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New States in ^{9}Li from the Reaction ^{7}Li(t, p)^{9}Li

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Proton spectra from the reaction ^{7}Li(t,p)^{9}Li have been measured at triton energies of 15 and 19 MeV. Evidence is observed for new states in ^{9}Li at excitation energies of 4.31 ± 0.03, 5.38 ± 0.06, and 6.41 ± 0.02 MeV, having widths of 0.25 ± 0.03, 0.6 ± 0.1, and <0.1 MeV, respectively. Angular distributions were obtained at $E_t = 15$ MeV for the ground, 4.31-, and 6.41-MeV states. The shape of the ground-state distribution is similar to an $L=0$ distorted-wave Born-approximation calculation, in agreement with the assignment $J^\pi = \frac{3}{2}^-$ for the ground state of ^{9}Li. The relative magnitude of the cross section to the first excited state, when considered with other work, provides support for the assignment of $J^\pi = \frac{1}{2}^-$.

INTRODUCTION

Although considerable experimental information is available for $T=\frac{1}{2}$ states in $A=9$ nuclei, only the first two $T=\frac{3}{2}$ states have been previously observed. Numerous studies[1,2] of the β decay (or subsequent neutron emission) of ^{9}Li have given information about the ground state, and ^{9}Li has been observed as a spallation product[3] as well as through the reactions ^{7}Li(t,p)^{9}Li and ^{18}O(^{7}Li, ^{9}Li)-^{16}O.[4,5] The only previous evidence for excited levels of ^{9}Li comes from the reaction ^{7}Li(t,p)^{9}Li performed with 11.28-MeV tritons.[4] In that experiment the first excited level was observed to lie at an excitation energy of 2.691 MeV; no additional levels were found up to 4-MeV excitation. The measured angular distribution of the ground-state proton group indicates an assignment of $J^\pi = \frac{3}{2}^-$, in agreement with shell-model predictions.

The formation of ^{9}C from the proton bombardment of carbon and natural boron targets has been observed[6] by detecting delayed protons following positron decay of ^{9}C. Accurate measurements of the mass of ^{9}C have been made by observing ^{6}He energy spectra from the reaction ^{12}C-(^{3}He, ^{6}He)^{9}C [7] and by detecting the delayed protons from ^{9}C near the threshold for the reaction ^{7}Be-(^{3}He, n)^{9}C.[8] No experimental observations of excited levels in ^{9}C have yet been made.

The lowest $T=\frac{3}{2}$ state has been observed in ^{9}B at $E_X = 14.67$ MeV by means of the reaction ^{7}Li-(^{3}He, n)^{9}B,[8] the reaction ^{9}Be(^{3}He, t)^{9}B,[9] the reaction ^{11}B(p, t)^{9}B,[10] and the reaction ^{7}Li(^{3}He, $n\gamma$)^{9}B.[11,12] Similarly, the lowest $T=\frac{3}{2}$ state in ^{9}Be has been observed at $E_X = 14.39$ MeV in the reaction ^{7}Li-(^{3}He, p)^{9}Be,[1,13] the reaction ^{9}Be(^{3}He, ^{3}He′)^{9}Be,[9] the reaction ^{10}B(t, α)^{9}Be,[14] the reaction ^{11}B(p, ^{3}He)^{9}Be,[10] and the reaction ^{9}Be(e, e')^{9}Be[15]; in addition, γ decay of the 14.39-MeV level has been observed[11,12] following the reaction ^{7}Li(^{3}He, p)^{9}Be. The second $T=\frac{3}{2}$ state at 16.97 MeV in ^{9}Be has been observed as resonances in the reaction ^{7}Li(d, p)^{8}Li[16,17] and in the reactions ^{7}Li(d, γ)^{9}Be and ^{7}Li(d, n)^{8}Be.[17] The 16.97-MeV level has also been observed in the reaction ^{9}Be(e, e')^{9}Be,[15] and γ rays from this level have been seen in the reaction ^{7}Li(^{3}He, $p\gamma$)-^{9}Be.[12] The spin and parity of this level is thought to be either $\frac{1}{2}^-$ or $\frac{5}{2}^-$, with a preference for the former.[16]

A number of shell-model studies[18-20] have been performed in the last few years covering normal-parity states of the configuration $(1s)^4(1p)^{A-4}$. For the $A=9$ system, several negative-parity low-lying (~few MeV) $T=\frac{3}{2}$ states are predicted.[19,20] The purpose of the present experiment was to search for additional states in ^{9}Li using the reaction ^{7}Li(t, p)-^{9}Li, and in the sections that follow, evidence is given for three new states at excitation energies of 4.31, 5.4, and 6.41 MeV.

EXPERIMENTAL

A triton beam from the Los Alamos three-stage electrostatic accelerator was used to bombard a self-supporting ^{7}Li target of thickness 0.32 mg/cm^2. The reaction products from the target passed through a 0.16-cm wide tantalum collimator and were detected in an E-ΔE counter telescope. A gas proportional counter was used for the ΔE detector, and a 980-μm fully depleted surface-barrier detector was used for the E detector. A second solid-state detector located immediately behind the E detector was employed to reject particles which had sufficient energy ($E_p > \sim 12$ MeV) to penetrate the ΔE and E detectors. The proportional counter gas consisted of a mixture of argon (90%) and CO_2 (10%) and had an equivalent silicon

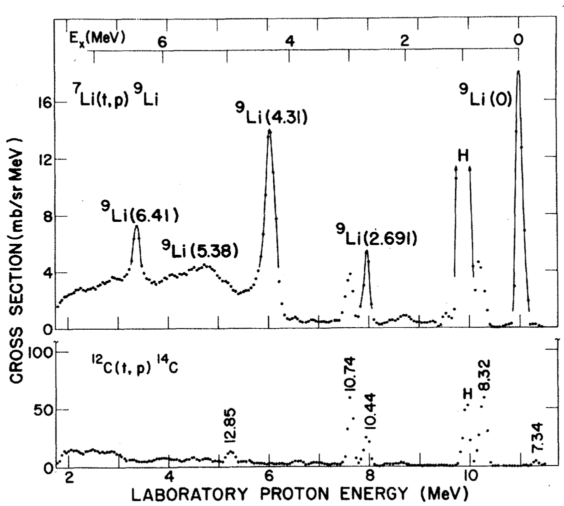

FIG. 1. Proton spectra from the reactions ^{7}Li(t,p)^{9}Li and ^{12}C(t,p)^{14}C at $E_t = 15$ MeV and $\theta_{lab} = 20°$. The height of the ^{12}C spectrum has been normalized to the amount of ^{12}C impurity present during the ^{7}Li run. The excitation-energy scale at the top of the figure is relative to the ground state of ^{9}Li.

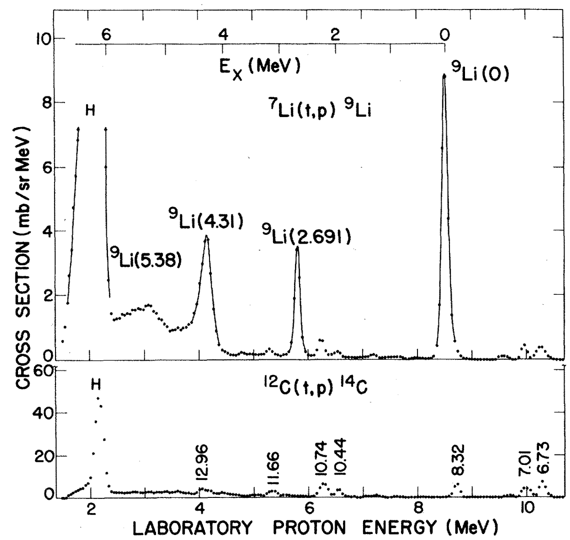

FIG. 2. Proton spectra from the reactions ^{7}Li(t,p)^{9}Li and ^{12}C(t,p)^{14}C at $E_t = 15$ MeV and $\theta_{lab} = 64°$. The height of the ^{12}C spectrum has been normalized to the amount of ^{12}C impurity present during the ^{7}Li run. The excitation-energy scale at the top of the figure is relative to the ground state of ^{9}Li.

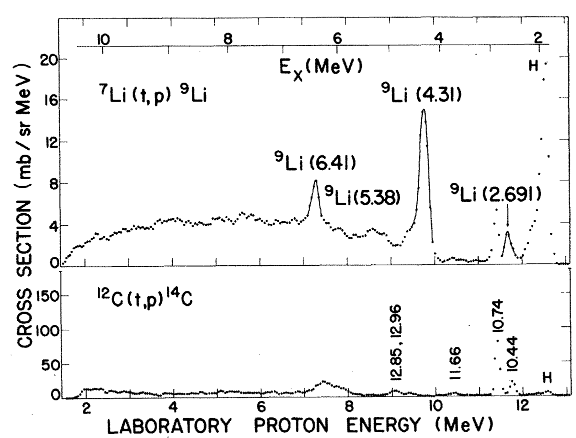

FIG. 3. Proton spectra from the reactions ^{7}Li(t,p)^{9}Li and ^{12}C(t,p)^{14}C at $E_t = 19$ MeV and $\theta_{lab} = 20°$. The height of the ^{12}C spectrum has been normalized to the amount of ^{12}C impurity present during the ^{7}Li run. The excitation-energy scale at the top of the figure is relative to the ground state of ^{9}Li.

thickness of 22 μm at the pressure used in the experiment ($\frac{3}{4}$ atm). This detector system has been used in several previous experiments requiring very thin ΔE detectors and is described more fully in an earlier paper.[21]

Data were collected with an SDS-930 on-line computer in an E by ΔE array of 128 by 64 channels. The analog-to-digital converters at the computer input were gated by a coincidence between the E and ΔE signals. Curve-fitting techniques were used to sort the E-ΔE arrays and to distinguish the desired proton spectra from the other particle spectra present. Finally, $E+\Delta E$ spectra were generated for each particle species. A parallel electronics system containing an analog particle identifier and a 400-channel pulse-height analyzer was used to monitor the proton spectra during data accumulation.

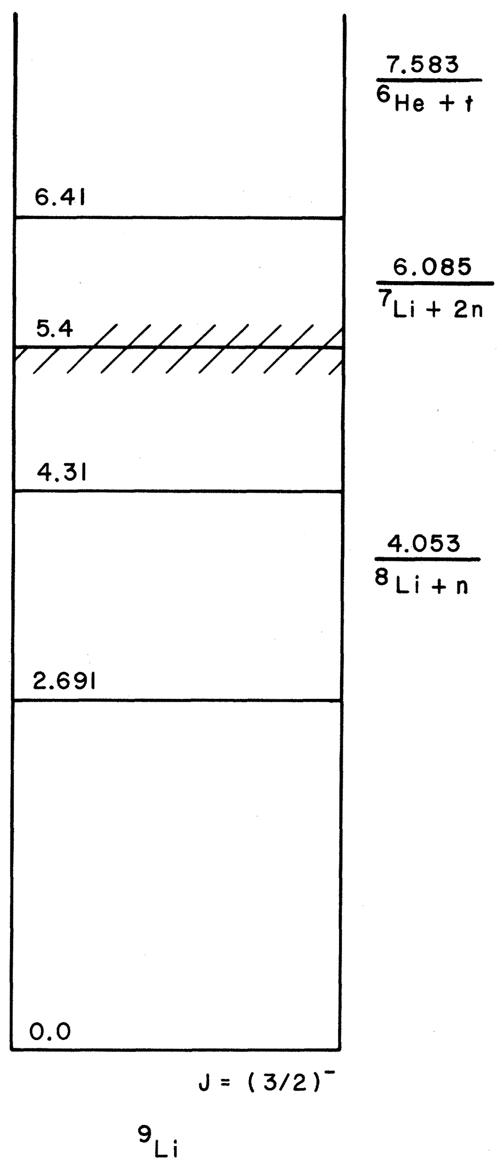

FIG. 4. Energy-level diagram for ^{9}Li.

RESULTS AND CONCLUSIONS

Spectra from the reaction ^{7}Li(t, p)^{9}Li were measured at 29 angles between $\theta_{1ab}=8$ and $96°$ for $E_t = 15$ MeV and at four angles between $\theta_{1ab}=20$ and $40°$ for $E_t = 19$ MeV. The major contaminant peaks present in the spectra resulted from hydrocarbon buildup on the ^{7}Li target. To aid in peak identification and to provide an energy calibration, proton spectra were measured at many of the same angles with a 0.05-mg/cm^2-thick carbon target. The spectra obtained with the ^{7}Li and ^{12}C targets for $E_t = 15$ MeV at $\theta_{1ab}=20$ and $64°$ are given in Figs. 1 and 2. Similarly, spectra measured at $E_t = 19$ MeV and $\theta_{1ab}=20°$ are given in Fig. 3. The excitation-energy scale shown at the top of each figure is relative to the ground state of ^{9}Li. The heights of

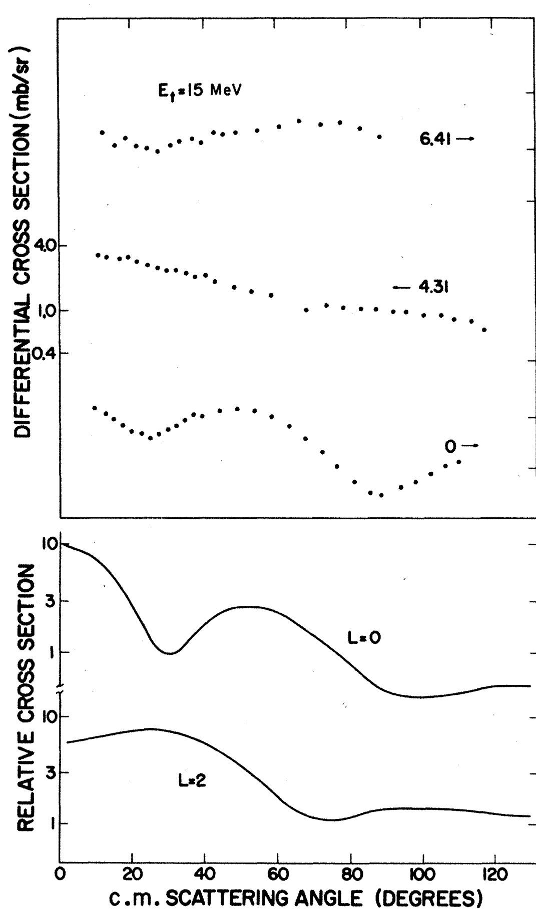

FIG. 5. Experimental angular distributions (dots) for the reaction ^{7}Li(t,p)^{9}Li to the ground, 4.31-, and 6.41-MeV levels. The solid curves labeled $L=0$ and $L=2$ are DWBA calculations as described in the text.

the $^{12}C(t,p)$ spectra have been normalized to the amount of ^{12}C impurity in the ^{7}Li target. The peaks in the ^{7}Li spectra due to the carbon impurity can be readily recognized from the corresponding $^{12}C(t,p)$ spectra. The large peaks labeled H in the figures are due to elastic recoil protons from the hydrocarbon impurity.

Peaks corresponding to excited levels in ^{9}Li at 2.69, 4.31, and 6.41 MeV are clearly seen in Figs. 1 and 3. The same groups are seen in Fig. 2 except the peak due to the 6.41-MeV level is obscured by the hydrogen-contaminant group. There is also persistent evidence in the spectra for a broad state in ^{9}Li near $E_X = 5.38$ MeV. The wide range of angles used ($\theta_{1ab} = 8-96°$) establishes that these observed groups can result only from the reaction $^{7}Li(t,p)^{9}Li$. The ground-state peak from the $^{7}Li(t,p)$ reaction was only observed in the $E_t = 15$-MeV measurements for which the E-ΔE detector system was thick enough to stop the high-energy proton group.

On the basis of 10 small-angle spectra obtained at $E_t = 15$ MeV, the excitation energies of the newly observed states in ^{9}Li are 4.31 ± 0.03, 5.38 ± 0.06, and 6.41 ± 0.02 MeV. These states are shown in the level diagram given in Fig. 4. The widths of the 4.31 and 5.38 MeV states are 0.25 ± 0.03 and 0.6 ± 0.1 MeV, respectively. The measured width of the 6.41-MeV level is approximately equal to the resolution of the detection system (0.14 MeV); therefore, only an upper limit of 0.1 MeV can be placed on the width of this level. It should be noted that the narrow width of the 6.41-MeV level occurs despite the fact that it is unstable by 2.36 MeV to decay by single-neutron emission and unstable by 0.32 MeV to decay by two-neutron emission.

Angular distributions were measured for the ground state and for the excited levels at 4.31 and 6.41 MeV, and these are presented in the upper portion of Fig. 5. (Because of contaminant groups, it was not possible to accurately establish the angular distribution of the 2.69-MeV level except at rather large angles.) Shown in the lower portion of Fig. 5 are distorted-wave Born-approximation (DWBA) calculations for the ground state made with the code CJULIE.[22] Optical-model parameters from fits of $t + {}^{12}C$ scattering[23] were used for the $t + {}^{7}Li$ channel; parameters resulting from our fit of $p + {}^{9}Be$ data[24] were used for the $p + {}^{9}Li$ channel. No attempt was made to fit the (t,p) data; however, the shape of the $L=0$ curve is quite similar to the experimental ground-state angular distribution and verifies the existence of a strong $L=0$ component. Therefore, since the target nucleus ^{7}Li has $J^{\pi} = \frac{3}{2}^{-}$, the ground state of ^{9}Li must also have $J^{\pi} = \frac{3}{2}^{-}$, which agrees with earlier observations.[4]

Because of the difficulty in applying two-particle stripping theory to particle unstable final states, no information has been obtained from the angular distributions regarding the spins and parities of the excited levels of ^{9}Li. An additional difficulty is, of course, that an $L=2$ momentum transfer in the reaction $^{7}Li(t,p)^{9}Li$ can excite all negative-parity states with $J \leq \frac{7}{2}$ in ^{9}Li. It is possible, however, to make some conjectures on the basis of shell-model calculations. The ordering of the normal-parity $T = \frac{3}{2}$ states of $A = 9$ predicted by Norton and Goldhammer[20] is $J = \frac{3}{2}$ (ground state), $\frac{1}{2}$ (3.23 MeV), $\frac{5}{2}$ (5.16 MeV), $\frac{3}{2}$ (5.97 MeV), and $\frac{7}{2}$ (6.81 MeV). While the spacing is somewhat different, this ordering is similar to that given by Barker.[19,25] In addition, Barker[25] has calculated relative probabilities for forming the $J = \frac{1}{2}$, $\frac{5}{2}$, $\frac{3}{2}$, and $\frac{7}{2}$ excited states with the reaction $^{7}Li(t,p)^{9}Li$ to be 1:15:7:2. From the present measurements we observe the integrated cross sections for the 2.69-, 4.31-, 5.4-, and 6.41-MeV levels to be very roughly in the proportions 2.8:15:5:3.5. Since there is previous evidence[16] that the 2.69-MeV level has $J^{\pi} = \frac{1}{2}^{-}$ or $\frac{5}{2}^{-}$ (with a preference for the former), the relative weakness of the 2.69-MeV transition measured here tends to support the $\frac{1}{2}^{-}$ choice. Finally, Barker[25] has estimated the widths of unbound states at 4.31, 5.4, and 6.41 MeV with $J = \frac{5}{2}$, $\frac{3}{2}$, and $\frac{7}{2}$ to be 0.16, 0.43, and 0.042 MeV, respectively. This calculation can be compared with the widths 0.25, 0.6, and <0.1 MeV which were measured for the levels at these same excitation energies. Considering the similarity of the experimental data to the calculated level energies, widths, and probabilities, it appears plausible that the newly observed levels at 4.31, 5.4, and 6.41 MeV correspond to the predicted $J^{\pi} = \frac{5}{2}^{-}$, $\frac{3}{2}^{-}$, and $\frac{7}{2}^{-}$ states. It is clear, however, that a conclusive answer must await additional experimental information. An attractive way to further study these states would be through the reaction $^{10}Be(d,{}^{3}He)$-^{9}Li ($Q = -14.1$ MeV), providing a satisfactory ^{10}Be target were available. Since ^{10}Be has $J^{\pi} = 0^{+}$, interpretation of angular distributions would be more straightforward than for the reaction $^{7}Li(t,p)^{9}Li$.

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Resonance Structure in Reaction ^{9}Be(d, γ)^{11}B†

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The reaction ^{9}Be(d,γ)^{11}B has been studied over the deuteron energy range of 0.56–3.56 MeV. A pulsed deuteron beam and time-of-flight electronics have been utilized to separate deuteron-capture γ rays from events due to neutrons and cosmic rays. From a graphical analysis of the excitation functions for the ground, first, and combined second and third excited states, two resonances have been identified corresponding to ^{11}B excitation energies of 17.44 ± 0.05 and 18.37 ± 0.05 MeV. The first of these occurs at the same energy as a level in ^{11}B found from other reactions. An interpretation in terms of $1s_{1/2}$ hole states is suggested. The overall behavior of the three excitation functions is used to justify a direct-capture reaction mechanism. Angular distributions were measured at 21 different deuteron energies. The near symmetry of the angular distributions about 90° and the peaking at 90° imply that a one-step deuteron-capture process is important for this reaction if the direct-capture mechanism is dominant. An appreciable forward peaking is observed for the first-excited-state angular distribution.

I. INTRODUCTION

The study of the radiative capture of energetic nucleons and composite particles has been undertaken primarily to understand the basic reaction mechanism. The capture of nucleons with an incident energy of less than a few MeV is adequately described by the compound-nucleus model. However, it has been definitely established that the capture of higher-energy neutrons and protons cannot be explained by statistical theory calculations.[1,2] Two types of direct-capture theories have been proposed. In the simplest of these, the incident nucleon is pictured as making a transition from a