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Systematic Study of the p, d and ^{3}He Elastic Scattering on ^{6}Li

A. Amar, N. Burtebayev, Kerimkulov Zhambul, Sh. Hamada, and N. Amangeldi

***Abstract*—**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.

***Keywords*—**Elastic scattering, Esis88 Code single and double folding model, phenomenological, DWBA.

I. 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.

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].

A. Amar is with Faculty of Physics, Kazakh National University, Almaty, Kazakhstan. Phone: 8707-356-99-41; (e-mail:_amar.physics@yahoo.com)

N. Burtebayev is with the Institute of Nuclear Physics of National Nuclear Center, Almaty, Kazakhstan. (e-mail: nburtebayev@yandex.ru)

Kerimkulov Zhambul is with the Institute of Nuclear Physics of National Nuclear Center, Almaty, Kazakhstan(e-mail: jambul@inp.kz)

Sh. Hamada is with Faculty of Physics, Kazakh National University, Almaty, Kazakhstan. Phone: 8707-344-7658; fax: 8707-356-99-42; (e-mail: sh.m.hamada@gmail.com).

N. Amangeldi is with the Eurasia National University, Astana, Kazakhstan. (e-mail: nur19792@mail.ru).

Appropriate estimates of the effect of compound elastic scattering at low energies are included [16].

II. Folding Model

The folding model has been used for years to calculate the nucleon-nucleus optical potential. A popular choice for the effective NN interaction has been one of the M3Y interactions [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 $r = R\text{-}r_1$, $\rho_1(r_1)$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

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

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:

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

where ρ_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 using the form:

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

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

III. Results And Discussions

A. 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. 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 strength parameters can be represented by: $V_0 = 56.10 - 0.61E_p$, $W_D = -0.66 + 0.46E_p$, respectively. Experimental data on elastic scattering of protons in the energy range above 3 MeV are taken from [21].

TABLE I Contains The Phenomenological Optical Parameters For Protons Scattering On Lithium Nuclei

E_p, MeV	V_0, MeV	a_0, fm	W_D MeV	aD, fm	VS, MeV	rs, fm	aS, fm	J_R, MeVfm3	Jw, MeVfm3
0.746	59	0.85	0.300	0.575	9.30	1.077	0.66	490	20.47
0.975	57.2	0.67	0.355	0.650	9.30	1.020	0.200	475	22.19
1.136	54	0.52	0.355	0.57	9.30	1.020	0.200	454	22.19
3	52	0.52	0.87	0.80	9.30	1.020	0.200	437	55.72
5	50	0.50	1.18	0.57	15.6	1.020	0.200	407	75.58
10	49	0.65	2.78	0.49	12.2	1.020	0.770	391	148.3
14	46.5	0.50	6.72	0.42	9.86	1.020	0.200	378	304
25	38	0.50	2.80	0.80	5.57	1.020	0.200	270	309
29.5	34	0.67	2.93	0.80	3.37	1.020	0.200	149	111
35	34.7	0.65	2.93	0.80	3.37	1.020	0.200	142	111
45	30	0.65	2.63	0.80	2.33	1.020	0.200	122	100
49	26	0.65	1.69	0.80	1.69	1.020	0.200	64	106

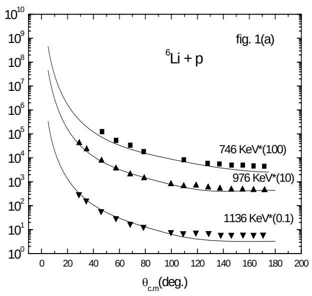


Fig.1 shows the comparison between calculated and experimental angular distribution of protons scattered from ^{6}Li at low energies where dots represent experimental data and lines represent the calculated values using optical model (OM).

At low energies between 0.4 MeV and 1 MeV, the experimental data on the proton elastic scattering on ^{6}Li have been also analyzed using single-folding model. The parameters obtained by single-folding model are shown in Table 2.

TABLE II
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)	V_s (MeV)	r_s (fm)	a_s (fm)	J_{mic}	N_R (MeV.fm^3)
0.4	39.0	1.74	0.74	3.03	1.92	0.91	7.61	1.45	0.25	420.24	0.70
0.74	39.0	1.74	0.74	5.78	1.92	0.56	8.47	1.28	0.60	436.31	0.70
0.975	39.0	1.74	0.74	5.78	1.92	0.56	8.47	1.28	0.60	436.31	0.70

B. Deuterons scattering

Measurements of elastic scattering of deuterons on ^{6}Li nuclei at E_d = 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 ^{6}Li nuclei, the most suitable parameters values are r_0 = 1.15 fm, r_C= 1.3 fm, r_D= 1.34 fm, a_s = 0.66 fm and r_s= 1.35 fm. The strength parameters (V_0, W_D) in Table 3 can be represented by: V_0 = 76.33 - 0.59E_d and $W_D = 0.327 + 0.352E_d - 0.004E_d^2$.

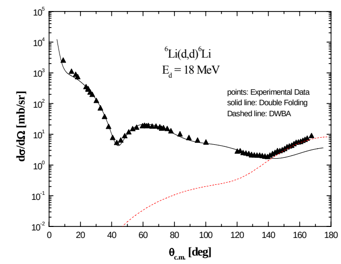


Fig. 2 shows the comparison of experimental angular distribution for the deuteron elastic scattering on ^{6}Li at 18 MeV (dots) with theoretical values (solid line) calculated with potential from Table IV with using the double folding model, DWBA calculation shown with dashed line.

TABLE III 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

The experimental data of differential cross section of scattering of deuterons on ^{6}Li between 4 MeV and 50 MeV have been also analyzed using double folding model. We will concern here on energy of 18 MeV using semi-microscopic double-folding model. Obtained potential parameters are shown in the Table 4.

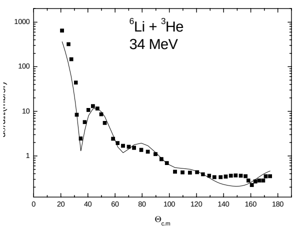
TABLE IV CONTAINS THE PARAMETERS OBTAINED USING DOUBLE FOLDING MODEL FOR DEUTERONS ELASTICALLY SCATTERING ON ^{6}LI

E_d,	V_0	r_0	a_0	W_D	r_D	a	V_S	R_S	a_S	J_m	N_R
18	**63.8**	**1.21**	**0.89**	**9.38**	**1.34**	**0.65**	**8.00**	**1.34**	**0.65**	**360.8 1**	**0.78**

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. 2 with dashed line.

C. ^{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, $r_D = 1.25$fm, $a_S = 0.85$ fm and $r_S = 1.25$ fm. The experimental data on ^{3}He elastic scattering from the ^{6}Li – nucleus, obtained in [28, 29], is given in figure 3. Optical model parameters and DWBA calculations for the mechanism of the elastic triton cluster transfer have been made by us [30] 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 3. The dashed curves in the figures represent the DWBA calculations for the triton exchange mechanism.



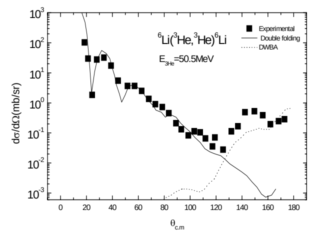


Fig. 3 show the comparison between calculated (using double folding) and experimental angular distribution of^{3}He scattered from ^{6}Li at 34 and 50.5 MeV where dots represent experimental data and line represents the calculated values.

TABLE IV CONTAINS THE PARAMETERS OBTAINED USING DOUBLE FOLDING MODEL FOR ^{3}HE AND ^{6}LI

E_{3He}	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**	

IV. 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}Li and ^{3}He + ^{6}Li interaction will be twice and three times as large as for *p* + ^{6}Liinteraction. We obtained the potential depths for deuterons 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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