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Description of the ^{11}Li$(p,d)^{10}$Li transfer reaction using structure overlaps from a full three-body model

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ABSTRACT

Recent data on the differential angular distribution for the transfer reaction ^{11}Li$(p,d)^{10}$Li at $E/A = 5.7$ MeV in inverse kinematics are analyzed within the DWBA reaction framework, using the overlap functions calculated within a three-body model of ^{11}Li. The weight of the different ^{10}Li configurations in the system's ground state is obtained from the structure calculations unambiguously. The effect of the ^{9}Li spin in the calculated observables is also investigated. We find that, although all the considered models succeed in reproducing the shape of the data, the magnitude is very sensitive to the content of $p_{1/2}$ wave in the ^{11}Li ground-state wave function. Among the considered models, the best agreement with the data is obtained when the ^{11}Li ground state contains a ∼31% of $p_{1/2}$ wave in the n–^{9}Li subsystem. Although this model takes into account explicitly the splitting of the 1^+ and 2^+ resonances due to the coupling of the $p_{1/2}$ wave to the $3/2^-$ spin of the core, a similar degree of agreement can be achieved with a model in which the ^{9}Li spin is ignored, provided that it contains a similar p-wave content.

1. Introduction

Halo nuclei have triggered intensive work in the nuclear physics community since their discovery back in the eighties [1,2]. The case of neutron Borromean nuclei, consisting of a compact core plus two valence neutrons [3], keeps being the subject of a considerable amount of experimental and theoretical studies. In these three-body systems, any two-body pair is unbound, which poses a real challenge from the theoretical point of view [4]. Examples of two-neutron halo nuclei are ^{6}He, ^{11}Li, ^{14}Be or ^{22}C. The understanding of their structure requires solid constraints on the neutron unbound binary subsystems, i.e. ^{5}He, ^{10}Li, ^{13}Be or ^{21}C.

Our present understanding of the peculiar properties of these exotic systems largely stems from the analysis of reactions in which these nuclei are part of the colliding systems or appear within some of the reaction products. In the former case, the experiments must be performed in inverse kinematics, and have therefore only become possible since the development of rare isotope beam facilities in the late eighties. Examples of these reactions are nucleon-removal (also named knockout) reactions [5,6], Coulomb dissociation [7], single- and multi-particle transfer and, most recently, quasi-free breakup reactions of the form (p,pn) or $(p,2p)$ [8–11]. The outcomes of these measurements are complementary to one another.

Theoretical works have shown that the structure of two-neutron halo nuclei results from the delicate interplay of several factors, such as the binding effect due to the pairing interaction between the halo neutrons, the coupling to the core collective excitations [12], the effect of Pauli blocking and the role of tensor correlations [13].

In the case of ^{11}Li, many theoretical and experimental efforts have been devoted to understanding its conspicuous structure. This system is bound by only $S_{2n} = 369.15(65)$ keV [14]. Its large spatial extension was first evidenced in the pioneering knockout experiments performed by Tanihata and collaborators [1] using an energetic ^{11}Li beam on a ^{12}C target. The analysis of the momentum distributions from subsequent fragmentation experiments [15–17], including the angular correlations of the fragments [18], revealed an admixture of s and p waves in the ^{11}Li ground-state and permitted to extract their relative weights. Reaction cross section data of these high-energy experiments have been also used to constrain the radius and s-wave content of the ^{11}Li ground state [19,20].

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A proper understanding of the ^{11}Li structure requires an accurate knowledge of the ^{10}Li subsystem. This is an interesting system by itself, located just beyond the drip-line for $N = 7$ isotones, and displaying an inversion of the $2s_{1/2}$ and $1p_{1/2}$ levels. The location and properties of these levels has been studied by means of several knockout and transfer experiments (see [21] and references therein). Most of these experiments predict a near-threshold concentration of $\ell = 0$ strength, consistent with the presence of a virtual state, and one or more narrow $\ell = 1$ resonances with a centroid around ∼0.5 MeV. However, the detailed parameters for the virtual state (e.g. scattering length) and the actual position and width of these resonances vary widely from one experiment to another and are still a matter of debate [22]. The relative amount of s- and p-waves in the ^{11}Li ground state varies also significantly between different works. Furthermore, none of these experiments was able to resolve the doublets arising from the coupling of the s-wave and p-wave to the $3/2^-$ spin of the ^{9}Li core. This introduces an additional ambiguity in the theoretical interpretation of these data, since the observed energy distributions are usually compatible with different model assumptions.

Many of these experiments provide information on the continuum spectrum of the isolated ^{10}Li, but not on the structure of ^{10}Li within the ^{11}Li nucleus. One of the few exceptions is provided by a recent measurement of the ^{11}Li$(p,d)^{10}$Li stripping reaction, performed at TRIUMF at $E/A = 5.7$ MeV [21]. The measured excitation spectrum of the produced ^{10}Li exhibits a resonant-like structure located at $E_r = 0.62(4)$ MeV. The comparison of the angular distribution of this peak, after subtraction of the non-resonant background, with standard DWBA calculations, was consistent with an $\ell = 1$ configuration with a spectroscopic factor of 0.67 ± 0.12. This corresponds to a 33% content of $(p_{1/2})^2$ in the ^{11}Li ground state. In addition to the assumptions inherent to the DWBA reaction framework, the theoretical analysis was based on a simple model for the overlap function of the transferred neutron, which was described using a Woods–Saxon well with standard parameters. While this model can be roughly justified for two-body systems, the underlying picture of a neutron orbiting a ^{10}Li *core* seems more questionable. Consequently, some of the conclusions of Ref. [21] could be biased by this oversimplification of the structure model.

In the present work, we reexamine the same data using also the DWBA method, but replacing the simple Woods–Saxon model by a more sophisticated and, in principle, realistic description of the ^{11}Li and ^{10}Li systems. The former is treated within a three-body model, with effective n–n and n + core interactions, whereas the ^{10}Li is described using $n + {}^9$Li scattering states generated with the same n–core interaction as that used for ^{11}Li. Our goal is to clarify the influence of the structure model on the extracted properties and, in particular, to see whether the conclusions of [21] are affected by the use of a more realistic structure model.

2. Reaction formalism

Let us consider a reaction in which an incident composite nucleus (A) collides with a proton target, which picks one neutron N_1 from the projectile, giving rise to a residual subsystem (B) and a deuteron (d). We focus on the particular case of a three-body projectile comprising an inert core (C) plus two valence neutrons (N_1, N_2), so the reaction takes the form

$$\underbrace{(C + N_1 + N_2)}_{A} + p \to \underbrace{(C + N_2)}_{B} + d, \tag{1}$$

which is schematically depicted in Fig. 1. If the nucleus B does not form bound states (e.g., the composite A is a Borromean system) the products of its decay after one neutron removal will provide spectroscopic information on the original projectile wave function.

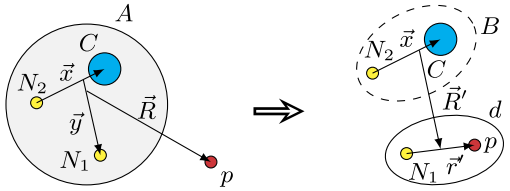

Fig. 1. Diagram for a (p,d) reaction induced by a three-body projectile in inverse kinematics.

For this process, the prior-form transition amplitude can be formally reduced to an effective few-body problem, leading to

$$\mathcal{T}_{if} = \sqrt{2}\langle \Psi_f^{(-)}(\vec{x},\vec{R}',\vec{r}')|V_{pN_1} + U_{pB} - U_{pA}|\Phi_A(\vec{x},\vec{y})\chi_{pA}^{(+)}(\vec{R})\rangle, \tag{2}$$

where Φ_A represents the ground-state wave function of the initial three-body composite (^{11}Li in our case), $\chi_{pA}^{(+)}$ is the distorted wave generated by the auxiliary potential U_{pA}, and $\Psi_f^{(-)}$ is the exact four-body wave function for the outgoing d–B system. The $\pm$ superscript refers to the usual ingoing or outgoing boundary conditions. Notice the explicit factor $\sqrt{2}$ arising from the two identical neutrons in the initial wave function. The origin of this factor is further discussed in Ref. [23].

In writing the transition amplitude in the form (2), we implicitly use a *participant/spectator* approximation, assuming that the reaction occurs due to the interaction of the incident proton with a single neutron (N_1) of A (the *participant*), whereas the system $B = N_2 + C$ remains unperturbed.

To reduce (2) to a tractable form, we approximate the exact wave function $\Psi_f^{(-)}$ by the factorized form,

$$\Psi_f^{(-)}(\vec{x},\vec{R}',\vec{r}') \approx \varphi^{(-)}_{\vec{q},\sigma_2,\zeta}(\vec{x})\chi^{(-)}_{dB}(\vec{R}')\phi_d(\vec{r}'), \tag{3}$$

where ϕ_d is the deuteron wave function, $\varphi^{(-)}_{\vec{q},\sigma_2,\zeta}$ is a two-body continuum wave function with wave number $\vec{q}$ and spin projections σ_2, ζ of the binary subsystem B (^{10}Li), and $\chi^{(-)}_{dB}$ is a distorted wave describing the d–B relative motion in the exit channel. The function $\varphi^{(-)}_{\vec{q},\sigma_2,\zeta}$ is the time-reversed of $\varphi^{(+)}_{\vec{q},\sigma_2,\zeta}$, which can be written as (cf. [24], p. 135)

$$\begin{aligned}\varphi^{(+)}_{\vec{q},\sigma_2,\zeta}(\vec{x}) = \frac{4\pi}{qx}\sum_{LJJ_TM_T} & i^L Y^*_{LM}(\widehat{q})\langle LMs_2\sigma_2|JM_J\rangle \\ & \times \langle JM_JI\zeta|J_TM_T\rangle f^{J_T}_{LJ}(qx)\left[\mathcal{Y}_{Ls_2J}(\widehat{x})\otimes\kappa_I\right]_{J_TM_T},\end{aligned} \tag{4}$$

where, for each component, the orbital angular momentum $\vec{L}$ and the spin $\vec{s}_2$ of the neutron N_2 couple to $\vec{J}$, and $\vec{J}_T$ results from coupling $\vec{J}$ with the spin $\vec{I}$ of the core. Note that $\vec{x}$ contains also the internal coordinates of C. The radial functions $f^{J_T}_{LJ}$ are obtained by direct integration of the two-body Schrodinger equation for the $N_2 + C$ system subject to the boundary condition

$$f^{J_T}_{LJ}(qx) \longrightarrow \frac{i}{2}\left[H^{(-)}_L(qx) - S^{J_T}_{LJ}H^{(+)}_L(qx)\right], \tag{5}$$

where q is related to the $N_2 + C$ relative energy as $q = \sqrt{2\mu_x\varepsilon}/\hbar$, with μ_x its reduced mass, and $H^{(\pm)}$ are Coulomb functions [25].

The ground state wave function of the initial three-body composite A is described within a full three-body model [26–28]. In this work, this wave function is calculated as an expansion in hyperspherical harmonics using a pseudostate basis for the radial part [29], which has been successfully applied to describe