Study of the Unstable Nucleus ^{10}Li in Stripping Reactions of the Radioactive Projectiles ^{11}Be and ^{11}Li

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(Received 20 December 1994)

Reactions of the halo systems ^{11}Be and ^{11}Li (at 460 and 280 MeV/nucleon) with a carbon target demonstrate that (n + ^{9}Li) has an (unbound) $l = 0$ ground state very close to the threshold. The neutron halo of ^{11}Li has appreciable $(1s_{1/2})^2$ and $(0p_{1/2})^2$ components.

PACS numbers: 25.60.+v, 21.10.Pc, 25.70.Mn, 27.20.+n

There is currently a surge of interest in the ^{10}Li problem caused by the work of Kryger *et al.* [1], who reported a narrow central peak in the relative velocity spectrum of the fragments (n + ^{9}Li) produced in fragmentation of an ^{18}O beam at 80 MeV/nucleon. The peak was interpreted as evidence either for the ground state of ^{10}Li, in this case probably the missing s state, or for an $l = 0, 1$ resonance near 2.5 MeV. Weak evidence for a structure close to threshold [2] favors the first interpretation. A low-lying p state is also present near 0.5 MeV according to very similar data presented by Young *et al.* [2] and by Bohlen *et al.* [3]. These two papers give a detailed summary of previous work on ^{10}Li.

The properties of ^{10}Li are essential for the understanding of the neutron halo associated with the ^{11}Li ground state [4]. Thompson and Zhukov [5] found that a neutron s state at low energy would lead to an ^{11}Li halo with about equal admixtures of $(1s_{1/2})^2$ and $(0p_{1/2})^2$. This gave much better agreement with the narrow momentum distributions observed in fragmentation experiments and was in line with the suggestion by Barranco, Vigezzi, and Broglia [6], who attributed the forward-peaked angular distributions of neutrons from ^{11}Li incident on light targets to the decay in flight of ^{10}Li. (The ^{5}He intermediate state also dominates the breakup of ^{6}He [7].)

We have produced the intermediate state ^{10}Li in single-nucleon stripping reactions of the halo states ^{11}Be and ^{11}Li. The word "stripping" is employed here in the sense introduced in 1947 by Serber to describe reactions of 190 MeV deuterons; see his recent remarks on the subject [8]. At high bombarding energies, the sudden approximation is valid, and the halo neutron will, after the collision, to a good approximation be in a state characteristic of the projectile and not in an eigenstate of (^{9}Li + n). We shall in the following develop a line of arguments that first infer the properties of ^{10}Li from the known structure of ^{11}Be and then use the results to draw conclusions about the ^{11}Li halo.

The radioactive beams were generated in a 8 g/cm^2 Be target by fragmentation of a ^{18}O beam from the heavy-ion synchrotron SIS at GSI and separated in the fragment separator [9] FRS by magnetic analysis. The secondary beams of 280 MeV/nucleon for ^{11}Li and 460 MeV/nucleon for ^{11}Be were transported via the storage ring ESR to a carbon target (thickness 1.29 g/cm^2) placed directly in front of the large-gap magnetic spectrometer [10,11] ALADIN. Neutrons coincident with the nuclear fragment were detected in the calorimeter LAND [12] placed 11 m behind the carbon target and having an active detector area of 2×2 m^2 and a total thickness of 1 m. The neutron data from the reactions $^{11}\text{Be} + \text{C} \rightarrow {}^{A}Z + n + X$ and $^{11}\text{Li} + \text{C} \rightarrow {}^{9}\text{Li} + n + X$ were projected out to give distributions in the radial momentum p_r corresponding to cylindrical coordinates with surface element $d\varphi\, p_r dp_r$ after integration over the component in the beam direction. This presentation exploits that the transverse momentum resolution, of the order of 6.5 MeV/c for ^{11}Be corresponding to a spatial resolution of LAND of 7 cm, is considerably better than the longitudinal one of 20 MeV/c.

The experimental results for ^{11}Be (Figs. 1 and 2) show that the widths are very sensitive to the nuclear fragment selected by the coincidence requirement. Expressed in terms of the parameter Γ of a two-dimensional Lorentzian [11], the values for ^{10}Be, ^{7}Li, and ^{9}Li are 98, 66, and 36 MeV/c, respectively, and reflect three principal mechanisms: (i) diffraction dissociation [13,14], (ii) the Serber mechanism, i.e., liberation of the neutron with the momentum preexisting in the halo [14,15], and (iii) the (n + ^{9}Li) final state interaction [1]. Our main concern here is the distribution (iii) which we calculate by expanding the wave function of the (bound) projectile halo taken at the moment of collision. The final states are continuum eigenstates of the (n + ^{9}Li) system.

The neutron wave functions are calculated from a single-particle potential-well model with fixed Wood-Saxon parameters $r_0 = 1.15$ fm and $a = 0.5$ fm, while the (real) well depth is adjusted individually for each initial and final state. Continuum states with angular momenta up to 3 are included, but only $l = 0, 1$ play a role. This is a model with a bare minimum of parameters; note especially that the resonance widths are fixed automatically by the resonance position, and that the spin-orbit interaction and the core spin are neglected. The fact that this works at all and, as it seems, brings out the essential physics is, of course, linked to the relative simplicity of the nuclei in question—and to that of the neutron-nucleus interaction at low energy. Theory [16] has the ^{11}Be ground state as 80% $1s_{1/2}$ in agreement with the measured [17] s spectroscopic factor of 0.77. Shell-model calculations for ^{10}Li suggest [18] that the coupling of the s neutron to the ^{9}Li core spin gives rise to a 2^- ground state with the 1^- partner near 0.5 MeV, while the p neutron gives a nearby $1^+, 2^+$ doublet. Our model replaces these four states with two, but as the 2^- state has the largest statistical weight the approximation may actually be quite good. (To include also an excited 1^- state might improve the fit in Fig. 1.) We keep, except for one curve in Fig. 2, the depth of the p well fixed to reproduce a resonance at 0.42 MeV [3]. Since there can be no s-state resonance, properly speaking, we quote this well depth in terms of the s-wave scattering length a_s, which makes our final results insensitive to the details of the shape of the potential, as we have verified in calculations with a square well.

The quintessential argument is now that by producing ^{10}Li in simple nucleon-removal reactions, we have created a situation in which we possess some information about the initial state. Consequently, it is possible to apply angular-momentum selection rules to identify states in the reaction partners. Assume, as is true to a first approximation, that the ^{9}Li fragment formed when the proton is stripped from the ^{10}Be core continues with no

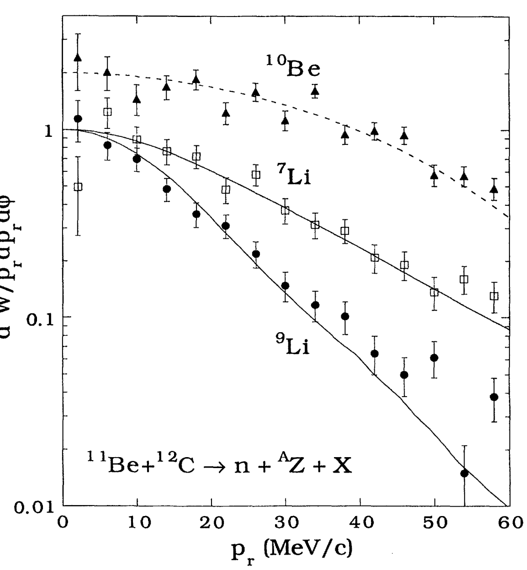

FIG. 1. Radial momentum distributions (arbitrary scale) of neutrons from ^{11}Be in coincidence with selected fragments. The results for ^{8}Li (not shown) were identical to those for ^{7}Li. The dashed curve is the black-disk diffraction shape used for the background estimates in Fig. 3. The two full drawn curves correspond to the calculations discussed in the text. They include the effect of the fragment recoil and assume for the s-wave scattering length a_s the values 0 (upper curve) and −20 fm (lower curve) and for both a p-wave resonance at 0.42 MeV.

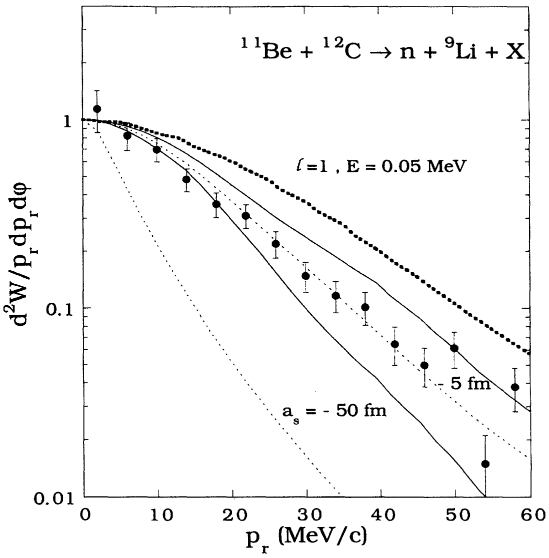

FIG. 2. Same as Fig. 1 with only the ^{9}Li data displayed. The top curve (dots) assumes an $l = 1$ resonance at 0.05 MeV, $a_s = -2$ fm and $\sigma_Q = 100$ MeV/c. Two pairs of theoretical curves correspond to $a_s = -5$ and -50 fm and recoil widths $\sigma_Q = 100$ MeV/c (full drawn) and $\sigma_Q = 0$ (short dashes).

change in velocity relative to the beam. The halo neutron, now unbound, will still remain in the original ^{11}Be s state ψ_0. (The "wound" [14] is of little importance and is neglected here.) A strict selection rule then identifies the state seen by Kryger *et al.* [1] and by us, namely, that it will be populated if it is an s state and if not, not. This rule is relaxed by the momentum transfer in the stripping reaction. Assume now that the ^{9}Li fragment after the collision has a momentum vector $-\mathbf{Q}$ relative to the coordinate system c.m. traveling with the projectile. If we denote the mass numbers of the neutron and the ^{9}Li fragment by A_H and A_F, the momentum vector $\mathbf{p}'$ of the neutron is in the new center-of-mass system c.m.′ (see [14]) $\mathbf{p}' = \mathbf{p} + \mathbf{q}$, where $\mathbf{q} = -A_H\mathbf{Q}/(A_F + A_H)$. For a sudden impulse, the wave function at the moment of the collision is then in c.m.′

$$\psi(\mathbf{r}') = e^{i\mathbf{q}\cdot\mathbf{r}'/\hbar}\psi_0(\mathbf{r}'), \quad (1)$$

and the time development of this system can be obtained by expanding in eigenstates. To obtain the distribution actually observed we must transform back from c.m.′ to c.m. and average over $\mathbf{Q}$. The latter was taken to be isotropically distributed with a Gaussian width $\sigma_Q = 100$ MeV/c; see the results of Kidd *et al.* [19], who also found that the distribution is centered almost exactly on beam velocity, an important feature in the present application. The integration over $\mathbf{Q}$ now leads to an isotropic distribution in p, which can conveniently be transformed to other distributions such as that of the radial momentum vector p_r.

The main results of the ^{11}Be calculation are shown in Fig. 1, where it should be kept in mind that the points at low transverse momentum are those that most directly convey information about the halo. It will be seen that the ^{9}Li data require a scattering length around $a_s = -20$ fm, a result that also approximately accounts for the velocity spectrum [1] and shows the state in question to be an s state. This is not necessarily in contradiction with McVoy and Van Isacker [20] who found it difficult to settle the controversy over the s and p nature of the ^{10}Li states. The analysis given here can be more specific because it concentrates on the dominant (single-particle) strength and because the experiment exploits approximate selection rules in angular momentum. We shall show below that the s state also must be the ground state.

The curve through the ^{7}Li data assumes $a_s = 0$ fm, a value that implies no interaction in the s state, so that the net result of the transformation to c.m.′ and back is to return to the ^{11}Be halo wave function in momentum coordinates [15]. This statement is not exact in two respects. The first is that in order not to vary two free parameters simultaneously, the calculations maintained unchanged interaction in the p channel corresponding to a resonance energy of 0.42 MeV, while a known state in ^{8}Li lies lower. Because of the angular-momentum selection rule the influence of the p state is, anyway, negligible. The second point concerns the scattering length, which is known experimentally [21] to be -2 fm, which would give a distribution only slightly narrower than that shown.

The validity of this analysis is examined in Fig. 2. It demonstrates that a low-lying p state (0.05 MeV, but 0.1 and 0.2 MeV gave nearly the same result) and a high-lying s state ($a_s = -2$ fm) will not account for the distribution in coincidence with ^{9}Li. It also illustrates the importance of the recoil broadening by combining two values of a_s with two values of σ_Q to show that the data are consistent with $a_s = -50$ fm and numerically larger values. The message is, evidently, that the s state is somewhere close to the neutron threshold, at which the scattering length becomes infinite.

The neutrons in coincidence with ^{9}Li fragments from single-neutron stripping of ^{11}Li also have a narrow distribution in radial momentum (Fig. 3). Assuming that this arises from the ^{10}Li s state identified above, we may immediately draw three important qualitative conclusions. The first rests on the selection rule in angular momentum, which implies that there must then be an appreciable amount of $(1s_{1/2})^2$ in the ^{11}Li halo wave function, exactly as proposed by Thompson and Zhukov [5] and suggested by an analysis of β decay data by Suzuki and Otsuka [22]. Noting further the marginal binding and low momentum of the ^{11}Li halo neutrons, we see, secondly, that the stripping of one of those will not excite the ^{9}Li core to 2.7 MeV, and hence that the ^{10}Li s state must be the ground state, and, thirdly, that we do not forsee any appreciable recoil contribution. The absence of a core recoil also means that the almost identical results of Figs. 2 and 3, both corresponding to $\Gamma = 36$ MeV/c,

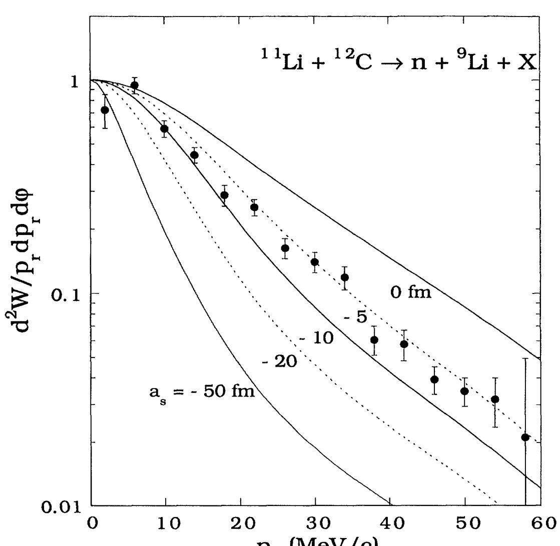

FIG. 3. As Fig. 1 but for the ^{11}Li projectile. All theoretical curves are a superposition of two contributions: (i) diffraction (1/3 intensity) and (ii) decay of the intermediate state (2/3 intensity), assumed to be a pure s state, to $(n + {}^9\text{Li})$ eigenstates characterized by their scattering length.

represent a numerical coincidence. It takes two additional mechanisms to account for the ^{11}Li data.

The first is a diffraction component similar to the top curve in Fig. 1. In the spirit of Barranco, Vigezzi, and Broglia [6], this must contribute 1/3 of the intensity, since there is no diffracted neutron per two ^{10}Li neutrons. But it is seen from Fig. 3 that this is not enough: The theoretical curve for $a_s = -20$ fm still is much narrower than the data. A plausible explanation is that there is also an appreciable $(0p_{1/2})^2$ component in the halo. A calculation with the parameters used for ^{10}Li in Fig. 1, which is $a_s = -20$ fm and $E_{l=1} = 0.42$ MeV and with equal weights of the two angular momenta in the initial state, turns out to work rather well. That the ground state of ^{11}Li is a superposition of two configurations is a signature of neutron-neutron correlations.

To sum up, our experiment carried out at high beam energies is a rich source of information on the structure of ^{10}Li and ^{11}Li in the range 0–0.5 MeV of excitation. We have attempted an analysis that contains the essential physics with the bare minimum of free parameters, two, both physically meaningful and measurable. It should be kept in mind, however, that there are enough unknowns left to make our results qualitative rather than quantitative. Although more states and better wave functions would mean a step in the right direction, there are essential questions about the model that can only be answered by novel theoretical or experimental input. Taking as an example the (^{10}Be, ^{9}Li) reaction, we may ask about the true distribution of the recoil momentum **Q**, about the probability that this reaction feeds the 2.7 MeV excited level, and, should this number be high, say, 33%, about what may be assumed for the s and p interaction strengths in the excited states. For these reasons it is premature to assign error bars to our conclusions which are as follows. (i) The ^{10}Li ground state has $l = 0$ and a scattering length $a_s = -20$ fm or less, corresponding to an excitation energy below 50 keV. (ii) The ^{11}Li halo contains appreciable $(1s_{1/2})^2$ and $(0p_{1/2})^2$ components.

This work was supported by the German Federal Minister for Research and Technology (BMFT) under Contracts No. 06 DA 641 I, No. 06 BO 103, and No. 06 MZ 465 and by GSI via Hochschulzusammenarbeitsvereinbarugen under Contracts No. DA RICK, BO FRE, F ELE, MZ Krak, and partly supported by the Polish Committee of Scientific Research under Contract No. PB1158/P3/92/02.

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