Microscopic Analysis of Elastic Scattering and Transfer Reaction in the ^{7}Li+^{10}B Collision at Energy 58 MeV

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The aim

We analyse, within the microscopic model of optical potential (OP) and DWBA approach, the following interactions at the beam energy $E_{LAB} = 58$ MeV:

- elactic scattering $^{7}Li+^{10}B \rightarrow ^{7}Li+^{10}B$;
- transfer reaction $^{7}Li+^{10}B \rightarrow ^{6}Li_{g.s.}+^{11}B$;
- transfer reaction $^{7}Li+^{10}B \rightarrow ^{6}Li_{0+}+^{11}B$ with excitation of the $^{6}Li_{0+}$ state (energy 3.56 MeV).

The calculated differential cross sections are compared with the experimental data on the elastic scattering channel and the nucleon transfer reactions obtained in 2023 at the U-400 cyclotron (FLNR JINR).

MicroOP: DF (1/2)

The **real OP** is calculated within the corresponding double folding procedure taking into account the antisymmetrization effects. Such OP depends on the nucleon density distributions of interacting nuclei and consists of direct V_D and exchange V_{EX} terms:

$$V_{DF}(r) = V_D(r) + V_{EX}(r)$$

Both V_D and V_{EX} terms are composed of the isoscalar and isovector parts.

Isoscalar term has a form:

$$V_D(r) = \int d^3 r_p d^3 r_t \rho_p(\mathrm{r}_p)\rho_t(\mathrm{r}_t) v_{NN}^D(s)$$

$$V_{EX}(r) = \int d^3 r_p d^3 r_t \rho_p(\mathrm{r}_p, \mathrm{r}_p + \mathrm{s})\rho_t(\mathrm{r}_t, \mathrm{r}_t + \mathrm{s}) \times v_{NN}^{EX}(s) \exp\left[\frac{i\mathrm{K}(r)\cdot s}{M}\right]$$

$\rho_{p,t}$ – projectile and target densities, $\mathrm{K}(r)$ – local momentum of nucleus-nucleus relative motion, $v_{NN}^{D,EX}$ – effective NN potentials

MicroOP: DF (2/2)

The effective nucleon-nucleon potential v_{NN} is taken in the Paris CDM3Y6 form:

$$v_{NN}(E,\rho,s) = g(E)\,F(\rho)\,v(s), \quad v(s) = \sum_{i=1,2,3} N_i \frac{\exp(-\mu_i s)}{\mu_i s},$$

$$g(E) = 1-0.003E/A_p, \;\; F(\rho) = C\Big[1+\alpha\exp(-\beta\rho)-\gamma\rho\Big], \;\; \rho = \rho_p+\rho_t,$$

where $C = 0.2658$, $\alpha = 3.8033$, $\gamma = 4.0$, and the parameters N_i and μ_i are done in D.T.Khoa & G.R.Satchler, Nucl. Phys. A 668 (2000) 3-41. The local nucleus-nucleus momentum:

$$\mathrm{K}(r) = \{2Mm/\hbar^2[E - V_{DF}(r) - V_C(r)]\}^{1/2}$$

$M = A_pA_t/(A_p + A_t)$, m is the nucleon mass, V_C – Coulomb potential.

Isovector part: $(\mathrm{r}_{p,t} + \mathrm{s})$ is replaced by $(\mathrm{r}_{p,t} - \mathrm{s})$; other parameters in expressions of $v_{NN}^{D,EX}$.

MicroOP: HEA

The **imaginary OP** is taken proportional to the real OP. Also, we use the imaginary OP suggested in (V.Lukyanov at al, Phys. At. Nucl. 69 (2006) 240). Within the optical limit of the Glauber theory, the microOP (both real and imaginary terms) takes the form:

$$U_{opt}^{H}(r) = -\frac{E}{k}\bar{\sigma}_N(i+\bar{\alpha}_N)\frac{1}{(2\pi)^3}\int e^{-i\mathbf{qr}}\rho_p(q)\rho_t(q)f_N(q)d^3q,$$

where $\bar{\sigma}_N$ – the isospin averaged NN total cross section, $\bar{\alpha}_N$ – the ratio of the real to imaginary part of the *NN* scattering amplitude at forward angles, $f_N(q) = \exp(-\beta_N \cdot q^2/2)$ is the form factor of *NN* amplitude.

So, for the imaginary potential, we obtain:

$$W_H(r) = -\frac{1}{2\pi^2}\frac{E}{k}\bar{\sigma}_N\int_0^\infty j_0(qr)\rho_p(q)\rho_t(q)f_N(q)q^2dq.$$

OP: general form

$$U(r) = [N_R \cdot V(r) + N_{Rsf} \cdot V_{sf}(r)] + i[N_I \cdot W(r) + N_{Isf} \cdot W_{sf}(r)]$$

Surface potentials:

$$(1) \quad V_{sf} = -\frac{dV}{dr}, \qquad W_{sf} = -\frac{dW}{dr};$$

$$(2) \quad V_{sf} = -r \cdot \frac{dV}{dr}, \quad W_{sf} = -r \cdot \frac{dW}{dr}.$$

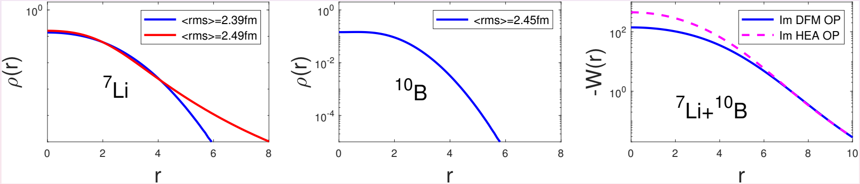
Hybrid OP: $V = V_{DF}$; $W = W_H$

Semi-microscopic OP: $V = V_{DF}$; $W = V_{DF}$

- N_R, N_{Rsf}, N_I, N_{Isf} are adjusted to experimental data.
- Cross sections are calculated via the wave functions of corresponding Schrödinger equation using the DWUCK4 code.
- Coulomb potential and SO potential (if needed) are included.

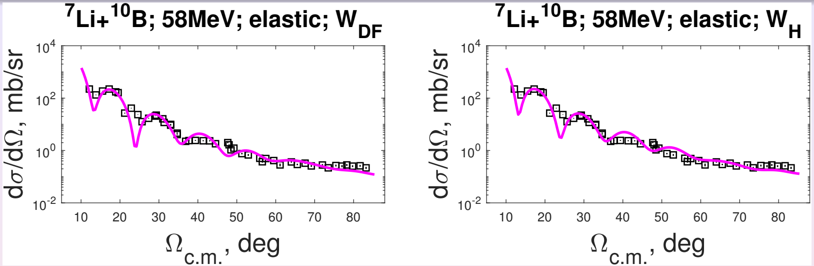
Densities of nuclei ^{7}Li and ^{10}B

- Blue: densities of ^{7}Li and ^{10}B from Patterson & Peterson, Nucl. Phys. A 717 (2003) 235 in the MHO form (blue)
- Red: density of ^{7}Li obtained within the density-matrix formalism in Knyazkov et al, Phys. Atomic Nucl. 59 (1996) 439



Right panel demonstrates that OPs W_H and W_{DF} are quite close in the peripheral region.

Elastic scattering ^{7}Li+^{10}B at 58 MeV



Left: $U(r) = [N_R \cdot V_{DF}(r) - N_{Rsf} \cdot \frac{dV_{DF}}{dr}] + i[N_I \cdot V_{DF}(r) - N_{Isf} \cdot \frac{dV_{DF}}{dr}]$

where $N_R = 1.05,\ N_{Rsf} = 0.01,\ N_I = 0.01,\ N_{Isf} = 0.55;$

Right: $U(r) = [N_R \cdot V_{DF}(r) - N_{Rsf} \cdot \frac{dV_{DF}}{dr}] + i[N_I \cdot W_H(r) - N_{Isf} \cdot \frac{dW_H}{dr}]$

where $N_R = 1.10,\ N_{Rsf} = 0.01,\ N_I = 0.001,\ N_{Isf} = 0.21.$

Note: contribution of the real surface OP and of the imaginary central OP is small.

The ^{7}Li+^{10}B elastic scattering E_{lab}=39 MeV

Small contribution of real surface and imaginary central terms is confirmed in analysis of the ^{7}Li+^{10}B elastic scattering at 39 MeV, experimental data from Etchegoyen et al. Phys. Rev. C 38 (1988) 2124. Authors reproduce their data using only central real and surface imaginary WS OP (left). We also obtain a reasonable agreement with experimental data using the same terms but calculated within the DF model (right).

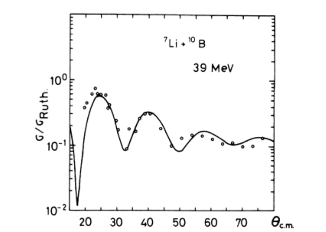
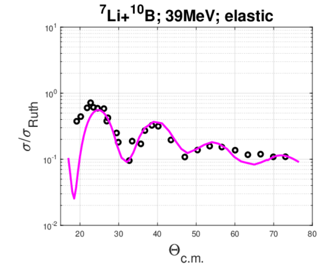
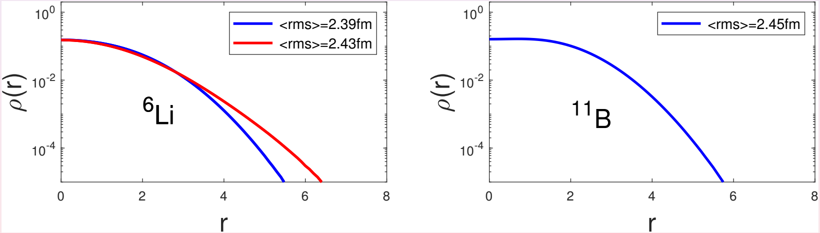


FIG. 3. Optical model fit to the ^{7}Li+^{10}B elastic reaction at 39 MeV.



Densities of nuclei ^{6}Li and ^{11}B

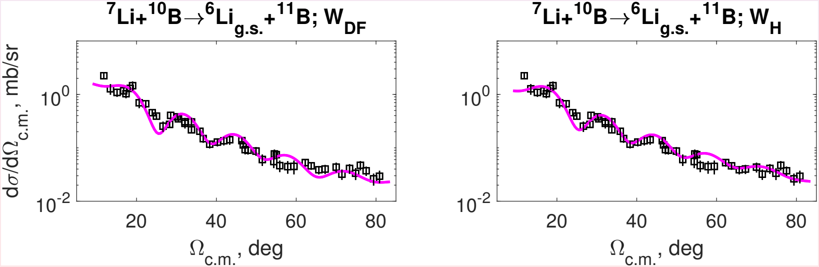
- Blue: densities of ^{6}Li and ^{11}B from Patterson & Peterson, Nucl. Phys. A 717 (2003) 235 in the MHO form (blue)
- Red: the Large Scale Shell Model (LSSM) density ^{6}Li from Karataglidis et al, Phys. Rev. C 61 (2000) 024319



Transfer reaction ^{7}Li+^{10}B→^{6}Li$_{g.s.}$+^{11}B

Left: semi-microcopic OPs; **right**: hydrid OPs (DF+HEA)

- Input system ^{7}Li+^{10}B: the same OP as for elastic scattering.
- Outcome system ^{6}Li+^{11}B:
  Left: $N_R = 0.9,\ N_{Rsf} = 0.001,\ N_I = 0.001,\ N_{Isf} = 0.33.$
  Right: $N_R = 0.9,\ N_{Rsf} = 0.05,\ N_I = 0.01,\ N_{Isf} = 0.1.$
- bound state of ^{11}B=n+^{10}B: parameters of WS OP were chosen to reproduce the binding energy



Transfer reaction ^{7}Li+^{10}B→^{6}Li$_{0+}$+^{11}B

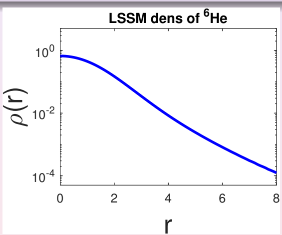
Density of the excited nucleus ^{6}Li$_{0+}$ is still open question. The halo structure of ^{6}Li$_{0+}$ is under discussion.

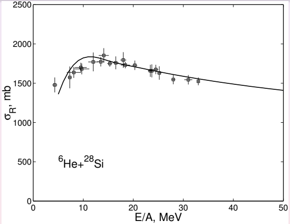
On the other hand, excited nucleus ^{6}Li$_{0+}$ is the isobar-analog state (IAS) of the neutron rich nucleus ^{6}He. IAS nuclei should have a close structure. In the recent work A.Demyanova et al, Phys. Part. Nucl. 55 (2024) 375, the rms-radii of ^{6}Li$_{0+}$ and ^{6}He are estimated to be close and this is an argument in favor of the similar structure of these nuclei. Because of the halo structure of ^{6}He=^{4}He+2n one can expect the halo structure of ^{6}Li$_{0+}$=^{4}He+pn.

Accounting the close structure of IAS nuclei ^{6}Li$_{0+}$ and ^{6}He one can expect they should have a similar nuclear density distribution. Thus, in our estimate calculation we approximate the ^{6}Li$_{0+}$ density by the density of its IAS nucleus ^{6}He.

LSSM density of $^{6}He_{g.s.}$ (IAS of $^{6}Li_{0+}$)

The LSSM model of the ^{6}He nuclear density distribution accounts for the halo structure of this nucleus which is considered as a cluster of ^{4}He and 2n-halo, S.Karataglidis et al,Phys. Rev. C 61 (2000) 024319 (rms-radius 2.586 fm).

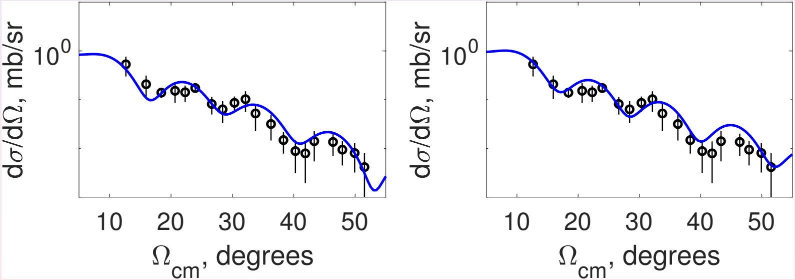




- Left: the LSSM density function of ^{6}He.
- Right: figure from K.Lukyanov et al, Bull. RAS: Phys 72 (2008) 356; calculation was done using LSSM density of ^{6}He.

Angle distribution of $^{6}Li_{0+}$ (E=3.56 MeV)

Estimate calculation of differential cross sections of $^{6}Li_{0+}$ (E=3.56 MeV) in $^{7}Li+^{10}B \to ^{6}Li_{0+}+^{11}B$ at the beam energy E_{lab}=58 MeV. Instead of the $^{6}Li_{0+}$ density, the LSSM density of its IAS nucleus ^{6}He was used to construct microscopic OPs.



Left: semi-microscopic OP;
Right: hybrid OP

Summary

- The theoretical approach based on the microscopic double folding OP and on the DWBA method is appropriate to explain experimental data on ^{7}Li+^{10}B elastic scattering and the transfer reaction ^{7}Li+^{10}B$\rightarrow^{6}$Li+^{11}B at the beam energy E_{LAB} = 58 MeV.
- Shown that HEA-based double folding imaginary OP can provide an agreeement with experimental data in spite of reasonably low beam energy.
- One sees that the absorption in this reaction plays a role only on the peripheral region of nucleus.
- The results can serve a framework for the further analysis of experimental data, including the transfer reaction ^{7}Li+^{10}B$\rightarrow^{6}$Li$_{0+}$+^{11}B.

Thank you
for your attention!