

## COUPLED-CHANNELS ANALYSIS OF ${}^6\text{Li}$ SCATTERING FROM ${}^{54}\text{Fe}$

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Differential cross sections for the elastic and inelastic scattering of  ${}^6\text{Li}$  at 38, 44 and 50 MeV from  ${}^{54}\text{Fe}$  are analysed applying the Watanabe superposition model to the real potential with a phenomenological imaginary potential. The real potential of  ${}^6\text{Li}$  ions is calculated in terms of alpha-particle and deuteron or triton and helion optical potentials. The calculated cross sections seem to be more consistent with the triton-helion model.

### *1. Introduction*

In a previous work<sup>1)</sup>, coupled-channels analysis of  ${}^{12}\text{C}$  and  ${}^7\text{Li}$  scattering have been made using the Watanabe superposition model. The optical potentials of  ${}^{12}\text{C}$  and  ${}^7\text{Li}$  ions were calculated in terms of the alpha-particle and triton optical potentials. Good fits to the experimental data and the phenomenological calculations were obtained for  ${}^{12}\text{C}$  projectiles. This may be due to the large binding energy of  ${}^{12}\text{C}$  against three-alpha break-up. One of the common properties of  ${}^6\text{Li}$  and  ${}^7\text{Li}$  is that they are weakly bound and with low thresholds for the break-up of  ${}^6\text{Li}$  and  ${}^7\text{Li}$  into alpha and deuteron clusters and alpha and triton clusters, respectively. It has been shown that the corrections to the elastic scattering of  ${}^6,{}^7\text{Li}$  projectiles due to the break-up effects are important<sup>2,3)</sup>.

Bergstrom<sup>4)</sup> has calculated the electromagnetic form factors of the ground and low excited states of  ${}^6\text{Li}$  using the alpha-deuteron and triton-helion cluster models for  ${}^6\text{Li}$  nucleus. It was found that the longitudinal form factors are adequately described by the alpha-deuteron model, but the transverse form factors seem

to be more consistent with a triton-helion model which is close to the shell model limit.

In the present work the data for  ${}^6\text{Li} + {}^{54}\text{Fe}$  elastic scattering and inelastic scattering at 38, 44 and 50 MeV to the  $2^+$ , 1.41 MeV state in  ${}^{54}\text{Fe}$  are analysed applying the Watanabe superposition procedure to the real potential with a phenomenological Wood-Saxon imaginary potential. The alpha-deuteron and triton-helion cluster models for  ${}^7\text{Li}$  nucleus of binding energies 1.47 MeV and 15.7 MeV, respectively, are used. The resulting differential cross sections are compared with the experimental data as well as the phenomenological calculations.

## 2. Analysis

The elastic and inelastic scattering differential cross sections of  ${}^6\text{Li}$  ions from  ${}^{54}\text{Fe}$  are calculated using the coupled-channels code *CHUCK*<sup>5)</sup>. The code *CHUCK* calculates the Coulomb and nuclear form factors as described in the previous work<sup>1)</sup>. The present calculations have been made using the phenomenological optical potential of Woods-Saxon form given in Table 1. Then the real part of the optical potential is substituted by the Watanabe potential. On the basis of the Watanabe superposition model, the optical potential of  ${}^6\text{Li}$  ions is expressed in terms of the triton and helion potentials as follows<sup>6)</sup>:

$$U_{6L}(r) = U_{t\text{-folded}}(r) + U_{h\text{-folded}}(r) \quad (1)$$

where

$$U_{t(h)\text{-folded}}(r) = U_{t(h)}(r) + \frac{7}{72\gamma} \left[ \frac{d^2 U_{t(h)}(r)}{dr^2} + \frac{2}{r} \frac{dU_{t(h)}(r)}{dr} \right]$$

with<sup>4)</sup>  $\gamma = 0.21 \text{ fm}^{-1}$ . Here  $U_t$  and  $U_h$  are the triton and helion optical potentials, respectively. The potential for  ${}^6\text{Li}$  projectiles can be expressed in terms of alpha-particle and deuteron potentials as<sup>6)</sup>:

$$U_{6Li}(r) = U_{\alpha\text{-folded}}(r) + U_{d\text{-folded}}(r) \quad (2)$$

where:

$$U_{\alpha\text{-folded}}(r) = U_{\alpha}(r) + \frac{7}{144\beta} \left[ \frac{d^2 U_{\alpha}(r)}{dr^2} + \frac{2}{r} \frac{dU_{\alpha}(r)}{dr} \right]$$

$$U_{d\text{-folded}}(r) = U_d(r) + \frac{7}{36\beta} \left[ \frac{d^2 U_d(r)}{dr^2} + \frac{2}{r} \frac{dU_d(r)}{dr} \right]$$

and<sup>7)</sup>  $\beta = 0.1989 \text{ fm}^{-2}$  and  $U_{\alpha}$  and  $U_d$  are the alpha-particle and deuteron optical potentials, respectively.

TABLE 1.

Reaction	Energy	$V_0$	$r_0$	$a_0$	$W_T$	$r_T$	$a_j$	$r_{oc}$
${}^6\text{Li} + {}^{54}\text{Fe}$	38, 44 50	201.0	1.19	0.83	22.3	1.73	0.72	1.439

The phenomenological optical potential parameters used in Figs. 1 and 2. They are parametrized in the form:  $U(r) = -V_0 f(r) - iW_T g(r)$ , where  $f(r) = \left[1 + \exp\left(\frac{r - R_0}{a_0}\right)\right]^{-1}$ ,  $g(r) = \left[1 + \exp\left(\frac{r - R_T}{a_T}\right)\right]^{-1}$  and  $R_x = r_x A_T^{1/3}$ . These parameters are taken from Ref. 8. All lengths are in fm and energies in MeV.

### 3. Results and discussion

The differential cross section angular distributions for elastic scattering and inelastic scattering to the  $2^+$ , 1.41 MeV state of  ${}^{54}\text{Fe}$  by  ${}^6\text{Li}$  projectiles at 38, 44 and 50 MeV incident energy are calculated simultaneously using the coupled-channels code *CHUCK*. The radial integrals have been carried out to 40 fm in 0.1 fm steps with 125 partial waves. The Coulomb potentials used here are those of uniformly charged spheres of radii  $R_c = r_{oc}(A_T^{1/3} + A_P^{1/3})$  where  $A_T$  and  $A_P$  are the mass numbers of the target and projectile, respectively.

The phenomenological optical potential for  ${}^6\text{Li} + {}^{54}\text{Fe}$  scattering given in Table 1<sup>8)</sup> is used in the present calculations. The Coulomb and nuclear deformation lengths used in the present calculations, namely  $\delta_2^c = 0.72$  fm, and  $\delta_2^N = 0.667$  fm, are taken from  ${}^7\text{Li} + {}^{54}\text{Fe}$ <sup>1)</sup>. Using the relations given in the previous work<sup>1)</sup> together with the parameters of Table 1 yields the Coulomb and nuclear deformation parameters  $\beta_2^c = 0.1324$ ,  $\beta_2^N(\text{Re}) = 0.1483$  and  $\beta_2^N(\text{Im}) = 0.102$ , where the same notations as in the previous work are used.

TABLE 2.

Reaction	Energy	$V_0$	$r_0$	$a_0$	$\delta_2^N(\text{Re})$
$t + {}^{54}\text{Fe}$	20.0	167.1	1.14	0.717	0.1548
$h + {}^{54}\text{Fe}$	22.0	96.8	1.069	0.873	0.1651
$\alpha + {}^{54}\text{Fe}$	29.6	192.6	1.31	0.59	0.1347
$d + {}^{54}\text{Fe}$	14.5	92.58	1.15	0.81	0.1535

The optical potential parameters and the associated deformation parameters for the triton, helion, alpha-particle and deuteron used in the Watanabe calculations shown in Figs. 1 and 2. Parametrization as in Table 1. These parameters are taken from Ref. 9.

Expressions (1) or (2) represent the Watanabe potential of  ${}^6\text{Li}$  ions in terms of the triton and helion or the alpha-particle and deuteron potentials, respectively.

Here  $U_D$ ,  $U_h$ ,  $U_\alpha$  and  $U_d$  included in expressions (1) and (2) are taken as the Woods-Saxon phenomenological potentials given in Table 2. These potentials are chosen from several sets of optical potentials for the triton, helion, alpha-particle and deuteron given by Perey and Perey<sup>9)</sup>. The potentials used here are of the largest diffuseness of the available potentials where the errors due to Taylor expansions used in deriving expressions (1) and (2) are expected to be minimum<sup>10)</sup>.

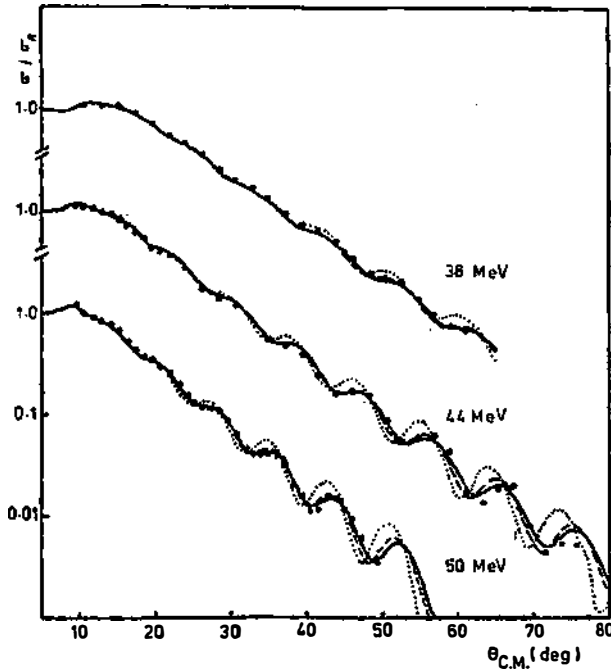


Fig. 1. The ratio to the Rutherford elastic scattering cross sections for  $\text{Li} + {}^{54}\text{Fe}$  at 38, 44 and 50 MeV. The full curves represent the calculations using the phenomenological potential with the parameters given in Table 1. The broken and dotted curves represent the calculations using the triton-helion and alpha-deuteron Watanabe potentials of expressions (1) and (2), respectively, with the parameters given in Table 2 for the real potential. The points represent the experimental data taken from Refs. 8 and 11.

The real part of  ${}^6\text{Li}$  potential calculated by expressions (1) or (2) together with the imaginary part of the  ${}^6\text{Li}$  potential given in Table 1 are used to calculate the differential cross sections for  ${}^6\text{Li} + {}^{54}\text{Fe}$  scattering. The resulting angular distributions for the elastic scattering and of inelastic scattering to the  $2^+$ , 1.41 MeV state in  ${}^{54}\text{Fe}$  are shown in Figs. 1 and 2, respectively, compared with the experimental data and the predictions of the phenomenological optical potential given in Table 1<sup>8,11)</sup>. In the case using the Watanabe potentials of expressions (1) or (2), the deformation parameters of the real potential are chosen so that the deformation lengths equal the deformation length of the real phenomenological potential. This yields the associated deformation parameters for the triton, helion, alpha-particle and deuteron potentials given in Table 2.

Figs. 1 and 2 show that the cross sections calculated with the triton-helion model of  ${}^6\text{Li}$  are in good agreement with the experimental data and the phenomenological calculations. The cross sections calculated using the alpha-deuteron model agree fairly with the experimental data at 38 MeV and oscillate around the experimental data and the phenomenological calculations at 44 and 50 MeV. These oscillations may be due to the break-up effects which are important in this case<sup>2)</sup>. Such effects are likely to increase as the incident energy increases.

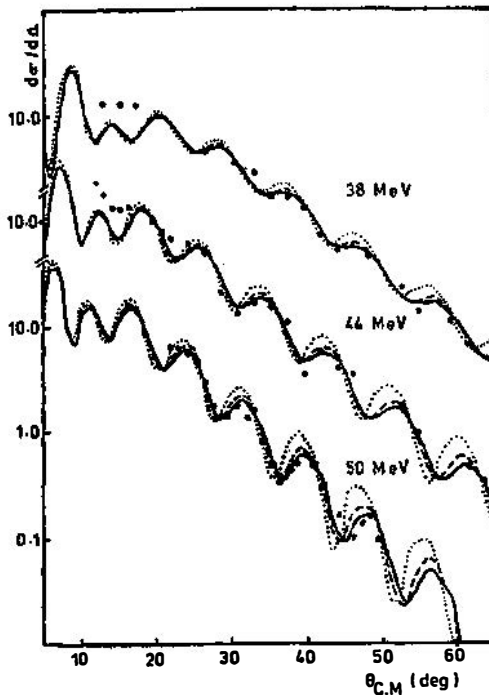


Fig. 2. The same as Fig. 1, but for the inelastic scattering cross section (in  $\text{m}^{-31} \text{sr}^{-1}$ ) of  ${}^6\text{Li}$  to the  $2^+$ , 1.41 MeV state in  ${}^{54}\text{Fe}$ .

Finally, the differential cross sections of  ${}^6\text{Li}$  scattering from  ${}^{54}\text{Fe}$  seem to be more consistent with the triton-helion model where the binding energy is more than ten times of the binding energy in case of the alpha-deuteron model.

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ANALIZA RASPRŠENJA  ${}^6\text{Li}$  NA  ${}^{54}\text{Fe}$  METODOM VEZANIH KANALA

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Diferencijalni udarni presjeci elastičnog i neelastičnog raspršenja  ${}^6\text{Li}$  na  ${}^{54}\text{Fe}$  pri energijama of 38, 44 i 50 MeV analiziraju se pomoću Watanabe-ovog superpozicijskog modela koji se koristi za konstrukciju realnog potencijala; imaginarni potencijal je fenomenološki. Realni potencijal je računat za dvije moguće konfiguracije  ${}^6\text{Li}$ : konfiguracija  $\alpha + d$  i konfiguracija  ${}^3\text{He} + t$ . Potencijal ovom posljednjom konfiguracijom daje rezultate koji se slažu s eksperimentom.