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STUDY OF ELASTIC SCATTERING OF DEUTERONS FROM ^{6}Li AT ENERGY 18 MeV

Abstract. Differential cross sections of elastic scattering of deuterons from ^{6}Li nuclei at energy 18 MeV were measured at U-150M accelerator. The measurements were performed with an accuracy of no more than 10%. One minimum and one maximum of cross sections are clearly seen in the angular distributions at small angles. The obtained data were analyzed within optical model, distorted wave method with a finite interaction radius and coupled reactions channel method. The optimal values of the optical interaction potential and spectroscopic factor were determined. It is shown that the potential scattering forms cross section only at low and medium angles. In the range of large angles cross sections are formed by α-cluster transfer mechanisms.

Key words: elastic scattering, light charged particles, optical potential, FRESCO, cluster transfer, spectroscopic factor.

Introduction. The study of the interaction of charged particles with lithium nuclei is of considerable interest in the light of that role to be played by these nuclei in nuclear technology, fusion energy and astrophysics. So, 6Li nucleus is one of the most important elements of the fuel cycle in the most promising projects of fusion reactors using deuterium-tritium fusion. In tritium reproduction it is assumed that lithium is included in the nearest shell to the plasma combustion region. This technique requires highly accurate data on the sections of different particles interaction with lithium nuclei, which can be obtained as by experimentation, and by calculations within certain nuclear models. Astrophysical aspect of relevance is connected primarily with questions of nucleosynthesis of light nuclei at the initial stage of evolution of the universe and the problem of unexpectedly high prevalence of lithium (and beryllium and boron) in cosmic rays, has on order above, as opposed to their theoretical estimates.

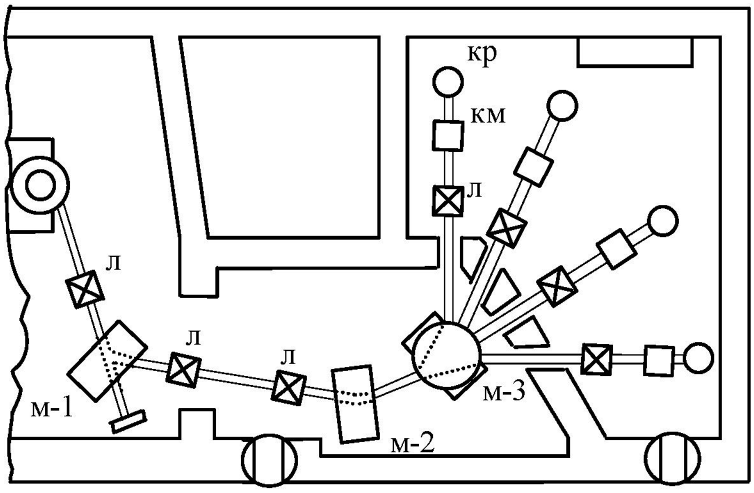
Experimental procedure and measurement results. Experiments were carried out in the isochronous cyclotron U-150M [1] of the Institute of Nuclear Physics of the Republic of Kazakhstan. The differential cross sections of elastic scattering of deuterons on 6Li nuclei were measured at an energy of 18 MeV in the angular range from 10° to 170° in the center-of-mass system. The total error of the data did not exceed 10%.

Charged particles in a cyclotron are formed in the source, located in the central part of the camera in an arc discharge when applying the appropriate gas (hydrogen, deuterium, helium-3, helium-4). Their accelerating happens in the interpolar space of 1.5-meter magnet at the time of flight of the particles between the dees.

When installing the operating parameters of particle acceleration special attention is given to the operating mode of the ion source, its duty cycle, microstructure of the current pulse and beam quality of the wiring on the target. This optimization of spatial and temporal characteristics of the beam made it possible to significantly reduce the level of various noise, uneven loading of electronic equipment.

The energy and the energy dispersion in the beam is determined by measuring the energy spectrum of the particles elastically scattered by thin gold targets set out in the laboratory cell scattering of low-energy nuclear reactions of the INP RK [2]. In this case, measurements at a small angle (about 10 °) avoids errors due to inaccurate knowledge of the target thickness and angular dispersion of particles in the beam. For absolute calibration of the energy scale the "triple" alpha source is used (^{241,243}Am+^{244}Cm).

Transporting scheme of the beam of accelerated ions from the cyclotron chamber to the scattering chamber, located at 24 meters from the exit of the beam is shown in Figure 1. It includes a quadrupole lens system, two rotary, diluting, two targeting magnets and the collimator system. All these installetions together with the elements of targeting and correction, provide at the target a charged particle beam of angle dulution of not more than 0.4 ° and a diameter of 3 mm. Adjusting the collimator and the scattering of the camera relative to the center axis of the ion guide was carried out by an optical method and was monitored using quartz twelve screens and television cameras, image transmission to remote control of the cyclotron.



Л – quadrupole lenses; М-1, М-2 – deflecting magnets;
М-3 – diluting magnet; КМ – correcting magnet;
КР – scattering chamber

Figure 1 - the transportation scheme of the ion beam of the cyclotron to the scattering chamber

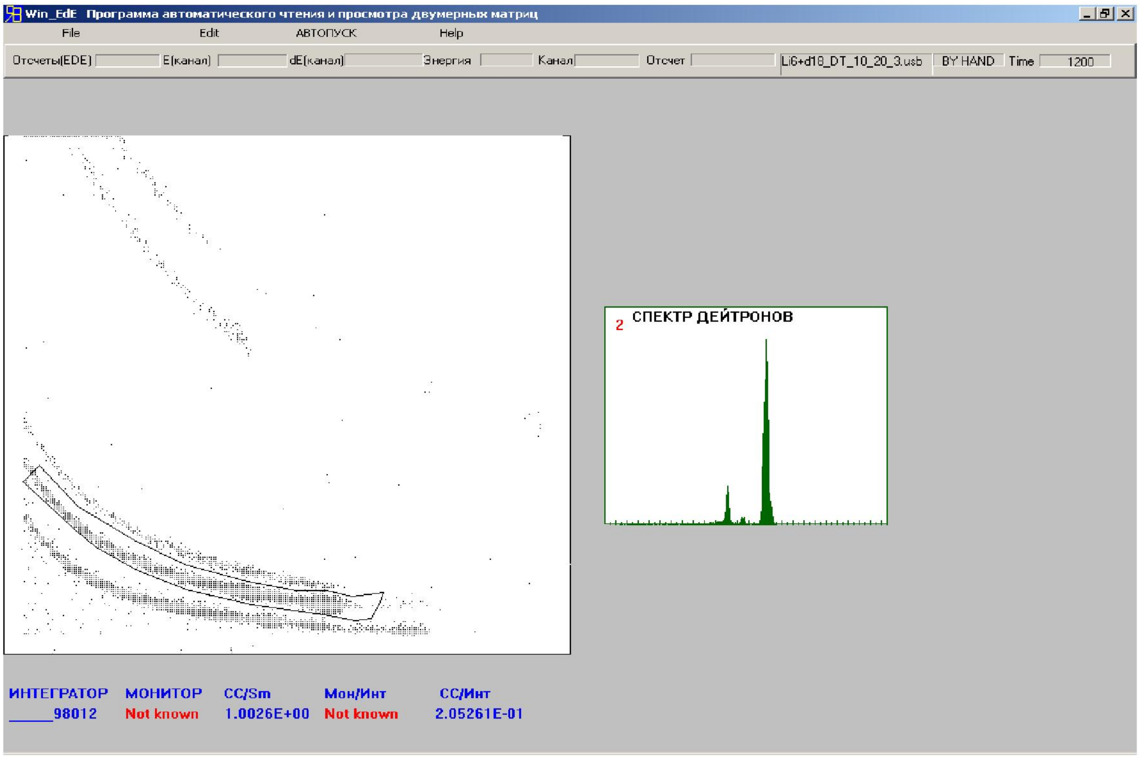
The measurements were made using a *ΔE-E* method of registration and identification of particles, based on the simultaneous measurement of specific losses of charged particle energy in *dE/dx* substance and its total kinetic energy *E*. The method is based on the Bethe-Bloch equation, binding energy of the emitted charged particle with its specific ionization in the matter:

$$\frac{dE}{dx}=\frac{kMz^2}{E}$$

where k – constant, weakly dependent on the types of particles, M and z – mass and charge of the emitted particles, E – energy of the incident particle.

Figure 2 shows the *ΔE-E* distribution of products of the interaction of deuterons with nuclei ^{6}Li

In the experiment, as targets there were used ^{6}Li thin film (thickness of 700-1100 ug/cm^2) deposited on a substrates of aluminum oxide (Al_2O_3) of 30-40 ug/cm^2 thick. In the measurements there were used silicon surface barrier detectors with a thickness of 10-100 microns (*ΔE* - detector) and 1,000-2,000 microns (*E* - detector). Beam current was varied in the range of 1-100 nA, depending on the scattering angle and the load of the electronic equipment. All measurements were carried out on the measuring and computing complex lab, which serves as the basis for a system of multivariate analysis processes based on electronic blocks ORTES and PC/AT [3]. Figure 3 shows the elastic scattering spectra of deuterons on ^{6}Li nuclei at two corners.



Li6+d18_DT_10_20_3.usb BY HAND Time 1200

ИНТЕГРАТОР	МОНИТОР	CC/Sm	Мон/Инт	CC/Инт
______98012	Not known	1.0026E+00	Not known	2.05261E-01

Lower loci - singly charged particles, upper loci - doubly charged particles

Figure 2 - *ΔE-E* distribution of interaction products of deuterons with 6Li nuclei (scattering angle - 24 degrees)

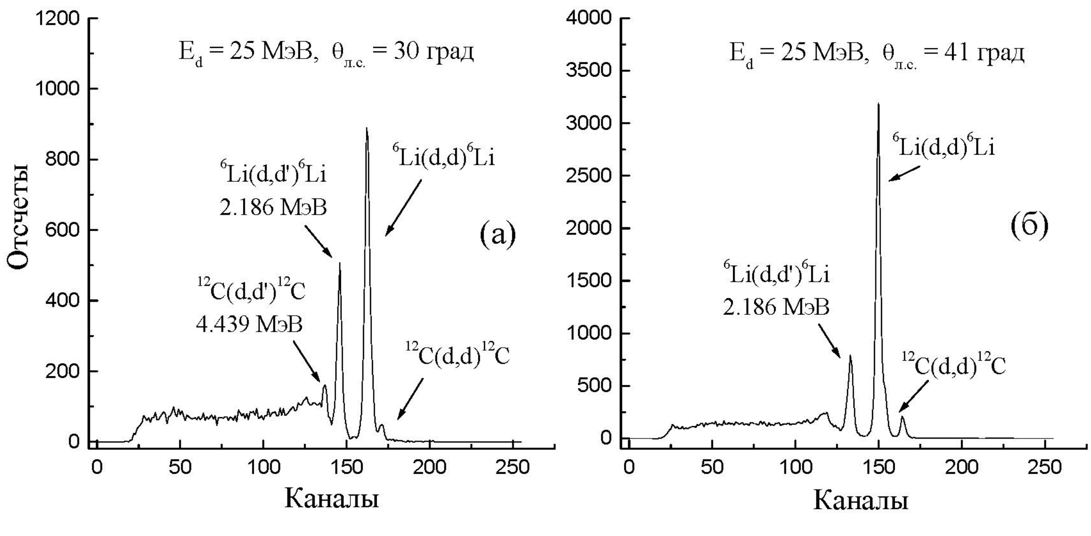


Figure 3 - the spectrum of the scattered deuteron measured at angles of 30 (a), 41 (b) degrees

Analysis and discussion of the results. The most developed method of extracting information about the potentials of the particles interaction with atomic nuclei is the phenomenological analysis of the experimental data on elastic scattering on the basis of the optical model of the nucleus, the argumentation and detailed mathematical formulation of which are expose in a number of studies [4].

In the optical model the effect of inelastic channels is considered by phenomenological introduction of imaginary absorbing part in the interaction potential between the colliding nuclei. In this approach, the problem of scattering on a many-particle system - core, is reduced to a simple process - scattering in the field of integrated optical potential, the shape and size of which are determined by optimizing the design values of the model parameters with the corresponding experimental data. Technically, this procedure is associated with the solution of the Schrödinger equation

$$\Delta\Psi + \frac{2\mu}{\hbar^2}\left[E - U(r)\right]\Psi = 0$$

with a complex potential $U(r)$. Here $\mu = mA_pA_t/(A_p+A_t)$ – reduced mass of the colliding nuclei, A_p and A_t – mass numbers of the incident nucleus and the target nucleus, m – nucleon mass, E – kinetic energy of the relative motion in the center-of-mass system (c.m.s.).

Usually calculations are limited to central potentials depending only on the distance between the centers of mass of the colliding nuclei. This is justified by the fact that, as shown by the detailed theoretical study, the spin-orbit interaction has virtually no influence on the differential cross section of elastic scattering in front corners. Thus, the optical potential can be written as

$$U(r) = V_C(r) - V(r) - i(W_V(r) + W_S(r))$$

The first member is the Coulomb potential. Since scattering is not sensitive to the particular form of the charge distribution, and therefore, there is no need to consider its diffuse edge, then for practical purposes it is sufficient to take the Coulomb potential of a uniformly charged sphere as

$$\begin{cases} V_C(r) = \dfrac{Z_pZ_te^2}{2R_C}(3 - r^2/R_C^2) & \text{для } r > R_C \\ V_C(r) = \dfrac{Z_pZ_te^2}{r} & \text{для } r < R_C \end{cases}$$

where $R_c = r_0(A_p^{1/3} + A_t^{1/3})$ - Coulomb radius, Z_P and Z_t – charge of the incident particle and the target nucleus. Other members of formula $\Delta\Psi + \frac{2\mu}{\hbar^2}\left[E - U(r)\right]\Psi = 0$ describe the nuclear force.

Usually as a nuclear it is taken Woods-Saxon potential with such set of phenomenological parameters, at which there is the best agreement with experiment, or the potential, calculated theoretically on the basis of fundamental nucleon-nucleon interaction.

In the first case the real part is given as

$$V(r) = V_0\left[1 + \exp\left(\frac{r - R_V}{a_V}\right)\right]^{-1}$$

imaginary volumetric

$$W_V(r) = W_0\left[1 + \exp\left(\frac{r - R_W}{a_W}\right)\right]^{-1}$$

and imaginary surface

$$W_S(r) = -4a_DW_D\frac{d}{dr}\left[1 + \exp\left(\frac{r - R_D}{a_D}\right)\right]^{-1}$$

As can be seen from formulas the radial dependence of the nuclear potential is determined by the Woods-Saxon form factor $\left[1 + \exp\left(\frac{r - R_i}{a_i}\right)\right]^{-1}$, where R_i and a_i – corresponding radius and diffuseness, which characterizes the decay rate of the potential. Woods-Saxon parameterization corresponds to the assumption that the internuclear interaction corresponds to the distribution density of the nucleons in the nucleus of the target.

Imaginary potential can be volumetric ($W_V \neq 0$, $W_D = 0$), surface ($W_V = 0$, $W_D \neq 0$) or mixed ($W_V \neq 0$, $W_D \neq 0$).

Theoretical calculations were performed on SPIVAL program. OP parameters were chosen so as to achieve the best agreement between the theoretical and the experimental angular distributions. Automatical search of the OP optimal parameters was made by minimizing the value χ^2/N of the least squares method. The initials were the potential parameters proposed in [5]. To reduce the ambiguity we tried not to go far from the recommended values of geometrical parameters (r_V, a_V) of the real potential. For a better agreement with the experimental data depth of the imaginary part (W_D) decreased only slightly. The final potential parameters are shown in Table 1.

To describe the direct mechanisms in the mid 50-ies it was developed the method of distorted waves (MDW) and the Born approximation with distorted waves (DWBA). This is the most common, but not the only model for the description of direct nuclear reactions [6].

Table 1 - Optimal parameters of optical potentials ща еру process ^{6}Li(d,d)^{6}Li at incident deuteron energy 18 MeV

V, MeV	r_V, fm	a_V, fm	W_D, MeV	r_D, fm	a_D, fm	V_{SO}, MeV	r_{SO}, fm	a_{SO}, fm
70.56	1.17	0.85	9.19	1.325	0.69	6.76	1.07	0.66

MDW can be considered as a generalization of the optical model to inelastic channels. Studying nuclear reactions, it cannot be, as in the case of elastic scattering, ignored the internal structure of the interacting particles. The wave function in each reaction channel is represented as (for example, for the input channels)

$$\Psi_i = \tilde{\Psi}_a \tilde{\Psi}_A \chi_i$$

where $\tilde{\Psi}_a$ и $\tilde{\Psi}_A$ - the wave function describing the incident particle and a target nucleus, χ_i - the wave function describing the relative motion of the particles in the channel.

The MIV uses the fact that the incident particle transfers its energy and impulse to a small number of degrees of nucleus freedom. This makes it possible to obtain an approximate solution of the many-particle Schrödinger equation using perturbation theory. Full Hamiltonian of the system can be written as

$$H = H^0 + H^{res}$$

where H^0 - Hamiltonian of the system consisting of two particles which interactions are described by optical potential V^{opt}, H^{res} – Hamiltonian of residual interaction, which is regarded as a small perturbation, transforming the system into the final state.

The process of interaction thus splits into three stages:

1. The motion of the incident particle in the "distorting" optical potential of the target nucleus;
2. The transfer of nucleons under the influence of the residual interaction;
3. The movement of the emitted particles in the field of the final nucleus.

The amplitude of the scattered wave has the form

$$f(\vec{k}_a,\vec{k}_b) = \frac{\mu_b}{2\pi\hbar^2}\left\langle \Phi_f(\vec{k}_b)\middle| H^{res} \middle| \Psi_i(\vec{k}_a)\right\rangle$$

where μ_b – reduced mass, $\vec{k}_a$ and $\vec{k}_b$ – the wave vectors of the input and output channels, $\Psi_i(\vec{k}_a)$ и $\Phi_f(\vec{k}_b)$ – wave functions in the input and output channel having the structure (H = H^0 + H^{res}), with $\Phi_f(\vec{k}_b)$ – optical wave function. In the Born approximation, the exact wave function $\Psi_i(\vec{k}_a)$ is replaced by an optical wave function. The expression for the cross section has the form:

$$\frac{d\sigma}{d\Omega}^{DWBA} = \frac{\mu_a k_b}{\mu_b k_a}\left| f(\vec{k}_a,\vec{k}_b)\right|^2$$

All the above mentioned formulas of the method of distorted waves were innate in the DWUCK5 program, which is calculated using the theoretical section. Figure 4 schematically shows the transmission mechanism of α-cluster.

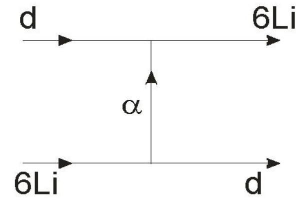


Figure 4 - transmission of alpha-cluster in the ^{6}Li(d,^{6}Li)d process

Accounting for exchange cluster transmission mechanism was held in the framework of the connected reaction channels using the FRESCO program [7]. In this method, the system of A nucleons, represented in the input channel with $A = A_p + A_t$, configuration, is replaced by N-related systems dividing them into two clusters ($A = A_{p';k} + A_{t';k}$). Here the indices p and t refer, respectively, to the incident particle and the target nucleus, and the index k varies from 1 to N. The total wave function in this case is the sum of products of pairs of internal basic wave functions of clusters φ_{pk}, φ_{tk} and wave function Φ_k,, describing relative motion of clusters in the channel k:

$$\Psi = \sum_{k=1}^{N} \varphi_{pk}\varphi_{tk}\Phi_k(\mathbf{R}_k)$$

where $\mathbf{R}_k$ – the radius vector between the fragments in the channel k. The corresponding radial functions $f_\alpha(R_k)$ to the relative wave function $\Phi_k(\mathbf{R}_k)$ are found by solutions of the system of coupled equations:

$$\left[E_k - T_{kL}(R_k) - U_k(R_k)\right] f_\alpha(R_k) = \sum_{\alpha',\lambda>0} i^{(L'-L)} V^{\lambda}_{\alpha\alpha'}(R_k) f_{\alpha'}(R_k) +$$

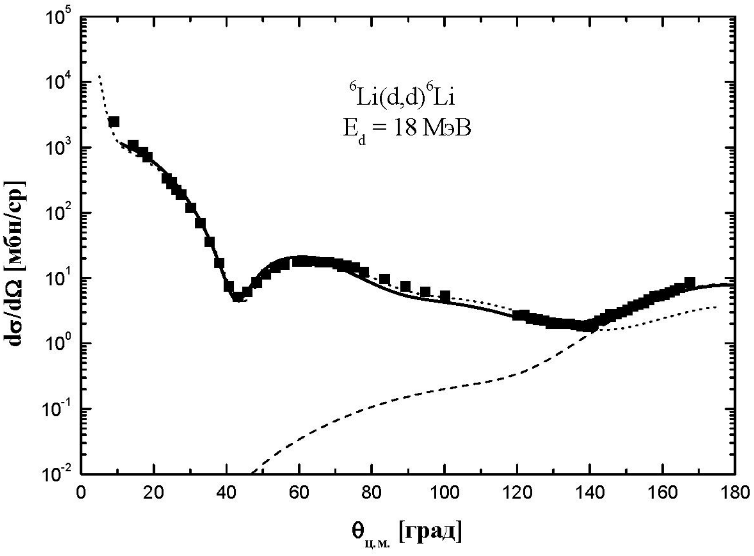
$$+ \sum_{\alpha',\lambda>0} i^{(L'-L)} \int_0^{R_m} V_{\alpha\alpha'}(R_k, R_{k'}) f_{\alpha'}(R_{k'}) dR_{k'}$$

where

$$T_{kL}(R) = -\frac{\hbar^2}{2\mu_k}\left(\frac{d^2}{dR^2} - \frac{L(L+1)}{R^2}\right)$$

– the kinetic energy operator. The α value is a composite index comprising the channel number k and the quantum numbers - the spins of the incident particle and the target nucleus (J_p, J_t), partial wave (L) and the total spin (J_T), ie $\alpha = (k, (LJ_p)J, J_t; J_T)$; $U_k(R_k)$ - interaction potential in the k channel, including nuclear and Coulomb part; E_k - asymptotic kinetic energy of the channel k: $E_k = E + Q_k - \varepsilon_{pk} - \varepsilon_{tk}$, где Q_k, ε_{pk}, ε_{tk} – Q - reactions and the excitation energy in the channel k; $V^{\lambda}_{\alpha\alpha'}(R_k)$ - local interaction for transitions in discrete states of nuclei with multipolarity λ (transferred orbital angular momentum); $V_{\alpha\alpha'}(R_k, R_{k'})$ - nonlocal interaction, connecting channels with the transfer of one or more nucleons.

In case of d^{6}Li-scattering, we took into account only two channels (N = 2): d+^{6}Li and ^{6}Li+d. Switching between channels, carried out through the transfer of alpha-cluster was calculated by distorted waves with a finite interaction radius. Thus, the elastic scattering and the reaction with alpha-cluster transmission were included in circuit communication channels. In the calculations of the transmission mechanism we used prior-representation. Cluster (d + α) wave functions for the ground state of the nucleus ^{6}Li were calculated using the standard method of adjusting the depth of the real part of the Woods-Saxon potential, which gives the desired energy cluster communication. Geometric potential parameters (radius and diffuseness) have fixed values: r = 1,25 fm, a = 0,65 fm. Cluster spectroscopic amplitudes (S_A = 0,85) were found from the calculated cross sections fit to the experimental data, agree well with cluster theoretical amplitude S_A = 1,02, calculated in the framework translationally invariant model [8].



Squares - experimental data, solid curve - cross sections, calculated by FRESCO program taking into account the interference of the elastic scattering cross-sections and sections of the transmission mechanism of α-cluster (coupled-channel method); dotted curve - cross sections, calculated by Spival program (optical model), dashed curve - cross sections, calculated by the DWUCK5 program (method of distorted waves)

Figure 5 - the angular distributions of elastic deuteron on 6Li nuclei at the energy of 18 MeV

It can be seen that the optical model reproduces the experimental sections up to 130° (dotted curve), the method of distorted waves describes the area of large angles (dashed line) and coupled-channel method, which takes into account the connection of both the above processes, in accordance with their interference, achieves a description of the experimental data in the full angular range.

Conclusion. The experiments on the elastic scattering of deuterons on ^{6}Li nuclei at energy E_d = 18 MeV in the range of angles from 10° to 170° in the center of mass with the use of *ΔE-E* - technique were carried out. The differential cross sections at angles of 40° and 60° have the minimum and maximum. Next comes the gradual decline to 135°. In large angles area it is observed the rise of cross-sections associated with a pronounced cluster structure of ^{6}Li nucleus.

From the analysis of experimental data in terms of the optical model of the nucleus there are found the best, physically reasonable parameters of the optical potential interaction, which are in good agreement with literature data. In the method of distorted waves method and coupled-channel method it was an analysis of the elastic scattering, taking into account the contribution of the transmission mechanism of α-cluster, which showed that for the studied process in large angles area, the effect of this mechanism on the formation of the scattering cross sections is considerable.

The obtained experimental and theoretical data will be used in studies of the processes taking place in the stars, in the development of new theoretical models of nuclear physics, and will also be useful for the characterization of the processes occurring in the high-temperature plasma fusion reactors.

REFERENCES

[1] Arzumanov A.A., Nemenov L.M., Anisimov O.K., Batalin S.S., Volkov B.A., Gromov D.D., Kravchenko E.T., Nigmanov M.H. Popov Y.S., Prokofiev S.I., Ribin S.N. Izochronnii cyclotron s reguliruemoi energiei ionov // Izvestiya AN KazSSR, Seriya fisiko-matematicheskaya, – 1973, – № 4, – S. 6-15.

[2] Artemov S.V., Bazhazhin A.G., Baktibayev M.K., Burtebayev N., Duisebayev A., Duisebayev B.A., Zarifov R.A., Kadirzhanov K.K., Karahodzhayev A.A., Sahiev S.K., Satpayev N.K., Sargaskaev A.M., Seitimbetov A.M. Kamera rasseyaniya dlya izmereniya sechenii yadernih reakcii v predelno malih uglah na vivedennom puchke izohronnogo ciklotrona U-150M // Izvestiya NAN RK, Seriya fisiko-matematicheskaya, – 2006, – № 6, – S. 61-64.

[3] Burtebayev N.T., Vinogradov A.A., Vongay A.D., Duisebayev A.D., Kurashov A.A., Mazurov I.B., Paramanov V.V., Prokovev S.I., Sakuta S.B., Sanichev V.I., Sytin N.P., Chesalov A.A., Chuev V.I. Sistema mnogomernogo analiza dlya issledovaniya yadernih reaksiy na siklotrone INP ANH KazSSR // Izvestiya AN KazSSR, Seriya fiziko-matematicheskaya. – 1975. – №2. – S.65-68.

[4] Hodgson P.E. The nuclear optical model. // Report of Progress in Physics. – 1971. – V.34. – P.765-819.

[5] Daehnick W.W., Childs J.D., Vrcelj Z. Global optical model potential for elastic deuteron scattering from 12 to 90 MeV // Physical Review C. – 1980. – Vol.21. – P. 2253-2274.

[6] Zelenskaya N.S., Teplov I.B. Metod iskazhennih voln v reaksiyah so slozhnimi chastisami // ЭЧАЯ. – 1979. – T.11, № 2. – S.342-410.

[7] Thompson Ian J. Coupled reaction channels calculations in nuclear physics // Computer Physical Reports. – 1988. – Vol. 7. – P. 167-212.

[8] Nemec O.A., Neudachin V.G., Rudchik A.T., Smirnov Yu.F., Chuvilski Yu.M. Nuklonnie associacii v atomnih yadrah b yadernie reakcii mnogonuklonnih peredach. – Kiyev: Naukova dumka, – 1988, – 488 s.

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18 МэВ ЭНЕРГИЯЛЫ ДЕЙТРОНДАРДЫҢ ^{6}Li ЯДРОЛАРЫНАН СЕРПІМДІ ШАШЫРАУЫН ЗЕРТТЕУ

Аннотация. 18 МэВ энергияға ие дейтрондар ^{6}Li ядроларынан серпімді шашырауының дифференциалдық У-150М үдеткішінде қимасы өлшенді. Өлшеулер 10 %-дан жоғары емес қателіктен жүргізілді. Бұрыштық таралулардың кіші бұрыштық аймағында қиманың бір минимумы және бір максимумы көрінеді. Алынған мәліметтер ядроның оптикалық үлгісі, бұрмаланған толқындар әдісі және реакцияның байланысқан арналар әдісі төңірегінде талданды. Әсерлесу оптикалық потенциалының және спектроскопиялық фактордың оптималды мәндері табылды. Потенциалдық шашырау тек қиманың кіші және орта бұрыштарында болатындығы көрсетілді. Қиманың үлкен бұрыштар аймағында α-кластер ауысу механизмі болатыны көрінеді.

Түйін сөздер: серпімді шашырау, зарядталған жеңіл бөлшектер, оптикалық потенциал, FRESCO, кластер ауысу, спектроскопиялық фактор.

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ИЗУЧЕНИЕ УПРУГОГО РАССЕЯНИЯ ДЕЙТРОНОВ НА ЯДРАХ ^{6}Li ПРИ ЭНЕРГИИ 18 МэВ

Аннотация. На ускорителе У-150М измерены дифференциальные сечения упругого рассеяния дейтронов на ядрах ^{6}Li при энергии 18 МэВ. Измерения выполнены с погрешностью не более 10 %. В угловых распределениях, в области малых углов, четко проявляется один минимум и один максимум сечений. Полученные данные проанализированы в рамках оптической модели ядра, метода искаженных волн с конечным радиусом взаимодействия и метода связанных каналов реакций. Найдены оптимальные значения оптического потенциала взаимодействия и спектроскопического фактора. Показано, что потенциальное рассеяние формирует сечения лишь в области малых и средних углов. В области больших углов сечения формируют механизмы передачи α-кластера.

Ключевые слова: упругое рассеяние, легкие заряженные частицы, оптический потенциал, FRESCO, передача кластера, спектроскопический фактор.