Excited States of ^{11}Li

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The excited states of the "halo" nucleus, ^{11}Li, have been investigated by means of the pion capture reaction, $^{14}C(\pi^-, pd)^{11}$Li. Excited states have been identified at 1.02 ± 0.07, 2.07 ± 0.12, and 3.63 ± 0.13 MeV. The continuum part of the ^{11}Li missing mass spectrum is found to contain a major component which is consistent with ^{11}Li breakup into one of the ^{9}Li excited states and two strongly correlated neutrons. [S0031-9007(98)07629-7]

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The particle stable nucleus ^{11}Li has become the most celebrated among the so-called exotic nuclei by virtue of the two-neutron halo ascribed to it [1]. The very small separation energy of its last two neutrons [$S(2n) =$ 0.32 MeV] and its exceptionally large radius, inferred from measurements of total cross sections [2] and momentum distributions [3], are counterintuitive to the ideas of the naive shell model. It would suggest a very tightly bound system of magic number $N = 8$ neutrons, with low-lying states arising mainly from the excitation of the odd proton which is in the $p_{3/2}$ orbit in ^{11}Li (g.s.). However, the picture that has emerged is quite different. It is believed that the effective core is that of ^{9}Li, and the two additional neutrons in ^{11}Li form a distinct halo at a considerably larger radius [4]. The excitation of the neutrons in the halo competes favorably with the odd proton excitation and may give rise to a complex spectrum of low-lying states.

A large number of model calculations attempting to describe ^{11}Li have been done. These belong to two general classes. The first class of calculations, in which the low-lying states of ^{11}Li are considered in terms of the two halo neutrons coupled to an inert ^{9}Li core, began with the first calculations of Hanson and Jonson [5]. Their most recent realization occurs in the work of Garrido *et al.* [6] in which both bound and unbound states of ^{11}Li are calculated. The second class consists of large basis shell-model calculations. These range from the early calculations of Poppelier *et al.* [7] to the latest calculation of Karataglidis *et al.* [8] in a basis which extends from $0s$ to $0f - 1p$ orbits, and in which $(0 + 2)\hbar\omega$ and $(1 + 3)\hbar\omega$ configurations are considered for negative and positive parity states, respectively. The results of these two types of calculations generally do not agree, and good experimental data are sorely needed. However, the experimental data on the low-lying states of ^{11}Li are sparse and often contradictory [9–15]. Many resonances have been claimed, but the claims generally suffer from small statistics and uncertainties due to impurity contributions. In this Letter we present results for the low-lying states of ^{11}Li obtained by the reaction $^{14}C(\pi^-, pd)^{11}$Li, i.e., by the coincident detection of a proton and a deuteron following the capture of a π^- by ^{14}C.

The measurements described here were carried out at the LEP channel at the Los Alamos Meson Physics Facility (LAMPF). A beam of 30 MeV π^- with $\Delta p/p =$ $\pm 1\%$ was moderated by a beryllium degrader and was stopped in the target under investigation. The π^- flux was $\sim 10^6\ \pi^-\ s^{-1}$ and the stopping rate was $\sim 6 \times 10^4\ \pi^-\ s^{-1}$. The resulting charged particles were detected and identified in two opposing solid state detector telescopes at ±90° to the π^- beam. The target and the detectors were in a vacuum enclosure. The targets consisted of 26 mm diameter disks, ~ 24 mg/cm^2 in thickness each, of natural carbon (98.9% ^{12}C) and enriched ^{14}C ($\sim$76% ^{14}C, $\sim$23% ^{12}C, trace ^{16}O). The targets were positioned at $\sim$22° to the pion beam. The ^{14}C target was contained in a special container with 50 μm mylar windows for the outgoing charged particles. The electrons ($E_{max} = 149$ keV) from the β decay of ^{14}C were prevented from reaching the detectors by permanent magnet annuli with 0.7 kG field mounted in front of the detector telescopes. Each detector telescope consisted of two surface barrier Si(Au) detectors of 100 and 400 μm thickness to provide dE/dx information, followed by a series of Si(Li) detectors, each of 3500 μm thickness. Each detector had a diameter of $\sim$32 mm. One telescope had a total silicon thickness of $\sim$44 mm [E_p(max) $\approx$ 103 MeV] and the other of $\sim$27 mm [E_p(max) $\approx$ 78 MeV]. The energy resolution achieved for single p, d, t detection ranged from 400 to 500 keV. The missing mass resolution for the coincidence detection of a proton and a deuteron varied from $\sim$950 to $\sim$720 keV depending on the depth in the detector telescopes at which the most energetic particles stopped. The absolute energy calibration was estimated to be correct to ±100 keV. A detailed description of the apparatus and the procedure for particle identification and the construction of missing mass spectra is given elsewhere

[16]. The ^{14}C and ^{12}C targets each required ~10 days of running.

In Fig. 1 we show the missing mass spectra for the (π^-, pd) reactions on the ^{12}C and ^{14}C targets. Both spectra were calculated using the kinematics for the $^{14}\mathrm{C}(\pi^-, \mathrm{pd})^{11}\mathrm{Li}$ reaction, so that in both spectra the ^{9}Li states appear displaced by −12.8 MeV (the Q value difference) with respect to the ^{11}Li states. The g.s. masses were taken from Ref. [17]. In the spectrum for the ^{14}C target a peak due to $^{16}\mathrm{O}(\pi^-, pd)^{13}\mathrm{B}$(g.s.) reaction on the trace ^{16}O contaminant is also visible at ~−17 MeV.

In Fig. 2 we show the ^{9}Li missing mass spectrum with its proper mass scale. We fit this spectrum primarily to obtain the shape of the instrumental resolution function as determined by the strong ground state transition. It is found that the g.s. peak is best fitted (for all fits described in this Letter, the method of maximum likelihood was used) by a line shape whose main component is a Gaussian with $\sigma_1 = 368$ keV. In order to fit the tails of the peak better a second Gaussian centered at the same energy as the main Gaussian but having $\sigma_2 = 2.7 \times \sigma_1$ and amplitude 14% of the main Gaussian was added. The composite shape had a half-width of 935 ± 30 keV. In Fig. 2 the full spectrum has been fit for the known levels of ^{9}Li—the g.s. and the 2.69 MeV state, which are clearly visible, as well as the 4.3, 5.4, and 6.4 MeV levels, which are not resolved. It is found that above ~7 MeV excitation the continuum region of the spectrum is fitted well with the sum of phase space contributions for ^{9}Li breakup into $^8\mathrm{Li} + n$ (curve *A*) and $^7\mathrm{Li} + n + n$ (curve B). The ground state missing mass is found to be ~−80 keV instead of zero, which is consistent with the uncertainty of ±100 keV in our absolute mass scale.

In Fig. 3 we show the spectrum for the ^{14}C target from which the contribution of the ^{12}C contaminant has been subtracted by normalizing at the ^{9}Li (g.s.) transition in the two spectra as shown in Fig. 1. A visual examination of the spectrum shows that the g.s. transition is accompanied by one or two satellite peaks between 1 and 2 MeV excitation, and there is an additional peak at ~3.7 MeV excitation. The main contribution to the continuum appears to start above 3 MeV. In order to determine the resonance parameters, we can either use a small empirical background of 2 to 4 counts/200 keV bin in the 0 to 5 MeV region of interest or take account of the continuum contribution as described in detail later. We have tried both methods, with completely consistent results.

The results are as follows. The ^{11}Li ground state is clearly accompanied by close-lying excited states. The best fit, using the two-Gaussian line shape obtained for ^{9}Li (g.s.) with a half-width of 715 ± 25 keV, yields a triplet of states with the following energies and normalized intensities: 0.03 ± 0.04 MeV (100%), 1.02 ± 0.07 MeV (37% ± 7%), and 2.07 ± 0.12 MeV (15% ± 5%). In addition, there is another state at 3.63 ± 0.13 MeV (21% ± 6%). The energies of these states are found to be stable well within the quoted errors with respect to uncertainties in background subtraction, line shape, and fits to the continuum. The quoted uncertainty in line width does not permit us to say anything about the intrinsic widths of the unbound excited states.

Several claims for excited states in ^{11}Li exist in the literature [9–15]. Only one state, with excitation energy ~1 MeV, has ever been reported in more than one experiment [9,10,12–15]. Claims for other states are unique to each investigation. The first excited state of ^{11}Li has been reported at 1.0 MeV by Sackett *et al.* [10] and Zinser *et al.* [15] from invariant mass analyses of $^9\mathrm{Li} + n + n$ from the breakup of ^{11}Li beams on C and Pb targets. Korsheninnikov *et al.* [13] have reported most likely the same state at 1.25 ± 0.15 MeV in their analysis of the inclusive proton spectrum from the collision

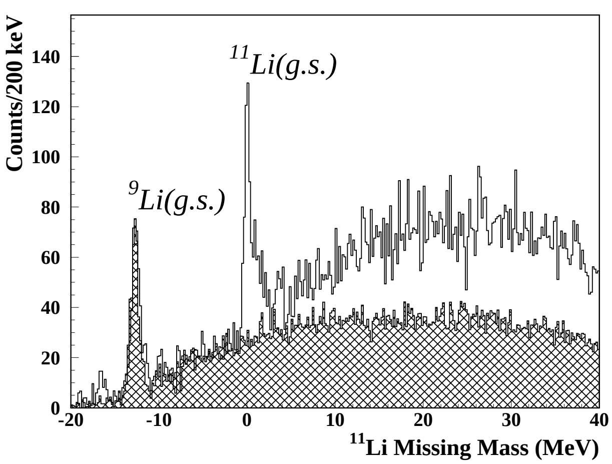

FIG. 1. Missing mass spectra for (π^-, pd) reactions on ^{12}C (solid histogram) and ^{14}C (open histogram) targets both analyzed with ^{14}C kinematics. The spectrum for the ^{12}C target has been normalized to that for the ^{14}C target at the ^{9}Li (g.s.) transition at −12.8 MeV.

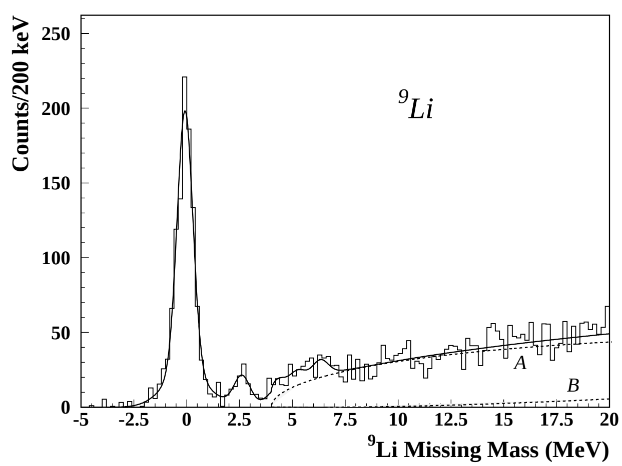

FIG. 2. Missing mass spectrum for $^{12}\mathrm{C}(\pi^-, pd)^9\mathrm{Li}$. The solid line fit is described in the text. Curve *A* corresponds to the phase space for breakup of ^{9}Li into $^8\mathrm{Li} + n$, while curve *B* corresponds to the phase space for breakup of ^{9}Li into $^7\mathrm{Li} + n + n$.

of a 75A MeV beam of ^{11}Li on a CH_2 target [18]. This state can be identified with the state seen by us at 1.02 ± 0.07 MeV. Korsheninnikov *et al.* [13] also report "tentative" evidence for states at 3.0 ± 0.2, 4.90 ± 0.25, 6.40 ± 0.25, and 11.30 ± 0.35 MeV. In contrast, in a study of ^{14}C(^{14}C, ^{17}F)^{11}Li and ^{10}Be(^{14}C, ^{13}N)^{11}Li reactions, Bohlen *et al.* [11] do not find a state at either 1.25 or 3.0 MeV, but find states at 2.47 ± 0.07, 4.85 ± 0.07, and 6.22 ± 0.07 MeV. It is difficult to identify any of these states with the states at 2.07 ± 0.12 and 3.63 ± 0.13 MeV which we observe. Admittedly, our data have limited statistics for the excited states, but we feel that our excited state information is more direct than that from the dissociation of ^{11}Li beams [10,13–15], and it does not suffer from contaminant problems which plague the heavy ion measurements [11].

As mentioned earlier, the latest three-body and shell-model calculations predict quite different excited state spectra for ^{11}Li. In their three-body calculations Garrido *et al.* [6] predict a $3/2^-$ g.s. and nearly degenerate $1/2^-$, $3/2^-$, and $5/2^-$ continuum states at both $\sim$1.30 and $\sim$1.88 MeV. Similarly, they predict nearly degenerate $1/2^+$, $3/2^+$, $5/2^+$ states at 0.97, 1.38, and 3.3(2) MeV, with a nondegenerate $3/2^+$ state at 1.60 MeV. The very large basis shell-model calculations of Karataglidis *et al.* [8] predict a $3/2^-$ g.s., and excited states at 1.49 MeV ($3/2^-$), 1.83 MeV ($3/2^+$), 1.87 MeV ($1/2^-$), 2.68 MeV ($1/2^+$), and 3.25 MeV ($5/2^+$) with energies estimated to be "accurate to about 1 MeV." It is difficult to identify our observed excited states at 1.02(7), 2.07(12), and 3.63(13) MeV with the theoretically predicted states with any degree of confidence. The reaction mechanism operative in our pion absorption measurements is not known. If we interpret the strong excitation of the $3/2^-$ g.s. as a preference for the excitation of negative parity states, we would be tempted to identify our 1.02(7), 2.07(12), and 3.63(13) MeV states with the 1.49 MeV ($3/2^-$), 1.83 MeV ($3/2^+$), and 3.25 MeV ($5/2^+$) states predicted by Karataglidis *et al.* We reiterate that these assignments are entirely conjectural.

We now address our attention to the continuum part of the ^{11}Li missing mass spectrum displayed in Fig. 4 with 400 keV bins in order to diminish statistical fluctuations. The first thing to notice here is that there are well-defined minima at $\sim$3.0 and 4.5 MeV, and any breakup contribution below $\sim$3.0 MeV is small. Thus, possible contributions due to breakups $^{11}\text{Li} \rightarrow {}^{10}\text{Li} + n$ (threshold = 0.32 MeV) or $^{11}\text{Li} \rightarrow {}^{9}\text{Li} + n + n$ (threshold = 0.30 MeV) are small. We note further that the near constancy of the observed spectrum from $\sim$15 to 40 MeV rules out a dominant contribution from a three- (or more)-body breakup of ^{11}Li, because all such contributions rise rapidly in this region. The observed shape is characteristic of a major contribution by a two-body breakup of ^{11}Li with a threshold $\geq$3.0 MeV. We find that the breakup of ^{11}Li into $^{8}\text{He} + t$, which has a threshold of 5.7 MeV does not fit the data, leaving a substantial excess of counts unaccounted for in the 4 to 7 MeV excitation region. The only other possibility is to consider breakup channels containing a dineutron (n^2, a nearly bound state of two neutrons), as have indeed been invoked for ^{8}He continuum before [19]. Once again, the data allow very little contribution due to the breakup $^{11}\text{Li} \rightarrow {}^{9}\text{Li(g.s.)} + n^2$ (threshold $\approx$0.30 MeV). On the other hand, it is found that the data are very well fitted with a combination of a dominant contribution due to the breakup of ^{11}Li into ^{9}Li(2.69 MeV) + n^2, or ^{9}Li(4.31 MeV) + n^2 (curve *A*) and a smaller contribution due to $^{9}\text{Li} + n + n$ (curve *B*). If our explanation in terms of the dineutron breakup of ^{11}Li is correct, it is extremely tempting to identify the dineutron cluster in the breakup with the two-neutron halo in ^{11}Li. Thus our results are in favor of strong correlation

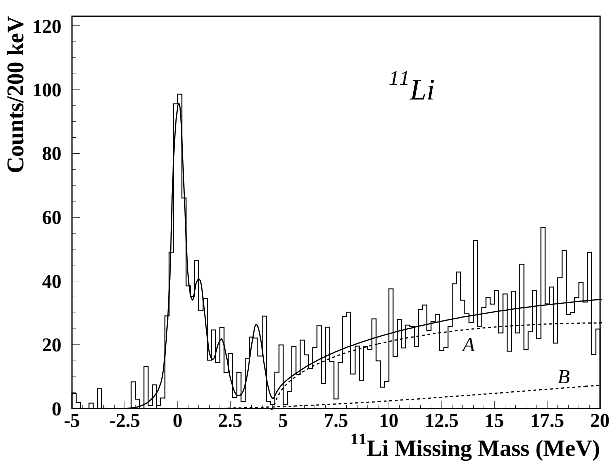

FIG. 3. Missing mass spectrum for ^{14}C(π^-, pd)^{11}Li, after subtraction of the ^{12}C(π^-, pd)^{9}Li contribution, as described in the text. The fit results are described in the text. Curve *A* represents the phase space for the breakup of ^{11}Li into ^{9}Li (4.3) + n^2, while curve *B* represents the phase space for the breakup of ^{11}Li into ^{9}Li (g.s.) + n + n.

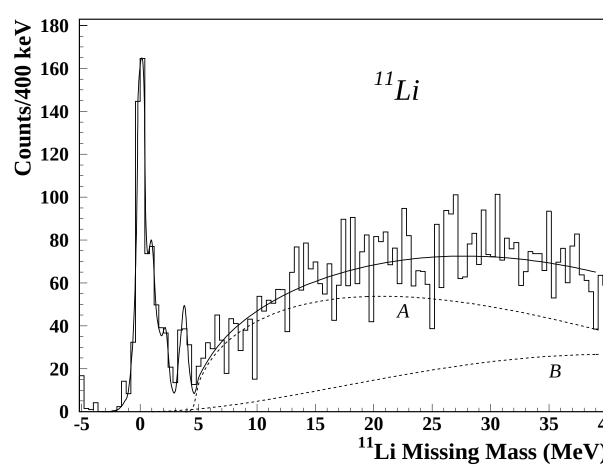

FIG. 4. Missing mass spectrum for ^{14}C(π^-, pd)^{11}Li over an extended range, in 400 keV bins. Curves *A* and *B* have the same designation as in Fig. 3.

between the two neutrons constituting the halo, as suggested in Refs. [4] and [20], and are in disagreement with the preferred interpretation of Refs. [10] and [15]. It is to be hoped that the shell-model calculations of Ref. [8] can shed light on this long-standing controversy by examining the overlaps between the states of ^{11}Li and ^{9}Li $+ (2n)$.

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