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Excitation modes of ^{11}Li at $E_x \sim 1.3$ MeV from proton collisions

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The cross section for p-^{11}Li inelastic scattering at 68 MeV/nucleon is evaluated using the multiple scattering expansion of the total transition amplitude (MST) formalism, and compared with the breakup in the shakeoff approximation. Three different potential models for ^{11}Li are used to calculate the $^{11}\mathrm{Li}(p,p')$ continuum excitations, and all show peaks below 3 MeV of excitation energy, both in resonant and some nonresonant channels. In the most realistic model of ^{11}Li, there is a strong dipole contribution associated with attractive but not a fully-fledged resonant phase shifts, and some evidence for a $J^{\pi}_{nn}=0^+_2$ resonant contribution. These together form a pronounced peak at around 1–2 MeV excitation, in agreement with experiment, and this supports the use of the MST as an adequate formalism to study excited modes of two-neutron nuclear halos.

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Halo nuclei are weakly bound structures in a vicinity of a breakup threshold, and the knowledge of the continuum properties is an essential tool for the understanding of these nuclei. These structures are of wide interest in other fields such as atomic and molecular as well as nuclear physics ([1] and references therein).

One timely issue is whether the correlations between the cluster systems of the halo nuclei are sufficiently strong enough to support excited states or resonances in the continuum. In particular, it is still an open problem whether there exists a new kind of collective motion, the ''soft dipole'' excited state or resonance at low energies in the breakup continuum, as predicted by some theories [2]. Some evidence for these modes was found for the Borromean two-neutron halo nucleus ^{11}Li [3,4] and ^{6}He [5], but an unequivocal signature remains to be found. A detailed study of the resonances in the continuum sea, which has just now begun to be possible, would help shed light on the existence of the excited modes of halo nuclei, and on other related issues. The study of these modes is also relevant for the comprehension of the ground state structure, because the mechanisms for the halo excitation depend on the ground state properties.

The aim of this work is to study the evidence of low lying excited states in ^{11}Li in inelastic collisions from protons within the few-body multiple scattering expansion of the total transition amplitude (MST) formalism [6] using different few-body potential models for the ^{11}Li ground state and continua, and results compared with those of simpler breakup models.

Several structure models have been developed to describe the structure of ^{11}Li [7–10]. These calculations predict different resonances for the valence neutron halo pair. In particular, it is unclear if the neutron-neutron and neutron-^{9}Li correlations are together sufficiently strong to constitute a soft dipole resonance $J^{\pi}_{nn}=1^-$. Moreover, a low lying resonance $J^{\pi}_{nn}=0^+_2$ was predicted in [8,9], but no evidence for this has been found up to now.

In parallel to the theoretical analyses, the low lying excited states of ^{11}Li have been experimentally investigated [3,11–13]. These very difficult studies, suffering in some cases from poor statistics, have shown contradictory results, in particular with respect to the existence of a low lying excited state at $E^* \sim 1.3$ MeV. Inelastic scattering from protons [3] can be a tool to find evidence for low lying states. The evident interplay between the extracted structure information and the scattering approach [3,10] calls for a clarification of the scattering framework when describing the scattering from halo nuclei.

Traditional calculations of inelastic cross sections assume collective excitations and use optical model potentials, with few-body dynamics perhaps only included approximately by means of effective interactions. The halo degrees of freedom can be explicitly incorporated in the scattering framework in a convenient way within the MST approach [6,14,15], and this has the advantages of including couplings to the continuum in all orders, of clearly delineating the structure and dynamics, and of treating up to four-body problems [6]. Alternative coupled channel approaches [16], which explicitly expand on continuum states, are only able to tackle up to three-body problems.

We consider then the scattering of a nucleon (particle 1) from $\mathcal{N}$ projectile subsystems. In the case of ^{11}Li, assumed to be well described by a three-body ($^{9}\mathrm{Li}+n+n$) model, $\mathcal{N}=3$. The total transition amplitude T can be written as a

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multiple scattering expansion in the transition amplitudes $\hat{t}_{\mathcal{I}}$ for proton scattering from each projectile subsystem $\mathcal{I}$ [6]

$$T=\sum_{\mathcal{I}} \hat{t}_{1\mathcal{I}}+\sum_{\mathcal{I}} \hat{t}_{1\mathcal{I}}G_0\sum_{\mathcal{J}\neq\mathcal{I}} \hat{t}_{1\mathcal{J}}+\cdots, \quad (1)$$

where the propagator $G_0=(E^+-K)^{-1}$, within the impulse approximation, contains the kinetic energy operators of the projectile and all the target subsystems. Here E is the kinetic energy in the overall center-of-mass frame [6]. It follows from Eq. (1) that in the MST expansion the few-body dynamics is properly included, and excitations of the projectile which involve changes in the relative motion of the subsystems are taken into account. The contribution of these to the calculated elastic cross section was investigated in [6,14,17].

We have in mind the scattering process of ^{11}Li, originally in a $|\phi_0\rangle$ state, to a final $|\phi_f\rangle$ state, by means of its interaction with a proton, with initial momentum $\vec{k}_i$ and final momentum $\vec{k}_f$ in the nucleon-nucleus center-of-mass frame. We describe the final state with angular momentum of the valence neutron pair $J^\pi_{nn}(f)$ and excitation energy E^*_f as $|\phi_f\rangle=|J^\pi_{nn}(f),E^*_f\rangle$, neglecting the spin of the core. In the experiment reported by [3], final states up to an excitation energy $E^*_f\leqslant 15$ MeV were detected. Previous studies [8] of ^{11}Li excitations show that it is sufficient to include contributions from dipole $J^\pi_{nn}=1^-$, spin-dipole $J^\pi_{nn}=0^-$, spinflip $J^\pi_{nn}=1^+$, and second $J^\pi_{nn}=0^+_2$, excitations in the scattering.

We use a single scattering approximation, so Eq. (1) reduces to

$$T=\hat{t}_{1\text{core}}+\sum_{n=1,2}\hat{t}_{1n}, \quad (2)$$

where $\hat{t}_{1\text{core}}$, $\hat{t}_{1n}$ are the transition amplitudes for the scattering from the core and valence neutrons, respectively.

In the work of Karataglidis *et al.* [10] the differential cross section is calculated using the shakeoff approximation (SA). This consists first of all, in taking into account only the proton-core contribution to the single scattering term, so Eq. (1) becomes

$$\langle\vec{k}_f\phi_f|T|\phi_0\vec{k}_i\rangle=\hat{t}_{1\text{core}}(\omega,q)F_{f0}(\alpha q), \quad (3)$$

where $\vec{q}=\vec{k}_f-\vec{k}_i$. In this equation, $F_{f0}(\alpha q)$ is the transition density, and $\alpha=2/11$ [6]. The transition amplitude $\hat{t}_{1\text{core}}(\omega,q)$ describes the scattering from the ^{9}Li core at the appropriate energy ω. Then, summing the contributions of *all* the continuum for the scattering process and using closure, the inelastic cross section is

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{SA}}=\mathcal{R}\left(\frac{d\sigma}{d\Omega}\right)_9[1-|F_{00}(\alpha q)|^2], \quad (4)$$

where $(d\sigma/d\Omega)_9$ is the differential elastic cross section for p-^{9}Li scattering and $F_{00}(\alpha q)$ the density distribution for the motion of the core center of mass [6]. The departure of

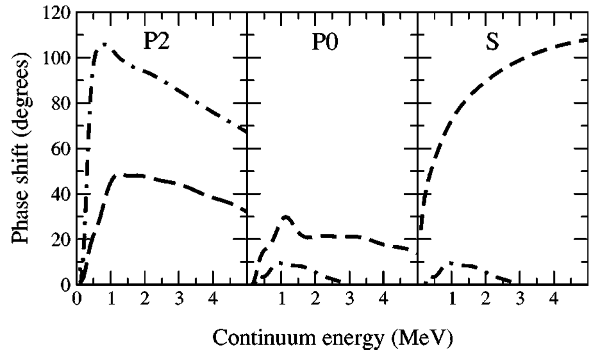

FIG. 1. Calculated phase shifts for the three structure model. The dashed line represents the $K=1$, $S=0$ channel for $J^\pi_{nn}=1^-$ the dashed-dotted the $K=0$, $S=0$ channel for $J^\pi_{nn}=0^+_2$, for three-body hypermoment K and two-neutron spin S as in [18,8].

$F_{00}(\alpha q)$ from unity at nonzero transferred momentum q arises from core recoil effects [6,17]. The renormalization factor $\mathcal{R}$ is somewhat arbitrary and is chosen to remove all the contributions from the continuum that are excluded by the experimental acceptance.

We show the results of MST calculations that take into account the contributions where the proton scatters both from the core and from the valence neutrons in Eq. (2), and we do not use the closure approximation.

In describing ^{11}Li, the internal and spin dynamical properties of the ^{9}Li core are included approximately through a nucleon-core effective interaction, and then the ground state and continuum wave functions are obtained by solving the Faddeev equations. We consider here three structure models for which all eigenstates are defined by different sets of n-core potentials. All models use the GPT nn potential [19]. The first model (S) uses n-core potentials from Johannsen, Jensen, and Hansen [20], and gives an s^2-dominated ^{11}Li wave function similar to that used in the shakeoff calculations of [10]. The second and third models are defined in [7], and include Pauli blocking operators for the $s_{1/2}$ and $p_{3/2}$ core states. The second model (P0) uses potentials similar to those of Bertsch and Esbensen [21], and gives $(0p_{1/2})^2$ halo wave functions as would be expected from normal shell model ordering. A final model (P2) is that advocated by Thompson and Zhukov [7], having an s-wave mixture arising from sd intruder levels in ^{10}Li. The intruder levels have a profound effect on the ^{11}Li structure [7,8], and the P2 model contains a superposition of $(0p_{1/2})^2$ and $(1s_{1/2})^2$ components with relative weights of 45% and 31%, in good agreement with [22].

The dominant hyperspherical phase shifts are shown in Fig. 1, calculated using the methods of [18]. According to [8] and these calculations, within the P2 model a low lying resonance can be found at $E^*_f=0.5$ MeV of width $\Gamma=0.6$ MeV for $J^\pi_{nn}=0^+_2$, as a superposition of s^2 and p^2 configurations orthogonal to those of the ground state, and such a resonance is not predicted in the case of the P0 and S models. There are enhanced soft-dipole 1^- final state interactions in both the P2 and S models, from $s_{1/2}p_{1/2}$ neutron states. In this channel the phase shift does rise rapidly, but only shows at most a resonant-like behavior, and strictly there is no dipole reso-

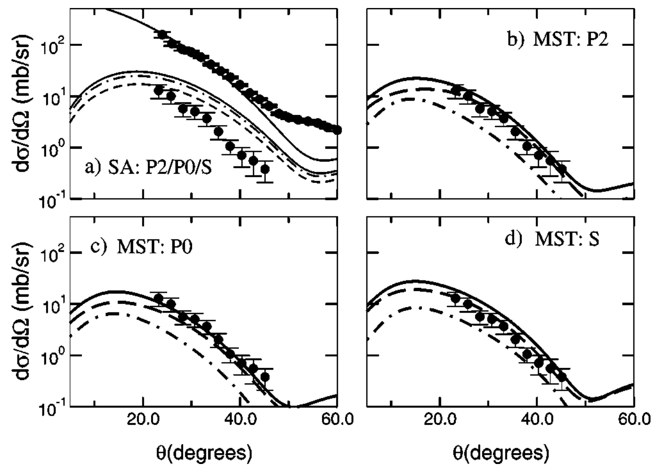

FIG. 2. Calculated inelastic cross section for p-^{11}Li inelastic cross section at 68 MeV/nucleon within the MST framework using the models for ^{11}Li described in the text.

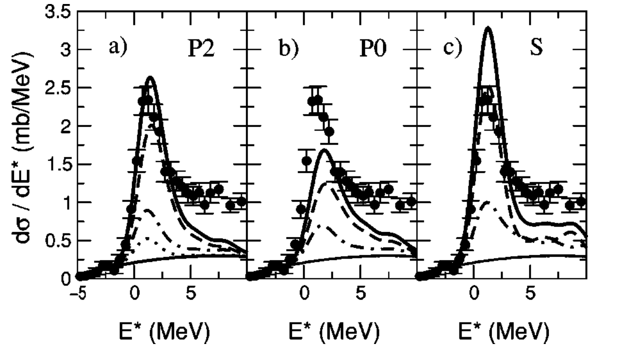

FIG. 3. Calculated energy spectrum for the 3 models described in the text. The dashed line represents the $J^{\pi}_{nn}=1^-$, the dashed-dotted the $J^{\pi}_{nn}=0^+_2$, and the solid line the sum. The lower thin solid line shows the background from materials other than protons in the target. In (a) the dotted curve gives the calculated spectrum with no contribution from the scattering of the valence neutrons to the $J^{\pi}_{nn}=0^+_2$ state.

nance in any of the models. In all three models, however, a large nonresonant contribution is expected that arises primarily from the large size of the ^{11}Li ground state, but the size of any such transitions will be enhanced by positive continuum phase shifts.

The transition amplitude for proton scattering from the ^{9}Li core was generated by the multiple scattering expansion of the optical potential in terms of the free NN transition amplitude, calculated in the single scattering approximation [23] with only a central interaction and neglecting the Coulomb interaction since this is only relevant at very low angles. We use the on-shell approximation for the matrix elements of the transition amplitude in momentum space, which should be a reasonable approximation in this energy regime and for low excitation energies. In the evaluation of the contribution from the valence neutrons, the spin dependence of the NN amplitudes given by the tensor representation of [24].

The ^{9}Li ground state was taken as in [15], which provides a reasonable description of the p-^{9}Li elastic data [25] in the angular region $\theta \leqslant 40°$ as shown in the upper curve of Fig. 2(a).

The experimental differential cross sections from [3] for p-^{11}Li inelastic scattering at 68 MeV/nucleon are shown in Fig. 2. We also show in Fig. 2(a) the inelastic scattering within the shakeoff approximation (SA), Eq. (4). The results for the three models with $\mathcal{R}=1$ are represented by the solid (P2), the dashed (P0), and the dashed-dotted (S) lines, and are all more than twice the experimental magnitude in the region where the scattering from the core is well described. Even when introducing a renormalization factor, $\mathcal{R}$, as in [10], the calculated cross sections using the shakeoff framework decay more slowly than the data, and thus do not give a good description of the scattering.

The calculated inelastic angular distributions using MST with the three structure models are plotted in Figs. 2(b)–(d), by integrating $d^2\sigma/d\Omega dE_f$ over the experimentally defined section of the energy spectrum [3], where we have calculated all the excited (resonant and nonresonant) contributions. In these figures, the solid line includes the sum of the $J^{\pi}_{nn}=1^-$ and $J^{\pi}_{nn}=0^+_2$ contributions. The inelastic transitions calculated with 1^- and 0^+_2 only are represented by dashed and dashed-dotted lines, respectively. The contributions from the spin-dipole 0^- and spinflip 1^+ excited states do not significantly alter the full calculations, and are thus not shown in Fig. 2 for simplification. When comparing the dashed and solid lines, it is evident that the major contribution comes from the dipole mechanism, with a small contribution from excited 0^+_2 states. For all three structure models the total differential cross section using the MST scattering framework agrees well with the available data.

We now analyze the energy spectrum, in Fig. 3. The double differential cross section $d^2\sigma/d\Omega dE_f$ was calculated up to 10 MeV; angular acceptance and energy resolution of the proton detection system was incorporated by simulation of the experimental apparatus. The experimental numbers of counts given in [3] are here converted to cross sections in mb/MeV. In Fig. 3, as in the case of the Figs. 2(b)–(d) the dashed line includes only the dipole contribution and the dashed-dotted the 0^+_2 contribution. The sum is given by the solid line. The other states give a small contribution to the energy spectrum, and therefore are not included. In the experiment, CH_2 was used as a target, and the thin solid line in Fig. 2 shows the background from materials other than protons in the target.

All of the models fail to reproduce the cross sections above $\sim$5 MeV, indicating that further mechanisms are occurring that are outside the scope of our few-body model, or that higher order terms of the multiple scattering expansion might have been important. However, the peak below 5 MeV *can* be reproduced, to varying degrees of accuracy in the various models, indicating that some structure information can be extracted from the very precise low energy spectrum. In the case of the P2 model Fig. 3(a), the dipole contribution underestimates the energy spectrum. When including the second 0^+_2 represented by the dashed-dotted line, however, the total spectrum with the two contributions reproduces well the low energy data. As for the P0 model Fig. 3(b), even when including the 0_2^+ contribution, the predicted energy spectrum underestimates the data. On the other hand, when including this state the S model Fig. 3(c) overestimates the experimental points. In Fig. 3(a) the calculated spectrum with no contribution from the scattering from the valence neutrons to the second 0_2^+ resonant state is represented by the dotted curve. The difference between this and the dashed-dotted curve shows that the scattering from the valence nucleons is essential for the 0_2^+ excitation. This contribution was not taken into account in the SA framework, in order to permit the closure summation.

We conclude that the shakeoff framework fails to describe both the shape and magnitude of the inelastic cross section, and find that MST is a useful scattering framework to obtain information about halo excitation modes from accurate inelastic energy spectrum data.

When considering the low lying energy spectrum up to 5 MeV, the P2 structure model for ^{11}Li reproduces well the differential cross section and the shape, position, and magnitude of the peak.

We see that the experimental data can be well reproduced by a three-body model of ^{11}Li in which there is a pronounced 1^- peak at low continuum energies, but yet in which there is not a fully-fledged resonance in this breakup channel. There is a 0_2^+ resonance which contributes to this peak, but most of the cross section arises from the 1^- nuclear dipole excitation mechanism. This is in partial agreement with [10], though here we do see definitive effects of attractive final-state interactions, as reflected in the continuum phase shifts of a more realistic ^{11}Li model (dashed curve in Fig. 1 for the P2 model).

Experimental evidence for the existence of a strong (but not a fully-fledged resonant) dipole peak is a further demonstration of the novel range of phenomena that occur already with three-bodies in quantum few-body dynamics. Furthermore, this work shows some first evidence of a 0_2^+ resonance contribution at 1–2 MeV excitation.

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