Breakup of $^{11}\text{Li}$ in a three-cluster model

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Abstract. The $^{11}\text{Li}$ breakup on a $^{208}\text{Pb}$ target is studied in the Coulomb corrected eikonal approximation by using a $^{9}\text{Li}+n+n$ three-body description of the projectile. The $^{11}\text{Li}$ wave functions are defined in the hyperspherical formalism for bound and scattering states, and are obtained from effective $^{9}\text{Li}+n$ and $n+n$ interactions. The $^{9}\text{Li}+n+n$ three-body phase shifts suggest the existence of a narrow $1^-$ resonance near 0.5 MeV above threshold. This resonance shows up as a peak in the breakup cross section, and is supported by experimental data.

1. Introduction

Breakup reactions represent an efficient tool for the experimental investigation of exotic nuclei [1]. In particular, reactions involving a radioactive $^{11}\text{Li}$ beam on various targets have been carried out in recent years (see Ref. [2] and references therein). An accurate theoretical description of the breakup process requires a reaction theory complemented by a precise description of the projectile wave function.

The goal of the present work is to investigate recent breakup data of $^{11}\text{Li}$ on a $^{208}\text{Pb}$ target at 70 MeV/nucleon [2]. These cross section data present a maximum near 0.3 MeV above the $^{9}\text{Li}+n+n$ threshold, which could be associated with a dipole resonance in $^{11}\text{Li}$ [3]. We describe $^{11}\text{Li}$ in the three-body hyperspherical formalism [4, 5], which provides the $^{11}\text{Li}$ ground state, but also $^{9}\text{Li}+n+n$ three-body scattering states [6, 7]. This theoretical framework for the projectile can be implemented in the eikonal theory [8]. This approximation [9, 10] allows to derive elastic and breakup cross sections in a unified way. As the traditional eikonal method is known to diverge for the Coulomb potential, we use the Coulomb corrected version [11–13], which avoids the convergence problem in breakup cross sections. More detail can be found in Ref. [14].

2. Theoretical framework

The hamiltonian of the $^{11}\text{Li}+^{208}\text{Pb}$ system is defined as

$$H = H_0 - \frac{\hbar^2}{2\mu_{PT}}\Delta_R + V_{PT}(R, x, y),$$

(1)

where hamiltonian $H_0$ is associated with the $^{11}\text{Li}$ projectile, $\mu_{PT}$ is the reduced mass, and $R$ the relative coordinate. In Eq. (1), $x$ and $y$ are scaled Jacobi coordinates defining the $^{11}\text{Li}$ nucleus as a three-body $^{9}\text{Li}+n+n$ structure. The projectile-target interaction is taken as $V_{PT} = \sum_{i=1}^{3} V_{iT}(R, x, y)$, where $i = 1$ labels the $^{9}\text{Li}$ core, and $i = 2, 3$ the external neutrons. Those interactions are simulated by complex optical potentials.
The first step is to determine the $^{11}\text{Li}$ wave functions in the hyperspherical formalism. The $^{9}\text{Li}+n$ potential is taken from Ref. [15]. This interaction generates a core+n s wave scattering length of $-5.7$ fm. It also reproduces a $p_{1/2}$ resonance near 540 keV in agreement with Ref. [16]. A scaling factor 1.0051 is applied in order to reproduce the experimental binding energy of $^{11}\text{Li}$. The $n+n$ potential is the central part of the Minnesota interaction with the standard value $u = 1$ [17]. Three-body continuum wave functions and eigenphases are determined with the $R$-matrix theory [7].

In the second step, $^{11}\text{Li}+^{208}\text{Pb}$ scattering wave functions are determined at the eikonal approximation, i.e. the wave function is factorized as

$$\Phi(R, x, y) = e^{iKZ}\hat{\Phi}(R, x, y).$$

(2)

This factorization is introduced in the Schrödinger equation with Hamiltonian (1), with the adiabatic approximation that consists in replacing $H_0$ by the $^{11}\text{Li}$ ground-state energy $E_0$ [18]. The eikonal wave function, valid at high energies, is given by

$$\hat{\Phi}_{\text{eik}}(R, x, y) = \exp\left(-\frac{i}{\hbar v}\int_{-\infty}^{Z} dZ' V_{\text{PT}}(b, Z', x, y)\right)\Psi_{d_{0}M_{0}\pi_{0}}(x, y),$$

(3)

where $v$ is the relative velocity between the target and the projectile, $b$ the transverse component of $R$, and $\Psi_{d_{0}M_{0}\pi_{0}}$ is the ground-state wave function. From wave function (3), elastic and breakup cross sections can be determined [8,14]. The Coulomb potential leads to two divergence problems in the eikonal phase. They are solved by using the Coulomb-corrected eikonal approximation, which has been applied to describe breakup reactions involving halo nuclei in Refs. [8,13].

For the $n+^{208}\text{Pb}$ interaction, we consider the central part of the complex optical potential given in Ref. [19] at 70 MeV. For the $^{9}\text{Li}+^{208}\text{Pb}$ system, we use the $\alpha+^{208}\text{Pb}$ potential of Bonin et al. [20] at 699 MeV with scaled radii for the real and imaginary components ($R_t = 7.36$ fm and $R_i = 7.12$ fm).

3. Three-body phase shifts and breakup cross sections

Figure 1 displays the dominant $0^+$, $1^-$ and $2^+$ eigenphases [7] of $^{9}\text{Li}+n+n$. The $0^+$ and $2^+$ curves exhibit a wide rise in energy with a resonant-like behavior. The $1^-$ eigenphase shows a sharp resonant behavior around 0.5 MeV. This energy is consistent with the maximum observed in the breakup experimental data, and suggests the existence of a low-lying resonance in $^{11}\text{Li}$.

Figure 2 displays the total and $1^-$ breakup cross sections, convoluted with the detector response and compared with the experimental data of Ref. [2]. We observe a fair agreement for energies above 1.5 MeV, but the peak energy is slightly too high in the model. Including the $0^+$ and $2^+$ contributions increases the total cross section beyond 1 MeV, in better agreement with the experimental data. In the literature, calculations of breakup cross sections of halo nuclei often use the equivalent photon method [21]. This approximation assumes a dipole breakup process, and ignores other contributions. In contrast, the present eikonal description of the breakup reaction is more accurate, since it allows a quantitative evaluation of other partial wave contributions.

4. Conclusion

The $^{9}\text{Li}+n+n$ phase shifts suggest the existence of a narrow $1^-$ resonance near $E = 0.5$ MeV, corresponding to $E_2 \approx 0.9$ MeV. Taking into account the $3/2^-$ spin of the $^{9}\text{Li}$ core nucleus, this resonance should correspond to $J = 1/2^+, 3/2^+$ or $5/2^+$ in $^{11}\text{Li}$. Such a resonance is supported by a low-energy maximum in the experimental breakup cross section. The existence of a dipole resonance in the $^{11}\text{Li}$ nucleus seems now to be well established from experiment as well as from
theory. The situation is less clear in $^6\text{He}$ [8] where a $1^-$ resonance (broader than in $^{11}\text{Li}$) is predicted by most theories, but not yet observed by experiment [22].

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