Analysis of the ^{11}Li Elastic Scattering on Protons and Breakup Processes Using the Microscopic Optical Potential Model

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The ^{11}Li nucleus is a typical example of a halo nucleus with a large radius of its matter distribution, with a very large interaction radius and a small separation energy. The idea of the existence of a two-neutron halo in ^{11}Li was experimentally verified in studies of the differential cross sections of the ^{11}Li+p elastic scattering in the energy range 60–75 MeV/nucleon. In [1, 2, 3, 4], we study the ^{11}Li+p elastic scattering and breakup at three incident energies 60, 68.4 and 75 MeV/nucleon using microscopically calculated optical potentials (OPs) within the hybrid model [5]. Note, the microscopic OP was also utilized in 2012-2013 for the ^{93}Nb(p,^{3}He) inclusive reaction mechanism investigation [6], for analysis of the ^{6,8}He scattering on protons [3] and ^{6}He on ^{12}C [7].

The main expression for the OP is as follows:

$$U_{opt} = N_R V^F(r) + iN_I W^H(r) + V_{LS}. \quad (1)$$

The real part V^F of the nucleon-nucleus OP is a result of a folding of the nuclear density and of the effective NN potential and involves the direct $V^D(r)$ and exchange parts $V^{EX}(r)$:

$$V^F(r) = V^D(r) + V^{EX}(r). \quad (2)$$

The imaginary OP W^H is based on the high energy approximation (HEA) and obtained as a folding of the form factors of the nuclear density ρ and the NN amplitude of scattering $f_{NN}(q)$:

$$W^H(r) = -\frac{\hbar v}{(2\pi)^2}\bar{\sigma}_{NN}\int_0^\infty dq q^2 j_0(qr)\rho(q)f_{NN}(q)$$

where $\bar{\sigma}_{NN}$ is the NN total scattering cross section averaged over the isospin of a nucleus.

The expression for the spin-orbit contribution V_{LS} to the OP has the form:

$$V_{LS}(r) = 2\lambda_\pi^2\left[V_0\frac{1}{r}\frac{df_R(r)}{dr} + iW_0\frac{1}{r}\frac{df_I(r)}{dr}\right](\mathbf{l}\cdot\mathbf{s}),$$

where λ_π^2=2 fm^2 is the squared pion Compton wavelength, V_0 and W_0 are the real and imaginary parts of the microscopic OP at r=0.

The cross sections are calculated by means of the DWUCK4 code for solving the respective Schrödinger equation. For the densities of protons and neutrons in ^{11}Li we use the Large Scale Shell Model (LSSM).

We show in Fig. 1 the results of our calculations of the ^{11}Li+p elastic scattering cross sections for the three energies $E = 62, 68.4$ and 75 MeV/nucleon. For each energy we present two curves, with and without accounting for the SO term. One sees, the above microscopic OPs provide a satisfactory agreement of our results with the experimental data.

In addition to the analysis of ^{11}Li+p elastic scattering cross section, we study other characteristics of the reaction mechanism, such as the ^{11}Li total reaction cross section, the breakup cross section and related quantities. A simple two-cluster model (previously applied in [8] for the ^{6}He+^{12}C breakup mechanism) in which two clusters are suggested, namely the ^{9}Li core (c) and the correlated pair of neutrons $h = 2n$ is considered. Within this model for the ^{11}Li nucleus, first, the density distributions of ^{9}Li core and h-halo should be introduced. Second, the folding potentials of interaction of each of the clusters with the incident proton have to be computed. Then, the sum of these two potentials must be folded with the respective two-cluster density distribution of ^{11}Li that causes the necessity to get the wave function of the relative motion of two clusters. We calculate the latter as a solution for the 0s or 1s states of the Schrödinger equation by using the WS potential for a system with reduced mass of both clusters. The WS parameters are obtained by fitting the binding energy of given states to the empirical separation energy value of h-cluster and the rms radius of the cluster function.

The s-state ($l = 0$) wave function of the relative motion of two clusters is

$$\phi_{00}^{(n)}(\mathbf{s}) = \phi_0^{(n)}(s)\frac{1}{\sqrt{4\pi}}, \quad n = 0, 1 \quad (3)$$

and thus, the respective density distribution is defined as a probability for clusters to be at a mutual

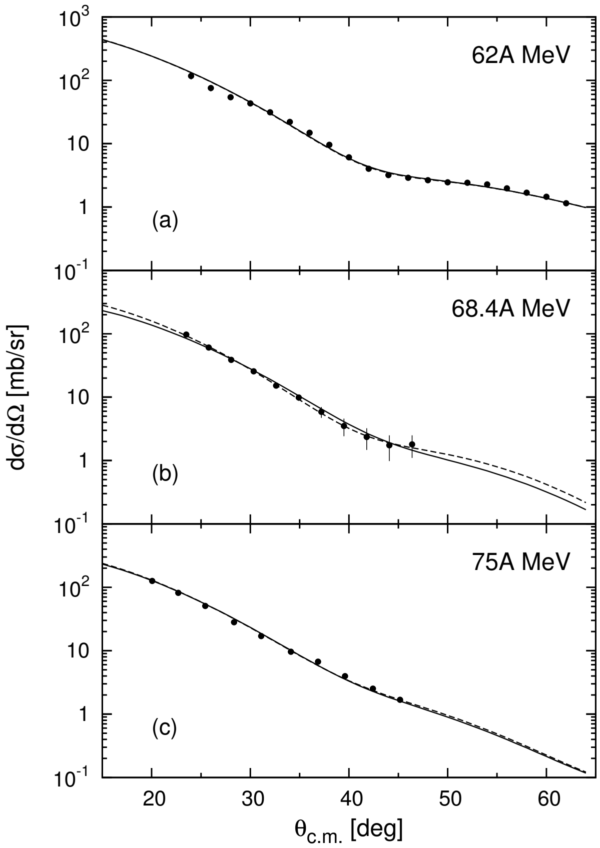

Figure 1: The ^{11}Li+p elastic scattering cross section at E = 62, 68.4, and 75 MeV/nucleon. Solid line: without SO term; dashed line: with SO term. The values of N's are given in [1].

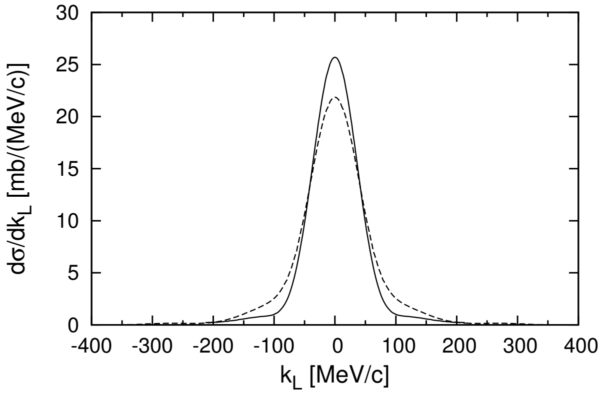

Figure 2: Cross section of diffraction breakup in ^{11}Li+p scattering at $E = 62$ MeV/nucleon for the cases of n=0 (dashed line) and n=1 (solid line).

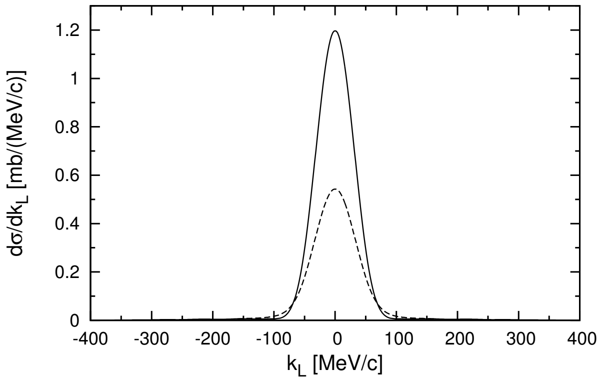

Figure 3: (The same as in Fig. 2 but for the stripping reaction.

distance s:

$$\rho_0^{(n)}(\mathbf{s}) = |\phi_{00}^{(n)}(\mathbf{s})|^2 = \frac{1}{4\pi}|\phi_0^{(n)}(s)|^2. \qquad (4)$$

In the framework of the ^{9}Li+$2n$ model of ^{11}Li one can estimate the ^{11}Li+p OP as a sum of two OP's of interactions of the c- and h-clusters with protons folded with the density $\rho_0^{(n)}(s)$ (n=0, 1)

$$U^{(b,n)}(r) = V^{(b,n)} + iW^{(b,n)} = \int d\mathbf{s}\rho_0^{(n)}(s)\times$$

$$\times \left[U_c^{(n)}\left(\mathbf{r} + (2/11)\mathbf{s}\right) + U_h^{(n)}\left(\mathbf{r} - (9/11)\mathbf{s}\right)\right]$$

The potential $U_c^{(n)}$ is calculated within the microscopic hybrid model of OP. For OP of the h-p interaction we use the sum of two v_{np} potentials as

$$U_h^{(n)} = 2v_{np} = 2v(r)(1 + i\gamma), \quad \gamma = 0.4, \qquad (5)$$

$$v(r) = 120e^{-1.487r^2} - 53.4e^{-0.639r^2} - 27.55e^{-0.465r^2}.$$

Using the eikonal formalism one can obtain the probability that after the collision with a proton ($z \to \infty$) the cluster h (or c) with an impact parameter b remains in the elastic channel:

$$|S_i(b)|^2 = \exp\left[-\frac{2}{\hbar v}\int_{-\infty}^{\infty} dz W_i\left(\sqrt{b^2 + z^2}\right)\right], \quad (6)$$

where $i = c, h$, W is the imaginary part of the microscopic OP $U^{(b,n)}$. Consequently, the probability for the cluster to be removed from the elastic channel is $(1 - |S|^2)$. Thus, the common probability of both h and c clusters to leave the elastic channel of the ^{11}Li+p scattering is $(1 - |S_h|^2)(1 - |S_c|^2)$. After averaging the latter by $\rho_0(s)$ (which characterizes the probability of h and c to be at a relative distance s), we obtain the total absorbtion cross section. The sum of both absorption and breakup cross sections gives the total reaction cross section. Our estimation gives that absorbtion channel contribution to the total reaction cross section is about 20%. In Figs. 2 and 3 we show the results for the diffraction breakup and stripping ^{11}Li+p scattering at $E = 62$ MeV/nucleon, respectively. These results give predictions because of missing experimental data for such processes accompanying the ^{11}Li+p scattering at $E \leq 100$ MeV/nucleon.

Conclusions of our study are following.

(i) The microscopic optical potentials and cross sections of ^{11}Li+p elastic scattering were calculated at the energies of 62, 68.4, and 75 MeV/nucleon and were compared with the available experimental data. The spin-orbit contribution to the OP was also included in the calculations. The regularization of our microscopic OP's is achieved by introducing the fitting parameters N_R, N_I, N_R^{SO}, N_I^{SO} related to the "depth" of the separate parts of OP. They are, in principle, the only free parameters of our approach, in contrast to other phenomenological ones. Using the physical criterion of the behavior of the volume integrals as functions of the energy we obtained a definite set of the fitted N's parameters that give satisfactory agreement of our results with the data on elastic ^{11}Li+p scattering cross section .

(ii) We consider another folding approach that includes ^{11}Li breakup suggesting a simple ^{9}Li+2n cluster model for its structure for estimations of the elastic scattering cross sections, as well as of the momentum distributions in the processes of the proton scattering on clusters and the corresponding S-functions in ^{9}Li+p and h+p scattering. Thus, the analysis of other types of the reaction mechanism, such as the ^{11}Li breakup, makes it possible to understand their significant role in the formation of the OP responsible for the ^{11}Li+p elastic scattering. It turns out that the breakup channel gives σ_{bu}^{tot} that exceeds 80% from σ_R^{tot}, while it is around a half of σ_R^{tot} in the case of ^{6}He+^{12}C.

(iii) Predictions are done for the longitudinal momentum distributions of ^{9}Li fragments produced in the breakup of ^{11}Li at 62 MeV/nucleon on a proton target. We calculated the diffraction and stripping (when the cluster 2n leaves the elastic channel) cross sections of the reaction of ^{11}Li on a proton target at energy 62 MeV/nucleon. We note that our breakup gives the width of the peak between 70 and 80 MeV/c, while the widths of about 50 MeV/c are known from the reactions of ^{11}Li on nuclear targets ^{9}Be, ^{93}Nb and ^{181}Ta at energy 66 MeV/nucleon. In relation with this, here we should mention that at the energy of the range 60-70 MeV/nucleon a distortion due to the nuclear and Coulomb forces could affect the cross sections as well as effects of the three-body admixture $n+n+c$ of a total wave function of ^{11}Li. We emphasize the necessity of experiments on stripping and diffraction reactions of ^{11}Li on proton targets at energy $E < 100$ MeV/nucleon.

(iv) We construct the single-particle density distribution of ^{11}Li in the framework of the two-cluster model. Our density is shown to be close to the phenomenological density obtained by fitting to the experimental differential cross sections of scattering of ^{11}Li at 700 MeV/nucleon on a proton target.

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