SYSTEMATIC STUDY OF THE p, d AND ^{3}He ELASTIC SCATTERING ON ^{6}Li

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The elastic scattering of protons, deuterons and ^{3}He on ^{6}Li at different incident energies have been analyzed in the framework of the optical model using ECIS88 as well as SPI GENOA codes. The potential parameters were extracted in the phenomenological treatment of measured by us angular distributions and literature data. A good agreement between theoretical and experimental differential cross sections was obtained in whole angular range. Parameters for real part of potential have been also calculated microscopically with single- and double-folding model for the *p* and *d*, ^{3}He scattering, respectively, using DFPOT code. For best agreement with experiment the normalization factor *N* for the potential depth is obtained in the range of 0.7-0.9. For the ^{3}He scattering, the elastic triton transfer mechanism has been taken into account by DWBA using DWUCK5 code.

Introduction

Solving the scattering or reaction problem with the Schrodinger equation requires knowledge of the interaction potential between the two colliding nuclei. Unlike the Coulomb potential, the nuclear one is less known, especially at small distances of the interacting nuclei. From the phenomenological studies, it got clear that the major part of the nuclear interaction potential can be approximated by a Woods-Saxon form which gives a simple analytic expression, parameterized explicitly by the depth, the radius, and diffuseness of the potential well.

In practice it is required to obtain the potential from the analysis of experimental data by varying their parameters to optimize the overall fit to the data, using appropriate optical model codes. But such analysis cannot give unique values of the all potential parameters; rather it is certain combinations that correspond to a particular set of data. Thus, for example, the fit to that data is insensitive to variations of V_0 and r_0 that keep $V_0 r_0^2$ constant, and similarly for $W_D a_D$. Since the potential determination from phenomenological analysis is insufficiently precise to resolve these ambiguities, it is usual to fix the geometrical parameters (radius, diffuseness) to average values and then to adjust the potential depths V_0, W_D, and V_s to fit the data. It is then possible to compare the basis of variation of these potentials with energy and from nucleus to nucleus. The purpose of the present work is to study the elastic scattering of proton, deuteron and ^{3}He on ^{6}Li and determine the potential depth, V_0 for each case, using phenomenological and double-folding model.

Many such analysis of nucleon scattering have now been made and it is found that the potentials are quite similar for all nuclei and vary other slowly with the incident energy. The optical model is thus a successful way of describing elastic scattering in a wide range of conditions, and this provides confirmation of the overall correctness of the derivations of the potential from more fundamental considerations. An extensive analysis of differential cross sections for the elastic scattering of 9-22 MeV protons by range of nuclei (Perey 1963) showed that the form factors are fixed to the average values r_0= 1.25 fm and a_0 = 0.65 fm and the depth of the real part, V_0, is given by: $V_0 = 53.3 - 0.55E_p - 27(N-Z)/A + 0.4\ Z/A^{1/3}$.This shows that there is linear dependence on the energy and the symmetry parameter $\alpha = (N - Z)/A$. It should be noted that coefficient at E_p is rather high; the values between 0.2 and 0.3 are found in more recent analyses. Elastic scattering of nucleon–nucleus data at intermediate energies are useful tools for testing and analyzing nuclear structure models and intermediate energy reaction theories [1–10]. The elastic scattering of proton– nucleus has been analyzed in order to determine ground state matter densities empirically for comparison with Hartree–Fock predictions [11–13]. The study of spin dependent effect at the intermediate energy proton scattering plays an important role [14]. The optical potential has been extensively used in studying the proton– nucleus scattering [15].

In the energy region below 50 MeV, extensive proton elastic scattering data exist. These have, in general been analyzed in terms of an optical model in which the interaction is represented as the scattering of a point particle (proton) by a potential of form:

$$V(r)=U_C(r)+U(r)+iW(r)+U_{so}(r)+iW_{so}(r),$$

where U_C(r) is the coulomb potential due to a uniform distribution of appropriate size and total charge. The real term $U(r)$ is almost taken to have a volume form $-V_R f_R(r)$ with $f_R(r)=\{1+\exp[(r-R_R)/a_R]\}^{-1}$, the Wood-Saxon form factor. This real central term thus involves three parameters V_R, R_R and a_R. The imaginary central term $W(r)$ has been taken to have a surface and volume or a mixture of surface and volume term. Below proton energies of about 20 MeV the surface form is satisfactory and may have a Gaussian or Wood- Saxon derivative shape. At proton above 20 MeV, a volume term as well as a surface term seems to be necessary, but good agreement with experiment is achieved with $R_s= R_v$(say R_I) and $a_s=a_v$ (say a_I), leaving four parameters W_s, W_v , R_I and a_I for the imaginary central term. The spin-orbit term $[U_{so}+iW_{so}(r)]$, in the absence of convincing evidence to the contrary, it is usual to take $W_{so}=0$, leaving the three parameters V_{so}, R_{so}, and a_{so}. The model thus involves ten parameters although several analysis have been performed using more restricted sets by equating some of the geometrical parameters and/or neglecting one the imaginary terms. A nuclear optical model calculation of neutron elastic scattering using five parameters has been made. Appropriate estimates of the effect of compound elastic scattering at low energies are included [16].

The Folding Model

The folding model has been used for years to calculate the nucleon-nucleus optical potential. It can be seen from the basic folding formulas that this model generates the first-order term of the microscopic optical potential that is derived from Feshbach's theory of nuclear reactions. The success of this approach in describing the observed nucleon-nucleus elastic scattering data for many targets suggests that the first-order term of the microscopic optical potential is indeed the dominant part of the nucleon optical potential. The basic inputs for a single-folding calculation of the nucleon-nucleus potential are the nuclear densities of the target and the effective nucleon-nucleon (NN) interaction. If one has a well tested, realistic effective NN interaction, the folding model is a very useful approach to check the target nuclear densities. A popular choice for the effective NN interaction has been one of the M3Y interactions. Although these density *-independent* M3Y interactions were originally developed for use in the DWBA analysis of (p, p') reaction, they have been used much more often in the doublefolding calculation of the heavy-ion interaction potential at low and medium energies [17].

The real part of the optical potential for the nucleon–nucleus elastic scattering is given for the single folding model, in the following form

$$U_F(R) = \int dr_1 \rho_1(r_1) V(r), \quad (1)$$

where $r = R-r_1$, $\rho_1(r_1)$is the matter density distribution of the target nucleus, $V(r)$ is the effective NN-interaction. In the present calculation the effective NN-interaction is taken according to [18] in the form of M3Y-interaction

$$V(R) = 7999\frac{\exp(-4R)}{4R} - 2134\frac{\exp(-2.5R)}{2.5R} - 276(1-\frac{0.005E}{A_p})\delta(R) \quad . \quad (2)$$

The density of the ^{6}Li target nucleus is considered in the form [19]

$$\rho = \frac{6}{8\pi^{\frac{3}{2}}}(\frac{1}{a^3}\exp(-\frac{r^2}{4a^2}) - \frac{c^2(6b^2-r^2)}{4b^7}\exp(-\frac{r^2}{4b^2})). \quad (3)$$

Where a, b, and c are constants parameters and in the range: $a := \sqrt{0.87}$ fm, $b := \sqrt{1.7}$ fm and

$c := \sqrt{0.205}$ fm. The analytical form of the real part of the optical potential is obtained by substituting Eqs. (2), (3) and (4) into Eq. (1) and carrying out the required integrations over r_1. The real part of the optical potential for the nucleus–nucleus elastic scattering is given for the double folding model, in the following form:

$$U_F(R) = \int dr^3{}_1\, dr^3{}_2 \rho_p (r_1)\, \rho_t (r_2)\, V(r+r_1-r_2), \qquad (1')$$

where $\rho_p$is the projectile matter density distribution, $\rho_t$is the matter distribution of the target.
The nuclear density distribution of deuteron is taken from [20].The nuclear density distribution of ^{3}He is calculated by the form:

$$\rho = \frac{A}{Z \times a^3 \pi^{\frac{3}{2}}} \left(1 + 2\left(\frac{r^2}{a^2}\right) + \left(\frac{r}{a}\right)^4 \exp\left(-\frac{r^2}{b^2}\right)\right). \qquad (4)$$

Where a =1.80, A=3, and Z=2. By using DFPOT code we could calculate potential depth, radius and diffuseness.

Results and discussion

Protons scattering

Measurements of elastic scattering of protons on ^{6}Li nuclei in low energy region were carried out with using the extracted beam from UKP-2-1 accelerator of the Institute of Nuclear Physics (National Nuclear Center, Republic of Kazakhstan, Almaty, Kazakhstan) in the angular range 40-170˚. The proton energy varied in the range 400 – 1200 keV. The beam intensity was 200 – 300 nA. Scattered particles were detected using surface-barrier silicon counters.

The analysis of protons data, carried out in wide energy range, had shown that for ^{6}Li nuclei, the most suitable parameters values are r_0 = 1.05 fm, r_C= 1.3 fm, r_D= 1.923fm, a_s = 0.20fm and r_s=1.20 fm. In the analogous approach with the use of measured and literature data on the elastic scattering there are determined parameters of the potential of protons scattering on ^{6}Li - nuclei for the wide energy range from the analysis of these data on the optical model. Obtained parameters of optical potentials of the interaction are presented in Table 1. The description of experimental data comparing with calculated values, obtained in the present work, for the protons elastic scattering is given in Fig. 1. The relations between $V(W_D)$ versus E_p are linear. The strength parameters can be represented by: $V_0 = 56.10 - 0.61E_p$, $W_D = - 0.66 + 0.46E_p$,respectively (Fig. 2). Experimental data on elastic scattering of protons in the energy range above 3 MeV are taken from [21].

Table 1. Contains the phenomenological optical parameters for protons scattering on Lithium nuclei

E_p, MeV	V_0, MeV	r_0, fm	a_0, fm	W_D,MeV	r_D, fm	a_D, fm	V_S , MeV	r_s, fm	a_S, fm	J_R, MeVfm^3	J_w, MeVfm^3
0.746	59	1.05	0.85	0.300	1.923	0.575	9.30	1.077	0.66	490	20.47
0.975	57.2	1.050	0.67	0.355	1.923	0.650	9.30	1.020	0.200	475	22.19
1.136	54	1.05	0.52	0.355	1.923	0.57	9.30	1.020	0.200	454	22.19
3	52	1.05	0.52	0.87	1.923	0.80	9.30	1.020	0.200	437	55.72
5	50	1.05	0.50	1.18	1.923	0.57	15.6	1.020	0.200	407	75.58
10	49	1.05	0.65	2.78	1.923	0.49	12.2	1.020	0.770	391	148.3
14	46.5	1.05	0.50	6.72	1.923	0.42	9.86	1.020	0.200	378	304
25	38	1.05	0.50	2.80	1.923	0.80	5.57	1.020	0.200	270	309
29.5	34	1.05	0.67	2.93	1.923	0.80	3.37	1.020	0.200	149	111
35	34.7	1.05	0.65	2.93	1.923	0.80	3.37	1.020	0.200	142	111
45	30	1.05	0.65	2.63	1.923	0.80	2.33	1.020	0.200	122	100

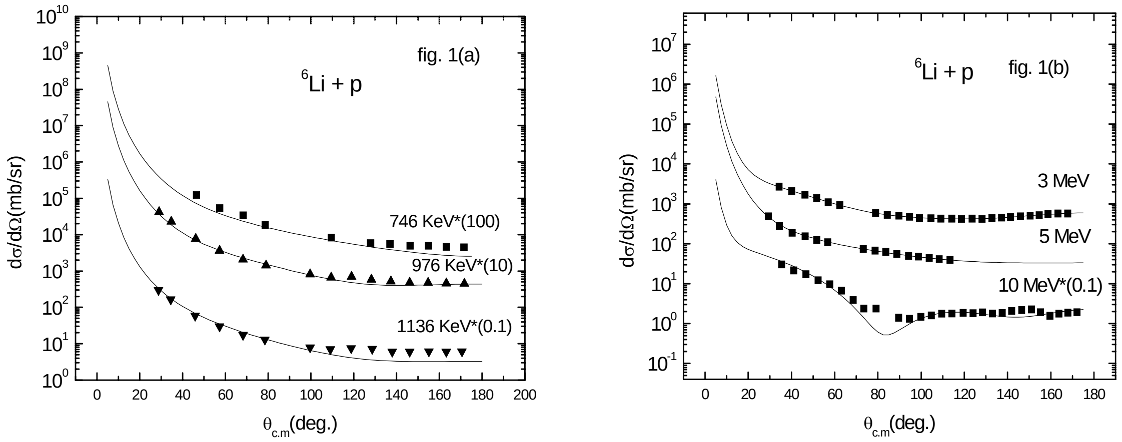

Fig.1. *a* and *b* show the comparison between calculated and experimental angular distribution of protons scattered from ^{6}Li at low energies where dots represent experimental data and lines represent the calculated values using optical model (OM)

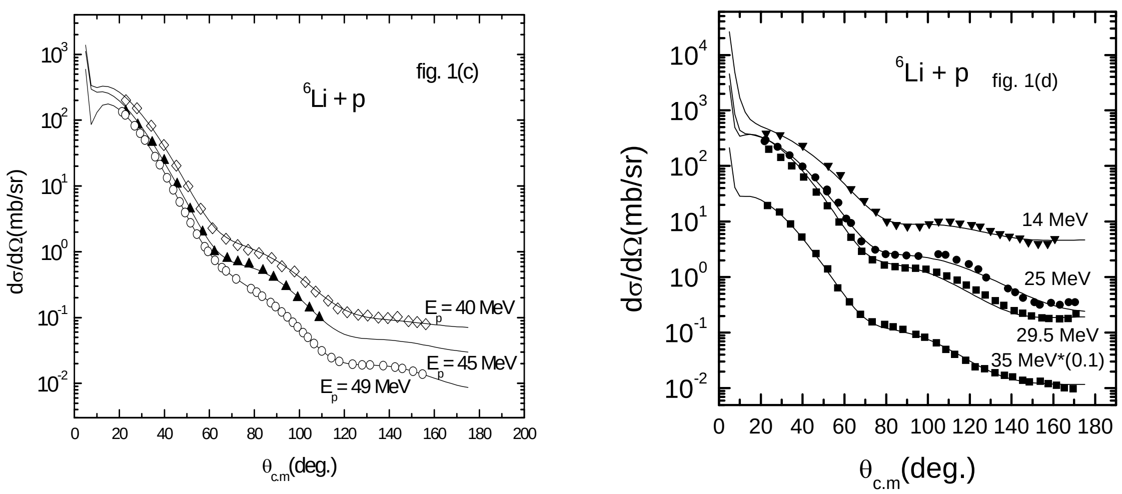

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Fig. 1c, 1d. Angular distribution of protons scattered from ^{6}Li where dots represent experimental data and lines represent the calculated values using OM

The imaginary central part of the optical potential consisted of a surface absorption term only. It was found that even at higher energies the inclusion of small volume absorption term did not improve the fits appreciably.

At low energies between 0.4 MeV and 1 MeV, the experimental data on the proton elastic scattering on ^{6}Lihave been also analyzed using single-folding model. The numerical calculations have been done using the DFPOT code. In the present calculation the effective NN-interaction is taken according to [18] in the form of M3Y-interaction. The variations of the real potential values according to the radius are directly put in to the calculations with the aid of this model, and the imaginary parts are defined by a phenomenological way. To be able to fit the calculations with the experimental data, the normalization factor and the imaginary potential parameters must be adjusted. The parameters obtained by single-folding model are shown in Table 2. This agreement might be improved by adjusting the normalization factor and imaginary potential parameters better.

We would like to mention that when we used another form of nuclear density with the same potential form we obtained V0 = 46MeV, a0 = 1.58fm and r0 = 0.56fm. So that the form of the density used is very important.

Table 2. Contains the parameters obtained using single-folding model for ^{6}Li

E_p, MeV	V_0, MeV	r_0, fm	a_0 , fm	W_D, MeV	r_D, fm	a_D, fm	W_S, MeV	r_S, fm	a_S, fm	J_{mic}, MeV fm^3	N_R
0.400	39.00	1.74	0.74	3.03	1.92	0.91	7.61	1.45	0.25	420.24	0.70
0.746	39.00	1.74	0.74	5.78	1.92	0.56	8.47	1.28	0.60	436.31	0.70
0.975	39.86	1.74	0.74	13.50	1.25	0.67	7.75	1.35	0.67	419.66	0.70

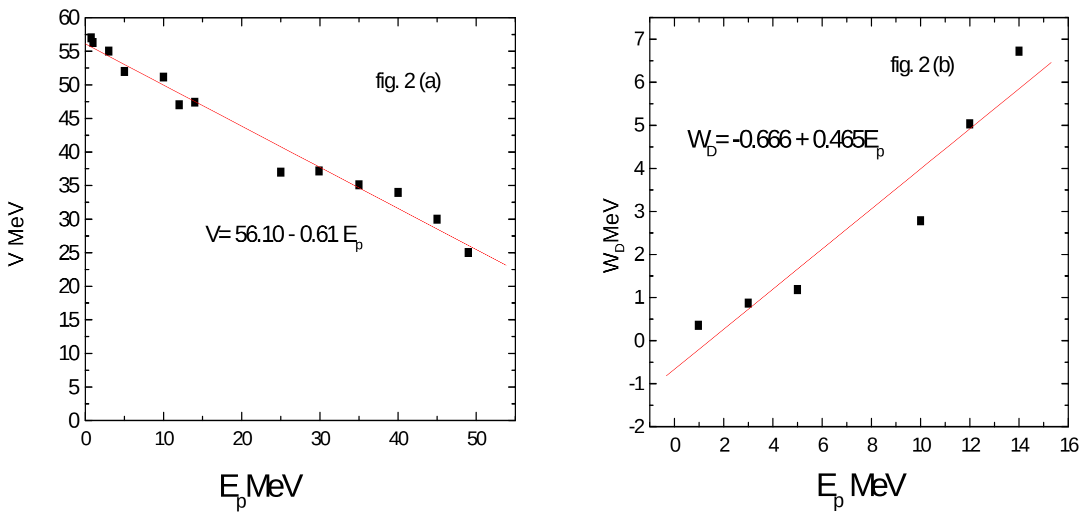


Fig. 2(a) and 2(b) show the linear relation between V_0, W_D and E_p for ^{6}Li respectively

Deuterons scattering

Deuterons have several special features that complicate the way they are scattered by nuclei. They are very loosely bound, and are therefore easily broken up when they encounter the nuclear field. The scattering is thus rather sensitive to the nuclear structure and it is corresponding more difficult to define overall optical potentials. The charge and mass centers of the deuterons are significantly separated and this give rise to forces tending to twist and break the deuteron even before it encounters the nuclear field. The nucleon potentials are to be taken at an energy one half of deuteron energy. Since the well-depth for the nucleon scattering is roughly 50 MeV, this leads to central potential of deuterons is about 100MeV. While experimental cross sections can be described with several discrete values (e.g. 50 MeV, 100 MeV, 150 MeV), the above argument leads to one to prefer 100 MeV deep potential [1].

Measurements of elastic scattering of deuterons on 6Li nuclei at Ed = 18 and 25 MeV [22] were carried out with cyclotron of the Institute of Nuclear Physics (National Nuclear Center, Republic of Kazakhstan, Almaty, Kazakhstan) in the angular range 5-175˚. Scattered particles were detected using surface-barrier silicon counters. The data on elastic scattering of deuterons in the energy range of E = 4-50 MeV [23-27] were also used in our analysis. The optical model parameters found for deuterons scattering on lithium nuclei are shown in Table 3. The analysis, carried out in wide energy range, had shown that for 6Li nuclei, the most suitable parameters values are r0 = 1.15 fm, rC= 1.3 fm, rD= 1.34 fm, as = 0.66 fm and rs= 1.35 fm. Figures 3 and 4 show the comparison between calculated and experimental angular distributions. As it is shown in Fig. 5, the strength parameters (V0, WD) in Table 3 can be represented by: V0 = 76.33 - 0.59Ed and WD = 0.327 + 0.352Ed– 0.004Ed2. WS, as it can be seen from the Table, near energy independent.

Table 3. Contains optical phenomenological parameters calculated for deuterons scattering on ^{6}Li

E_d, MeV	V_0, MeV	r_0, fm	a_0, fm	W_D, MeV	r_D, fm	a_D, fm	W_S MeV	r_C, fm	a_S, fm	J_R, MeV fm^3	J_w , MeV fm^3
4	78	1.15	0.82	1.13	1.34	0.62	12.86	1.34	0.69	356	11.93
6	71.68	1.15	0.80	2.48	1.34	0.65	6.75	1.35	0.66	324	26.18
9	66	1.15	0.79	2.75	1.34	0.90	7.89	1.35	0.66	289.66	54.60
14.7	65	1.15	0.80	10.5	1.34	0.65	7.90	1.34	0.65	285.32	119.43
18	68.88	1.15	0.87	6.42	1.34	0.79	9.84	1.34	0.65	282.35	111.69
19.6	64	1.15	0.81	5.75	1.34	0.89	11.52	1.34	0.65	275.63	115
25	61	1.15	0.82	5.84	1.34	0.90	14.44	1.34	0.66	284.82	115.96
50	57.47	1.15	0.83	5.97	1.34	0.90	6.76	1.38	0.66	266	112

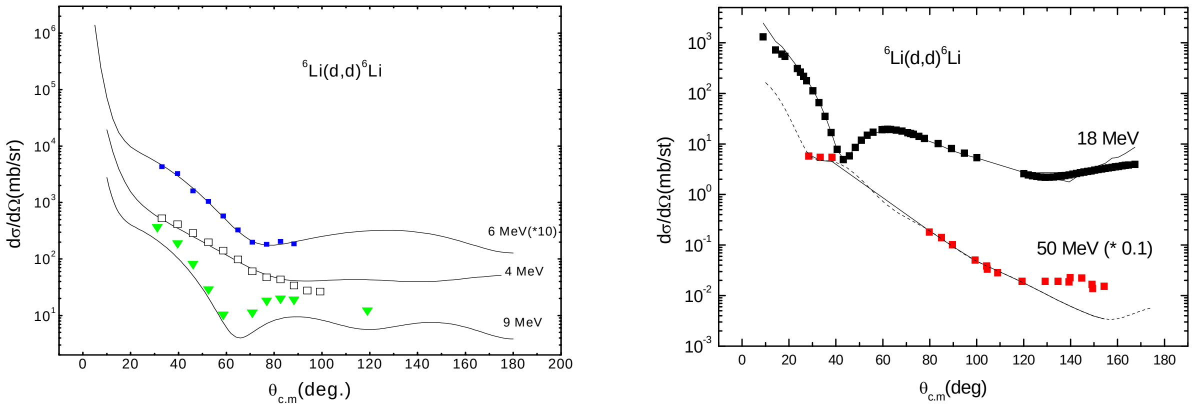


Fig. 3. Shows the comparison between calculated and experimental angular distributions of deuterons elastic scattering from ^{6}Li

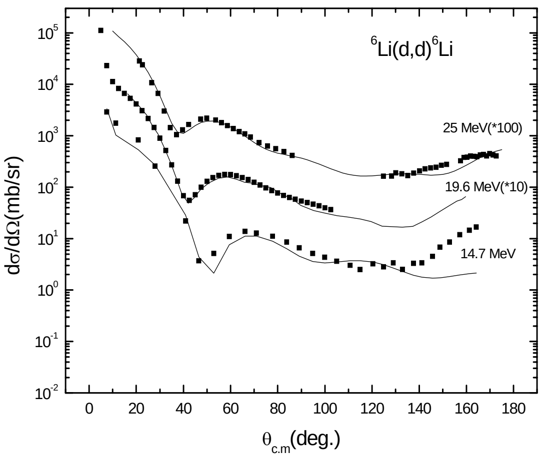
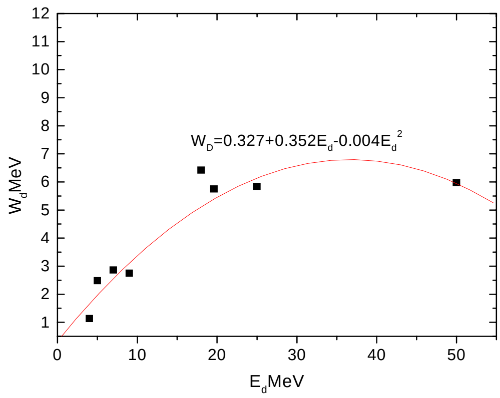


Fig. 4 shows the comparison between calculated (solid lines) and experimental angular distribution of deuterons (points) elastic scattering from ^{6}Li at the energies of 14.7, 19.6 and 25 MeV



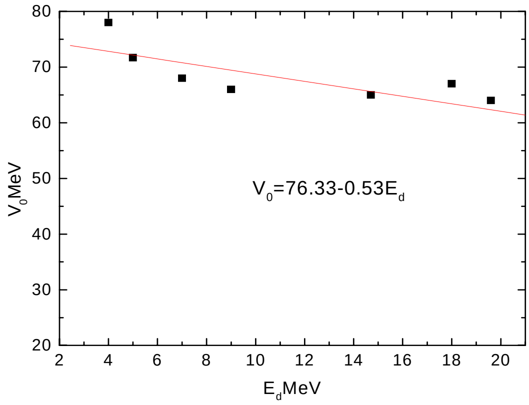


Fig. 5 shows the energy dependence V_0, $W_D$for ^{6}Li + *d*

The experimental data of differential cross section of scattering of deuterons on ^{6}Libetween 4 MeV and 50 MeV have been also analyzed using double folding model. The numerical calculations have been done using the DFPOT code. In the present calculations, we have derived different analytical expressions for the real part of the optical potential in the frame of double folding model. The variations of the real potential values according to the radius are directly put in to the calculations with the aid of this model, and the imaginary parts are defined by a phenomenological way. To be able to fit the calculations with the experimental data, the normalization factor and the imaginary potential parameters must be adjusted. We will concern here on energy of 18 MeV using semi-microscopic double-folding model. Obtained potential parameters are shown in the Table 4.

Table 4. Contains the parameters obtained using double folding model for deuterons elastically scattering on ^{6}Li.

E_d, MeV	V_0, MeV	r_0, fm	a_0, fm	W_D, MeV	r_D, fm	a_D, fm	V_S, MeV	R_S, fm	a_S, fm	J_{mic}, MeV fm^3	N_R
18	63.8	1.21	0.89	9.38	1.34	0.65	8.00	1.34	0.65	360.81	0.78

From table 4 we could enhance the results on radius r_0 = 1.21 fm obtained from double-folding model. The comparison of experimental angular distribution with calculated cross sections is presented on Fig. 6. The experimental increase in the elastic scattering at backward direction, as it is seen from the figure, may be a manifestation of the well-known mechanism of the elastic α-particle transfer ^{6}Li(*d*, ^{6}Li)*d*. This mechanism is well reproduced by DWBA calculation shown in Fig. 6 with dashed line.

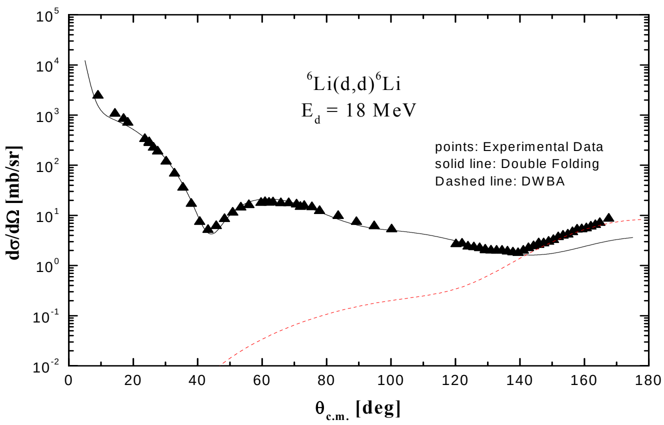


Fig. 6 shows the comparison of experimental angular distribution for the deuteron elastic scattering on ^{6}Li at 18 MeV (dots) with theoretical values (solid line) calculated with potential from Table 4 with using the double folding model

It is known that by the interaction of complex particles with light nuclei there is often observed the specific effect, called as an anomalous large-angle scattering (ALAS), which it is impossible to explain in the framework of the standard optical model [28-30].The nature of this phenomenon can be caused by different reasons, but in certain cases when, for example, targets are ^{6}Li and ^{7}Linuclei, having the pronounced cluster *(a + d* and *a + t)* structure, the increase of cross-sections at large angles is almost entirely connected with the cluster exchange mechanism, physically undistinguished from potential scattering. So, in order to obtain optical potentials from data on scattering it is necessary directly to take into account the contribution of exchange mechanisms apart from potential scattering. The purpose of the present work is the obtaining of reliable information about potential parameters for interaction of light charged particles with ^{6}Li nuclei from the optical model analysis of elastic scattering taking into account cluster exchange effects, the investigation of energy dependence of these parameters as well as studying the double folding in our case. This will be useful to carry out cross-sections calculations for charged particles, being of great significance for thermonuclear and astrophysical applications.

^{3}He scattering

The analysis of ^{3}He data, carried out in wide energy range, had shown that for ^{6}Li nuclei, the most suitable parameters values are r_0 = 1.15 fm, r_C= 1.3 fm, r_D = 1.25fm, a_S= 0.85 fm and r_S= 1.25 fm. The experimental data on ^{3}He elastic scattering from the ^{6}Li – nucleus, obtained in [31, 32], is given in figures 7- 8. Optical model parameters and DWBA calculations for the mechanism of the elastic triton cluster transfer have been made by us [32] and we will concern only at the double folding analysis. The numerical calculations using double folding model for ^{6}Li + ^{3}He have been done using the DEPOT code. Results on obtained potentials are shown in the Table 5. Comparison with the experimental data is presented in figures 7-8. The dashed curves in the figures represent the DWBA calculations for the triton exchange mechanism. The good overall agreement is seen on the figures. The real well depth (V_0), as it is shown in Fig.9, linearly depends on energy of ^{3}He: $V_0 = 127.345 – 0.358E_{3He}$.

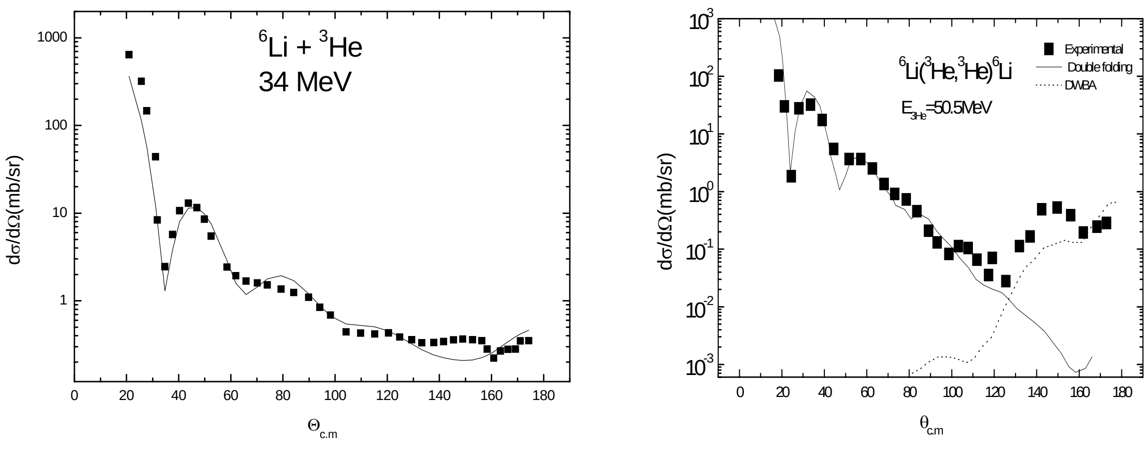


Fig. 7 show the comparison between calculated (using double folding) and experimental angular distribution of^{3}He scattered from ^{6}Li at 34 and 50.5 MeV where dots represent experimental data and line represents the calculated values.

Table 5 contains the parameters obtained using Double folding model for ^{3}He and ^{6}Li

E_{3He} MeV	V_0, MeV	r_0, fm	a_0, fm	W_D, MeV	r_D, fm	a_D, fm	V_S, MeV	R_S, fm	a_S, fm	N_R
72	110.72	1.12	0.90	16.50	1.46	0.87	5.36	1.25	0.83	1.01
60	95.95	1.12	0.755	30.67	1.25	0.578	6.57	1.25	0.777	0.949
50	107.33	1.12	0.99	18.39	1.92	0.77	12.39	1.25	0.90	0.841
34	120.8	1.12	0.81	20.21	1.25	0.64	15.93	1.25	0.64	

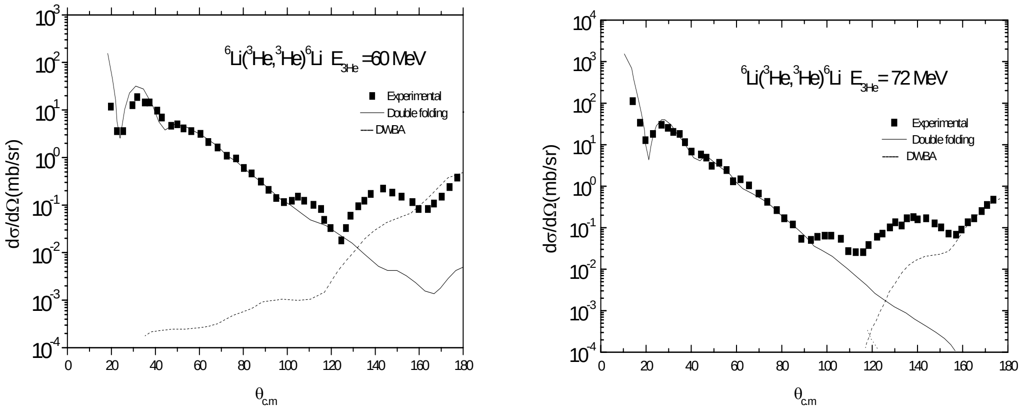


Fig. 8 shows the comparison between calculated (using double folding and DWBA) and experimental angular distribution of ^{3}He scattered from ^{6}Li at 60 and 72 MeV where dots represent experimental data and lines represent the calculated values

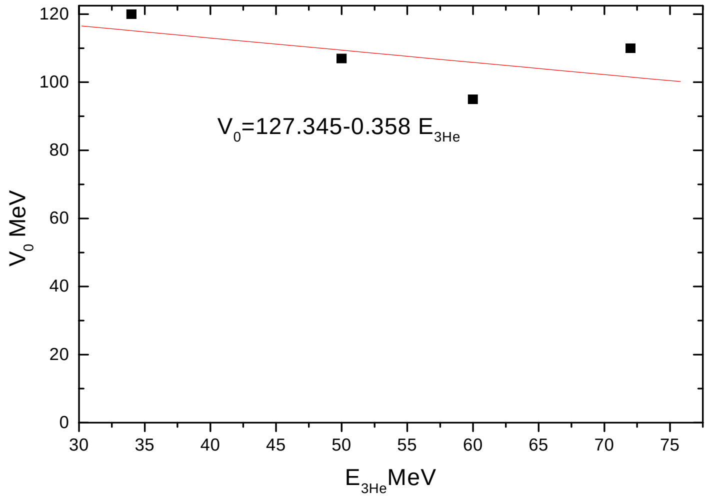


Fig. 9 shows the energy dependence of V_0 for ^{6}Li + ^{3}He

We will extend our work to calculate the double folding of α+^{6}Li depending on an excellent analysis for α + ^{6}Li that have been made by Sakutaet. al [33].

Conclusion

In general we started these calculations in spite of we made it phenomenological but now we want to calculate the potential using double folding model. The main idea is to prove that the potential depth depends on the number of incident nucleons. We calculated single folding for proton ^{6}Li interaction and obtained the potential depth 39 MeV. Thus we can expect that potentials for *d* + ^{6}Liand ^{3}He + ^{6}Liinteraction will be twice and three times as large as for *p* + ^{6}Liinteraction. We obtained the potential depths for deuteron and ^{3}He as 76 and 127 MeV, respectively. These values are close to predicted ones. We will try to calculate the potential depth of ^{4}He and ^{6}Li using double-folding model and we expect it to be lower than 160 MeV as systematic variation because ^{4}He has no spin.

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АНАЛИЗ УПРУГОГО РАССЕЯНИЯ p, d И ^{3}He НА ЯДРЕ ^{6}Li

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Анализ упругого рассеяния p, d и ^{3}He на ядре ^{6}Li был проделан в рамках оптической модели при разных энергиях пучка. Упругое рассеяние p, d and ^{3}He на ядре ^{6}Li при разных энергиях анализировалась в рамках модели свёртки. В качестве эффективного нуклон-нуклонного потенциала использовалось m3y взаимодействие, расчеты по DWBA для механизма упругой передачи тритон кластера использовался Dwuck5

p, d ЖӘНЕ ^{3}He ИОНЫНЫҢ ^{6}Li ЯДРОСЫНДА СЕРПІМДІ ШАШЫРАУЫН ТАЛҚЫЛАУ

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p, d және ^{3}He ионының ^{6}Li ядросында серпімді шашырауы әр түрлі энергияларда оптикалық моделі аясында жасалды. p, d and ^{3}He ионының ^{6}Li ядросында серпімді шашырауы бүктеме моделі бойынша тұжырымдалынып көрінді. Эффективті нуклон-нуклондық потенциал ретінде m3y әсерлесуі қолданылды, DWBA бойынша серпімді тритон кластерлік алмасу үшін Dwuck5 пайдаланылды.