obtained from MCC. An analogous conclusion is the same for ${}^3\text{He}$ ions scattering. For example, for ${}^7\text{Li}$ nucleus, the value $\beta_2 = 0.9$, obtained from ${}^3\text{He}$ ions scattering analysis, is lower than its value, determined in the work /3/ (calculation by distorted channels method).

The experimental data on scattering of α -particles and ${}^3\text{He}$ ions on ${}^9\text{Be}$ nuclei were analyzed within the framework of MCC according to coupling scheme $3/2^- + 5/2^- + 7/2^-$, (for ${}^3\text{He}$ - $3/2^- + 5/2^-$).

The use of set “B”, as in the case of ${}^{11}\text{B}$ nucleus, allows to describe elastic and inelastic scattering of α -particles over the total angular range. It leads to some contradiction, as ${}^9\text{Be}$ nucleus is sufficiently strong cluster nucleus, so at the last maximum of angular distributions the visible contribution of heavy stripping mechanisms should take place. It is confirmed by the results of work /6/, where a significant raise of ${}^3\text{He}$ ions elastic scattering section at backward angles at the energy of 60 MeV was completely possible at the account of heavy stripping mechanism contribution in to elastic channel (see fig. 4).

In this connection the following calculations were performed by using the set “A”. There was carried out an assessment for β_4 parameter. A neglect of this parameter leads to an increase of β_2 value up to 20% at the calculations by MCC for ${}^9\text{Be}$ nucleus. With the account of this the experiment optimal description at $E_\alpha = 50.5$ MeV was achieved at $\beta_2 = 0.6$ и $\beta_4 = 0.2$ (Fig. 2b).

It is possible to reproduce the experimental data on ${}^3\text{He}$ ions elastic scattering on ${}^9\text{Be}$ nuclei at the energy of 60 MeV over the total angular range by MCC only with account of heavy stripping mechanism contribution, calculations of which were taken from the works/6/.

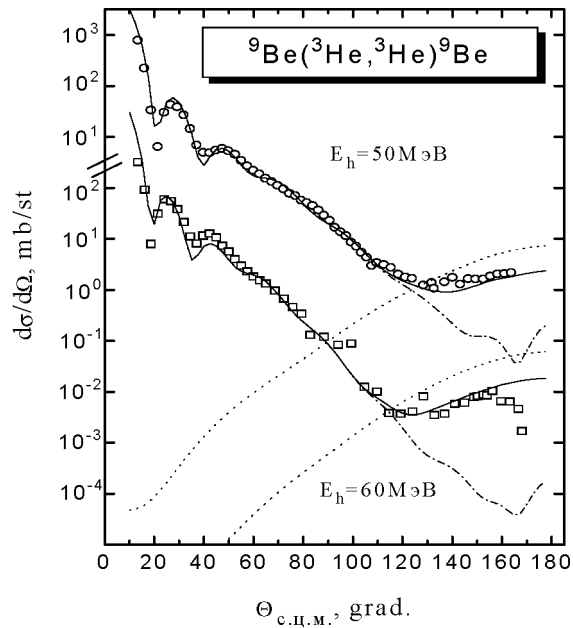


Fig.4. Differential cross sections of ^3He ions elastic scattering on the ^9Be nucleus. Dashed curve - calculation under optical model; dotted curve - calculation with account of heavy stripping mechanism contribution; solid curve - Σ section.

Deformation parameters and spectra-factors of observed nuclei, determined from the description of experimental data by MCC jointly with literature data are presented in Table 2.

According to the table, such combined analysis of experimental data has significantly allowed to restrict the spread of β_2 value for ^9Be nucleus.

Table 2. Parameters of deformations and spectra-factors

Nucleus	Reaction	E_i , (MeV)	Set OP	β_2	S
^7Li	(α, α)	50.5	A	1.0	0.95 /3/
^7Li	(h, h)	60	A	0.9	0.26 /6/
^9Be	(α, α)	50.5	A	0.6	
^9Be	(h, h)	60	A	0.8	0.23 /6/
^{11}B	(α, α)	40	A	0.50	
^{11}B	(α, α)	50.5	A	0.45	

CONCLUSION

Thus, the account of channels coupling and heavy stripping mechanism contribution has allowed to describe angular distributions of ^3He scattered ions on ^7Li and ^9Be nuclei over the total angular range. As regards to data on α -particles scattering on these nuclei, there is occurred a significant improvement of description in the range of intermediate angles in comparison when channels coupling is neglected.

The complex analysis of experimental data on α -particle and ^3He ions scattering on ^7Li , ^9Be and ^{11}B nuclei has significantly allowed to restrict a spread of β_2 value.

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