Non-monotonic potential description of the cross-section, vector and tensor analyzing powers of the $^6$Li+$^{12}$C elastic scattering at 30 and 50 MeV†

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Abstract. This work illustrates, for the first time, the analysis of tensor analyzing powers ($T_{20}$, $T_{21}$, $T_{22}$) along with the differential cross-section (CS) and the vector analyzing power $iT_{11}$ for the $^6$Li+$^{12}$C elastic scattering at 30 and 50 MeV within the framework of an optical model (OM) using microscopic shallow non-monotonic (NM) potentials. The NM potential is generated from the energy density functional formalism (EDF) [Brueckner et al., Phys. Rev. 168 (1968) 1184] using a realistic two-nucleon interaction incorporating Pauli Exclusion principle. The shallow NM potential can describe the experimental angular distributions of CS and analyzing powers of the elastic scattering data. The OM analysis of the data at this energy does not indicate their sensitivity on the nuclear matter incompressibility $K$.

1. Introduction

Elastic scattering is the simplest nuclear reaction between a projectile and a target that can be induced by a hadronic interaction. It is treated as a doorway through which the system must go before other processes are manifest. The standard framework for the study of elastic scattering is the optical model (OM). The first step in the description of the collision of two nuclei is the introduction of a simple one-body potential (optical potential) that describes some average features of the collision. The real part of the OM potential represents the elastic scattering whereas the imaginary part takes into account the loss of the flux i.e. the absorption.

The investigation of $^6,^7$Li, with their transitional features between light and heavy ions, has been of considerable interest for the last few decades. Lithium induced reactions, e.g. ($^6$Li, d), ($^7$Li, t) play an important role in nucleosynthesis involving transitions from $^{12}$C to $^{16}$O etc. [1]. Also, the investigation of elastic scattering of $^6$Li projectile is of considerable interest because this ion with a mass number $A = 6$ lies between light ions ($A \leq 4$) and heavy ions ($A \leq 12$) and is expected to exhibit transitional features [2] between the light and heavy ions. Knowledge of projectile-target potential between lithium-isotopes and other nuclei may hold the key to shed some light on our present understanding of stellar nucleosynthesis.

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Standard optical model (OM) potentials like phenomenological Wood-Saxon (WS) [3, 4], squared WS (SWS) [5] and double folding (DF) [5] potentials are usually deep and monotonic. The DF approach [9] using a realistic nucleon-nucleon (NN) M3Y potential [6], which does not contain a tensor component.

The DF potentials of \(^{6,7}\)Li in the framework of the OM model need an arbitrary normalization factor of \(N_E = 0.5 - 0.7\) [7, 8] for the description of the elastic scattering cross section (CS) and are unable to account for the opposite signs of vector analyzing powers (VAPs) \(iT_{11}\) of \(^{6}\)Li and \(^{7}\)Li elastic scattering at the same incident energy by \(^{58}\)Ni at 20 MeV and \(^{120}\)Sn at 44 MeV. These deficiencies can only be resolved in complicated coupled-channels calculations [9, 10].

Microscopic potential, derived from the energy density functional (EDF) theory [11] which incorporates the Pauli effect of anti-symmetrization microscopically, has been found to be non-monotonic (NM) and shallow [12]. Apart from accounting well for the detailed feature of the \(\alpha\) elastic scattering [12 and references therein], NM potentials have also been found successful in reproducing the correct order of CS for \(\alpha\) induced non-elastic processes [13, 14, 15] including the (\(\alpha, p\)) reaction. Simple OM calculations using the EDF-generated potentials can describe the correct CS without the need of renormalization and can reproduce the correct signs of VAPs for the \(^{6}\)Li and \(^{7}\)Li elastic scattering [16]. The NM potentials have also enjoyed success in accounting for the experimental data of the \(\alpha^{+90}\)Zr \([12, 13, 16, 24]\) and \(^{16}\)O\(^{16}\)O elastic scattering [17] with prominent nuclear rainbow scattering [18] arising from the refractive scattering.

The prime purpose of the present study is to investigate the ability of the NM potential to describe the general features of angular distribution of the \(^{4}\)Li\(^{12}\)C elastic scattering data involving CS, \(iT_{11}\) and tensor analyzing powers (\(T_{20}, T_{21}, T_{22}\)) at the \(E_{lab} = 30\) and 50 MeV projectile energy.

2. Li-nucleus potential

A detailed discussion on the derivation of NM potential from the EDF theory of Brueckner, Coon and Debrowski (BCD) [11] and the sensitivity of the EDF potentials on \(K\) are given in Basak et al. [17]. Following [17], the present work has generated the EDF potentials corresponding to the equation of state (EOS), given in BCD for \(K = 188\) MeV [12, and references therein] and a simulated harder EOS for \(K = 219\) MeV. The reason for picking up \(K = 219\) MeV is that Basak et al. [17] have derived \(K = 222 \pm 5\) MeV from the analysis of the \(^{16}\)O\(^{16}\)O elastic scattering data and our simulated one corresponds to \(K = 219\) MeV. The mean-field parameters for symmetric homogeneous nuclear matter, \(\lambda_1 = -741.28, \lambda_2 = +1179.89\) and \(\lambda_3 = -467.54\), for \(K = 188\) MeV, are taken from [19] and those for \(K = 219\) MeV, given in Table 2, are computed from the EDF theory following the procedure of [17]. For application to the finite nuclei, the EDF theory has been extended to include an inhomogeneity parameter \(\eta\) by Brueckner et al. [20] for reproducing the experimental nuclear binding energies.

The EDF calculations involve the sudden approximation where the density distribution (DD) of the composite system is calculated in the sudden approximation, \(i.e.,\) as a simple sum of the density distributions of the projectile and target nuclei. The ansatz of sudden approximation needs an explanation as it seems to violate the Pauli effect as the total density of the composite system goes higher than its saturation value due to a large overlap of the colliding nuclei. However, at higher energies the time of interaction is too small for the composite system to settle to its saturation density. At lower projectile energies the time of interaction although becomes large, the collision is dominated at the surface region where total density of the composite system in the sudden approximation does not exceed its saturation value due to small overlap. Hence the \textit{a priori} application of the sudden approximation seems to be justifiable.

The parameters of the original DD functions of \(^{6}\)Li and \(^{12}\)C, respectively, from [21] and [22], are transformed to the two-parameter Fermi (2pF) function, \(\rho(r) = \rho_0 [1 + \exp\{(r - c)/\lambda\}]^{-1}\), for use in the EDF calculations. The equivalent parameters of the 2pF function are taken from [16] and given in Table 1. The DD parameters in Table 1 and the mean-field parameters are employed in the EDF theory of BCD [11] to derive the \(^{6}\)Li\(^{12}\)C potentials. In achieving these, the inhomogeneity parameter \(\eta\) is adjusted for \(K = 219\) MeV, over the value \(\eta = 8\) normally used for \(K = 188\) MeV [12, 13, 16, 24], to obtain the same
Table 1. The parameters of the equivalent 2pF DD function for the nuclei with the sources given in the text. $c$ and $z$ are in fm, $\rho_0$ in fm$^{-3}$ and binding energies, calculated (calc.) and experimental (Expt.) in MeV.

| Nucleus | 2pF DD parameters | Binding energy |
|---------|--------------------|---------------|
|        | $C$ | $z$ | $\rho_0$ | Calc. | Expt. |
| $^6$Li  | 1.333 | 0.577 | 0.2118 | 33.1 | 32.0 |
| $^{12}$C | 2.294 | 0.434 | 0.1752 | 91.9 | 92.2 |

Table 2. Mean-field parameters $\lambda$’s for individual $K$-values, the corresponding volume integral per nucleon pair $J_0/72$ for the EDF-derived potentials and the inhomogeneity parameter $\eta$ to reproduce the observed binding energies of $^6$Li and $^{12}$C.

| $K$ (MeV) | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\eta$ | $J_0/72$ (MeV.fm$^3$) |
|-----------|-------------|-------------|-------------|-------|---------------------|
| 188       | -741.28     | +1179.55    | -467.54     | 8.0   | -145.25             |
| 219       | -756.50     | +1195.63    | -451.07     | 8.95  | -143.75             |

calculated binding energies. The calculated values for $^6$Li and $^{12}$C are in agreement with the observed values in Table 2. The DD parameters in Table 1 and the mean-field parameters are employed in the EDF theory of BCD [11] to derive the $^6$Li-$^{12}$C potentials. In achieving these, the inhomogeneity parameter $\eta$ is adjusted for $K = 219$ MeV, over the value $\eta = 8$ normally used for $K = 188$ MeV, to obtain the same calculated binding energies. The calculated values for $^6$Li and $^{12}$C are in agreement with the observed values in Table 2.

The EDF-derived nuclear potential has been parametrized as

$$ V_N (R) = -V_0 \left[ 1 + \exp \left( \frac{R - R_0}{a_0} \right) \right]^{-1} + V_1 \exp \left[ -\left( \frac{R - D_1}{R_1} \right)^2 \right] $$

(1)

for empirical adjustment of the real central part of the nuclear potential in the optical model (OM) analysis to accomplish best possible fits.

The OM potential between projectile and target nuclei separated by a distance of $R$ is given by

$$ U (R) = V_C (R) + V_N (R) + iW (R) + U_{SO} (R) + U_{TR} (R). $$

(2)

Here $V_C(R)$, $V_N(R)$ and $W(R)$ denote, respectively, the Coulomb, nuclear real and nuclear imaginary potentials. $V_C(R)$ is assumed to be due to a uniformly charged sphere of radius $R_C$.

The imaginary part is always assumed as

$$ W (R) = -W_0 \exp \left[ -\left( \frac{R}{R_W} \right)^2 \right] - W_S \exp \left[ -\left( \frac{R - D_S}{R_S} \right)^2 \right]. $$

(3)

This comprises a volume term with the Gaussian shape and a surface term with the shifted Gaussian one mainly to supplement the volume term at all incident energies.

The effective spin orbit (SO) part of the $^6$Li potential is assumed to have the standard WS form with only the real part as

$$ U_{SO} (R) = 2 \frac{V_{SO}}{R} d \left[ 1 + \exp \left( \frac{(R - R_{SO})}{a_{SO}} \right) \right]^{-1} \vec{l} \cdot \vec{j} $$

(4)

Here, $\vec{l}$ and $\vec{j}$ are, respectively, the partial wave and spin of $^6$Li. The depth parameter $V_{SO}$, and the geometry parameters $R_{SO}$ and $a_{SO}$ have been adjusted for the best possible fit to the $iT_{11}$ data.
Table 3. Nuclear real parameters for the $^6\text{Li}$-$^1\text{C}$ central potential with $J_R/2$-values and $\chi^2$ for the fits. The Coulomb radius is $R_C = 3.612$ fm. The parameters of the EDF-188 and EDF-219 sets correspond to the EDF-derived potentials for $K = 188$ and 219 MeV, respectively. Set-1 and set-2 refer to the sets of parameters, all adjusted empirically for a best possible fit to the 30 and 50 MeV experimental data, respectively. $E_{lab}$, $V_0$ and $V_1$ are in MeV; $R_0$, $R_1$, $a_0$ and $D_1$, in fm; and $J_R/2$, in MeV.fm$^3$.

| Set      | $E_{lab}$ | $V_0$ | $R_0$ | $a_0$ | $V_1$ | $R_1$ | $D_1$ | $J_R/2$ | $\chi^2$ |
|----------|-----------|-------|-------|-------|-------|-------|-------|---------|---------|
| EDF-188  | 30/50     | 37.3  | 4.00  | 0.736 | 33.8  | 2.43  | 0.133 | -145.25 | 388.9   |
| EDF-219  | 30/50     | 41.0  | 4.00  | 0.734 | 46.7  | 2.49  | 0.118 | -143.75 | 342.3   |
| Set-1    | 30        | 28.0  | 4.602 | 0.54  | 75.0  | 0.35  | 2.175 | -141.2  | 18.0    |
| Set-2    | 50        | 32.0  | 4.006 | 0.82  | 150.0 | 0.47  | 1.076 | -141.0  | 15.3    |

The tensor part of the $^6\text{Li}$ potential is taken, following Reber et al. [24], as complex with

$$U_{TR}(R) = -\frac{8}{6\sqrt{3}} \left[ V_T a_T^2 \frac{d^2}{dR^2} f_6(R) + i W_T a_T^2 \frac{d^2}{dR^2} f_7(R) \right] \left[ (\hat{R} \cdot \hat{R})^2 - \frac{2}{3} \right],$$

where $\hat{R}$ refers to the unit vector along $\hat{R}$. The form factors are given by

$$f_i(R) = \left[ 1 + \exp \left( (R - R_0)/a_i \right) \right]^{-1}.$$

3. Analysis and results

The experimental CS, $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$ data for the $^6\text{Li}+^1\text{C}$ elastic scattering have been taken from [25, 26]. A systematic error of 15% has been assumed for the experimental CS data normalized to the Rutherford cross-sections $\sigma/\sigma_R$ for the angular points without the error bars. The optical model (OM) analyses have been carried out using the code SFRESCO, which incorporates the coupled-channels code FRESCO2.5 [27] coupled with the $\chi^2$-minimization code MINUIT [28]. The fitting parameters are obtained by minimizing $\chi^2$, normalized per degree of freedom $N$-$F$ with $N$ as the number of data points for a given incident energy and $F$ as the number of adjusted parameters. The Coulomb radius is set to $R_C = 3.612$ fm.

3.1. Fits with EDF-generated nuclear real part

In the initial stage, the 30.0 MeV data have been analyzed. Here in the first step, the EDF-derived central potentials for $K = 188$ MeV (Table 3) are kept unchanged and the imaginary central potential parameters are optimized for fitting the experimental CS ($\sigma/\sigma_R$) data only. In the next step, the SO parameters are searched upon for minimizing $\chi^2$ for the $iT_{11}$ data only. This is followed by optimization of both the imaginary central and SO parameters for the best $\chi^2$ in fitting the CS and $iT_{11}$ data simultaneously. In next step, the tensor potential parameters are added and optimized for the minimization of $\chi^2$ in fitting the $T_{21}$ data. In the final step, the imaginary, SO and tensor parameters are adjusted through a sequence of grid and global searches to minimize $\chi^2$ in fitting the $\sigma/\sigma_R$, $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$ data simultaneously. The best fit parameters are listed in Table 4 for the imaginary and SO parameters and Table 5 for the tensor parameters with the overall $\chi^2 = 388.9$. The predicted values from the OM calculations are compared with the experimental data in Fig. 1. The overall description of the data is satisfactory. Although the $iT_{11}$ and $T_{21}$ data are reproduced well, the discrepancies between the calculated results and the $\sigma/\sigma_R$ data at large scattering angles, the $T_{20}$ data around $\Theta_{CM} \sim 75^\circ$ and $T_{22}$ data at $\Theta_{CM} \sim 75^\circ$ and beyond $\Theta_{CM} = 120^\circ$ are clearly observed. Consideration of the imaginary parameters for the tensor potential or further readjustment of the other parameters in the central imaginary and SO parts has not produced any improvement in the description.

In the next stage, the steps of the previous stage for the 30.0 MeV data have been repeated with the EDF-219 parameters, generated by the EDF theory for $K = 219$ MeV. However, the imaginary central,
Figure 1. Predicted $\sigma/\sigma_R$, $ iT_{11}$, $T_{20}$ and $T_{22}$ for the $^6\text{Li}+{^{12}\text{C}}$ elastic scattering at 30 MeV by the OM potentials with the real central nuclear parts (a) EDF-derived for $K = 188$ MeV (dash-dot lines), (b) EDF-derived for $K = 219$ MeV and (c) from empirically adjusted (solid lines) are compared with the experimental data. The central real parts of the nuclear potentials are also displayed to show their NM feature.

SO and tensor parameters have been found identical. In the overall picture, although the $\chi^2 = 342.3$ for the fit is slightly improved from the previous $\chi^2 = 388.9$ for $K = 188$ MeV, no significant improvement in the description of the data over that with the EDF-188 set is sighted in a visual inspection on Fig. 1.

The whole procedure adopted in the analysis with the 30.0 MeV data is then followed for the 50 MeV data using the EDF-188 and EDF-219 sets. The generated fits are displayed in Fig. 2. All the experimental data are described well excepting the $T_{20}$ data beyond $\Theta_{CM} = 40^\circ$ where large discrepancies exist between the predicted values and data. The overall chi-square for the fits are $\chi^2 = 50.0$ and 44.0, respectively, for $K = 188$ and 219 MeV. Here again the $\chi^2$ is slightly improved for $K = 219$ MeV.
Table 4. Same as in Table 3 for the imaginary potential parameters with the corresponding volume integral per nucleon-pair \( J_I/256 \) and the parameters of SO part of the OM potential. \( J_I/72 \) is in MeV.fm\(^3\) and the depth and geometry parameters are, respectively, in MeV and fm. \( E_{lab} \) is in MeV.

| Set    | \( E_{lab} \) | \( W_S \) | \( D_S \) | \( R_S \) | \( W_0 \) | \( R_W \) | \( V_{SO} \) | \( R_{SO} \) | \( a_{SO} \) | \( J_I/72 \) |
|--------|---------------|-----------|-----------|-----------|----------|---------|-------------|-----------|-----------|-------------|
| EDF-188| 30            | 25.0      | 3.365     | 0.22      | 13.0     | 4.0     | 0.15        | 5.495     | 0.17      | -83.7       |
|        | 50            | 5.0       | 5.723     | 0.12      | 17.5     | 4.0     | 0.16        | 5.678     | 0.10      | -92.8       |
| EDF-219| 30            | 25.0      | 3.365     | 0.22      | 13.0     | 4.0     | 0.15        | 5.495     | 0.17      | -83.7       |
|        | 50            | 5.0       | 5.723     | 0.12      | 17.5     | 4.0     | 0.16        | 5.678     | 0.10      | -92.8       |
| Set-1  | 30.0          | 21.0      | 4.396     | 0.10      | 14.0     | 3.9     | 0.4         | 5.266     | 0.55      | -76.1       |
| Set-2  | 50.0          | 5.8       | 5.952     | 0.10      | 19.0     | 3.9     | 0.12        | 5.941     | 0.10      | -93.5       |

Table 5. Same as in Table 4 for the tensor part of the OM potential and \( \chi^2 \) for the fits.

| Set    | \( E_{lab} \) | \( V_T \) | \( R_{RT} \) | \( a_{RT} \) | \( W_T \) | \( R_{IT} \) | \( A_{IT} \) | \( \chi^2 \) |
|--------|---------------|-----------|-------------|-------------|---------|---------|-----------|---------|
| EDF-188| 30            | +0.234    | 4.304      | 0.45        | -       | -       | -         | 388.9   |
|        | 50.0          | -0.140    | 4.922      | 0.55        | -       | -       | -         | 50.0    |
| EDF-219| 30.0          | +0.234    | 4.304      | 0.45        | -       | -       | -         | 342.3   |
|        | 50.0          | -0.140    | 4.922      | 0.55        | -       | -       | -         | 44.0    |
| Set-1  | 30.0          | 0.173     | 4.235      | 0.30        | -0.488  | 3.892   | 0.65      | 18.0    |
| Set-2  | 50.0          | -0.135    | 5.151      | 0.50        | -       | -       | -         | 10.1    |

However, no significant \( K \)-dependence can be seen in the predicted values. The parameters for imaginary, SO and tensor parts of the potential for the fits are listed in Tables 3 – 5.

3.2. Fits with empirically adjusted nuclear real part

Here we analyzed the experimental data at the \( E_{lab} = 30 \) and 50 MeV energies after freeing the EDF-generated potential-parameters for their adjustment in order to obtain better quality fits to the experimental data. In the process, the parameters of the imaginary, SO and tensor parameters have been further tuned following the step-wise procedure outlined in 3.1. This approach results in much better descriptions of data with much reduction in the respective \( \chi^2 \) values and the final parameters are presented in Tables 3 – 5 as set-1 for 30 MeV and set-2 for 50 MeV. However, the predictions with the empirically adjusted nuclear part of the central potential fail to improve description of the \( T_{20} \) data beyond \( \Theta_{CM} = 40^\circ \). The predicted \( \sigma/\sigma_R, iT_{11}, T_{20}, T_{21} \) and \( T_{22} \) are compared with the experimental data in Fig. 2.

4. Discussion and conclusions

This study examines for the first time the NM potential on the tensor analyzing powers. The \( T_K \)-tensor potential, originally proposed by [29] and tried on the \( ^6 \)Li by [24] and the effective SO part in conjunction with the NM central real potential part are able to reproduce the features of all the analyzing power data. In particular, \( iT_{11}, T_{21} \) and \( T_{22} \) data are well accounted for in the simple OM framework without the need of \( J \)-dependent absorption as found very crucial for data description [24].

The OM analysis in terms of the EDF-derived real part of \( ^6 \)Li-\( ^{12} \)C central potentials does not indicate a significant dependence of the CS and analyzing power data on the incompressibility \( K \) at the projectile energies considered. However, the EDF-derived real part of the central potential in collaboration with the SO, tensor and imaginary central parts are able to reproduce the features of the experimental data. Moreover, the EDF calculations provide the starting parameters for the real part of the central potential to explore.

No significant \( K \)-dependence can be evidenced in the predicted values of \( \sigma/\sigma_R, iT_{11}, T_{20}, T_{21} \) and \( T_{22} \) at the projectile energies considered. This is not surprising as at lower energies the surface effect...
Figure 2. Same as in Fig. 1 for $^6$Li+$^{12}$C elastic scattering at 50 MeV.

dominates the elastic scattering while the $K$-dependence of the nuclear potentials occurs in the nuclear interior which contributes to the refractive scattering leading to nuclear rainbow oscillation, as discussed in the presentation of Basak et al. [17]. Although Michel and Ohkubo [30] suggests that the broad dip at $\Theta_{CM} \sim 105^\circ$ in the CS angular distribution of $E_{lab} = 30$ MeV is due to the second Airy minimum (A2) arising from the refractive scattering, the effect of potential in the deep interior region where $K$-dependence is not adequately strong to produce the $K$-sensitive effect on the data including the analyzing powers. One needs to study the elastic scattering at higher energies where primary Airy minimum followed by exponential-type falloff in cross sections [17, 31, 32] is visible in the angular distribution.

It remains to be investigated why $T_{20}$ at $E_{lab} = 50$ MeV beyond $\Theta_{CM} \sim 40^\circ$ could not reproduced even with empirical adjustment of the nuclear real part of the central potential. It may be related to a correlation effect existing amongst the central, SO and tensor terms of the total nuclear potential due to
dynamic polarization potential [6, 33]. Moreover, the effect of SO and tensor parts may be important on the large angle CS data.

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