OBSERVATION OF $T=\frac{3}{2}$ LEVELS IN Li^7-Be^7 AND THE UNCHARACTERIZED NUCLEI He^7, B^7, AND He^8†

Claude Détraz,* Joseph Cerny, and Richard H. Pehl

Department of Chemistry and Lawrence Radiation Laboratory, University of California, Berkeley, California

(Received 29 March 1965)

The location and properties of the hitherto unestablished $T=\frac{3}{2}$ levels in the $T_Z=\pm\frac{1}{2}$ nuclei Li^7 and Be^7 are important nuclear structure information; in addition, the question of particle stability of the controversial nuclei He^7, B^7, and He^8 should be answerable by extrapolation from these $T=\frac{3}{2}$ states.

As has previously been shown,[1-3] (p,t) and (p,He^3) reactions can be a valuable spectroscopic tool for locating states of high isospin in the residual nuclei. To investigate these mass-7 nuclei, the reactions $Be^9(p,t)Be^7$ and $Be^9(p,He^3)Li^7$ were induced by 43.7-MeV protons from the Berkeley 88-inch cyclotron. Tritons and He^3 emitted from the 650-μg Be^9 target were detected by a (dE/dx)-E counter telescope which fed a particle identifier.[4] Figure 1 shows two typical spectra obtained at 32.5 degrees; the energy resolution averaged 170 keV for tritons and 200 keV for He^3.

One would, in general, expect the angular distributions of the $T=\frac{1}{2}$ mirror states of Be^7 and Li^7 formed in these reactions to differ both in shape and magnitude. This arises since the (p,t) transitions occur predominantly by ${}^1S$, $T=1$ pickup of two neutrons, while the (p,He^3) transitions can occur by pickup of a proton-neutron pair in a predominant ${}^3S$, $T=0$ or ${}^1S$, $T=1$ configuration. Marked differences are in fact observed in the compared mirror angular distributions and are even apparent in Fig. 1.

However, transitions to $T=\frac{3}{2}$ states in Li^7 and Be^7, assuming the charge independence of nuclear forces, proceed from identical initial to final states through only ${}^1S$, $T=1$ pickup of the two nucleons; as such, identical cross sections are expected for such transitions after phase-space and isospin-coupling corrections (here only 1.1 %) are included (see reference 1). Indeed, Fig. 2 shows that the transitions to the pair of previously unobserved "mirror" levels at 11.13 ± 0.05 MeV in Li^7 and 10.79 ± 0.04 MeV in Be^7 are identical, considering the background subtraction and statistical errors. Therefore, these two states can be assigned a $T=\frac{3}{2}$ isospin. Their excitation energies are close to the theoretical estimates for the lowest $T=\frac{3}{2}$ state[5,6]

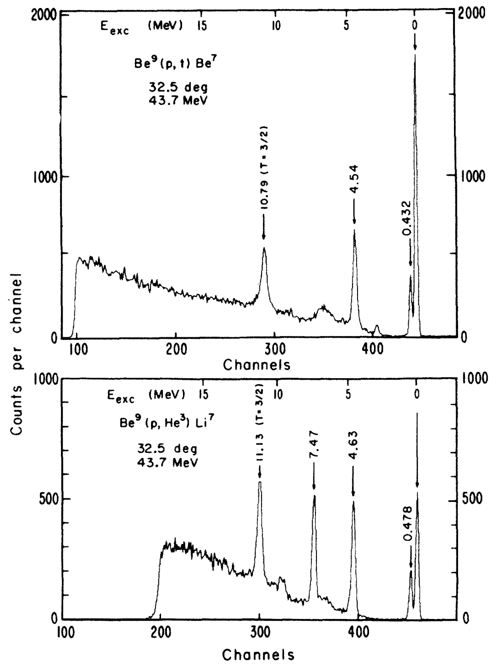

FIG. 1. Energy spectra for the reactions $Be^9(p,t)Be^7$ and $Be^9(p,He^3)Li^7$ at 32.5° in the laboratory system.

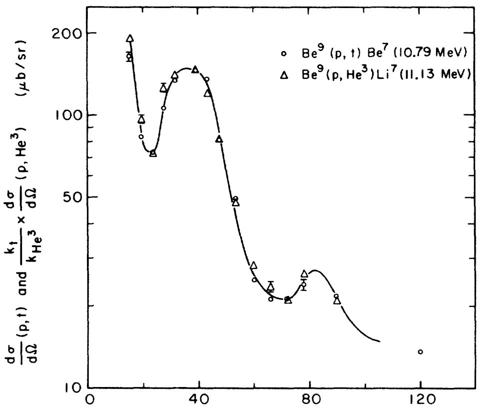

FIG. 2. Angular distributions for the $T=\frac{3}{2}$ states at 10.79 MeV in Be^7 and 11.13 MeV in Li^7. The cross sections for the Li^7 state have been corrected for phase space and isospin coupling by the factor of 0.989. The errors which appear on the figure are only statistical.

in Li^7—the first three $T=\frac{3}{2}$ states are predicted to be $\frac{3}{2}^-$ (10.9,[5] 10.1[6]); $\frac{1}{2}^-$ (~12.4[5,6]), and $\frac{5}{2}^-$ (13.7,[5] 13.2[6] MeV).

We note that the angular distributions in Fig. 2 have the same shape as is standardly observed for known $L=0$ transitions at 43.7 MeV (see Fig. 3 of reference 3). Due to angular-momentum conservation, this also restricts our transitions to be to the $\frac{3}{2}^-$ states. These two $T=\frac{3}{2}$ states are therefore the lowest ones—analogs of the He^7 and B^7 ground states.

The difference between the two excitation energies in Li^7 and Be^7, which is about 340 keV, is qualitatively in accord with the variation of the Coulomb energy with excitation, as calculated by Fairbairn[7]; with the difference in pairing energies between the $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states, estimated by Wilkinson[8] for the 1p shell; and with a probable Thomas-Ehrman shift.

These two $T=\frac{3}{2}$ levels are broad. Correcting for the experimental energy resolution, we find full widths at half maximum of 268 ± 30 keV for Li^{7*} and 298 ± 25 keV for Be^{7*}. These two widths are very similar, and both states can decay through three $T=\frac{3}{2}$ channels: He^6+p, Li$^{6*}(T=1)+n$, He$^4+p+2n$ for Li^{7*}; and Be^6+n, Li$^{6*}(T=1)+p$, He$^4+2p+n$ for Be^{7*}.

The mass of the He^7 nucleus can be obtained from the mass of Li$^{7*}(T=\frac{3}{2})$, taking into account the neutron-hydrogen atom mass difference and calculating the Coulomb energy difference from the pair He^6–Li$^{6*}(T=1)$. We find for He^7 a mass excess of[9] 26.03 ± 0.15 MeV in the C^{12} system; therefore, He^7 is definitely unbound to neutron emission by about 360 keV.[10] Assuming the first $T=\frac{3}{2}$ level of Li^7 to be lower than 10.81 MeV, Balashov[6] found that He^7 would be a β emitter with a half-life of 30-100 msec. He^7 being unbound, the assignment of 50 μsec for its half-life, which appears in the Chart of the Nuclides,[10] presumably quoted from reference 6 through a misprint in its abstract,[11] should be dropped.

A similar calculation to that for He^7, but using the $T=\frac{3}{2}$ state in Be^7 and the Coulomb energy difference from the pair Be^{10}–B$^{10*}(T=1)$, indicates a mass excess of[9] 27.99 ± 0.15 MeV for B^7. Though this value is smaller than the one predicted by Goldanskii[12] (29.4 ± 0.5 MeV in C^{12} system), B^7 is still quite unstable for particle emission, decaying to Li^5+2p, Be^6+p, and $\alpha+3p$.

To estimate the mass of He^8, we can use the arguments reported by Goldanskii,[13] namely that the difference between the binding energies of the fourth and third neutrons of the 1$p_{3/2}$ shell, $B_n(\text{He}^8)-B_n(\text{He}^7)$, is smaller than for the second and first neutrons, $B_n(\text{He}^6)-B_n(\text{He}^5)$, but larger than $B_n(\text{Li}^9)-B_n(\text{Li}^8)$, where the extra proton disturbs, by a deuteron-like bond, the pairing between the two neutrons. Using the mass of He^7 as calculated above, we obtain the following double inequality:

$$31.6\text{ MeV} < \text{mass excess (He}^8) < 32.4\text{ MeV}.$$

Since the lightest particle-unstable channel is He^6+2n, the mass excess of which is 33.74 MeV, He^8 should be stable to neutron emission by at least 1.3 MeV.[14]

After theoretical predictions[13,15] and experimental hints,[16] the particle stability of He^8 has recently received its most reliable proof with the observation by Nefkens[17] of what is thought to be its β decay. He^8 can decay to the 3.22-MeV (1$^+$) level and, if it is a 1$^+$ level,[18] the 0.978-MeV level of Li^8. If the latter decay is possible, our He^8 mass predicts an end-point energy lying between 9.7 and 10.5 MeV, which is slightly outside the values given by Nefkens, 13 ± 2 MeV. A lower energy than his would produce a lower value of logft; his value of 4.3 seems somewhat high for this allowed transition.

These results for He^8 can be used to limit the mass excess of the tetraneutron n^4, which has recently "regained" stability with the apparent discovery that the trineutron n^3 is bound by about 1 MeV.[19] Our He^8 mass and the observed β decay[17] require a mass excess of more than 29.2 MeV for n^4; if Goldanskii's treatment[13] is still meaningful for such very light nuclei, the pairing energy for the last two neutrons $[B_n(n^4)-B_n(n^3)]$ would be at most 1 MeV, which appears somewhat low.

To summarize, the determination of the lowest $T=\frac{3}{2}$ level energies and widths in Li^7 and Be^7 implies that He^7 is unbound by about 360 keV with a very short half-life (some 10^{-21} sec), that B^7 is even more unbound, but that He^8 is bound, decaying by β^- emission with a maximum energy of the order of 10.1 ± 0.4 MeV.

---

†Work performed under the auspices of the U. S. Atomic Energy Commission.

*CNRS and NATO fellow, visitor from Laboratoire

Joliot-Curie de Physique Nucleaire, Orsay, France.

[1] J. Cerny and R. H. Pehl, Phys. Rev. Letters 12, 619 (1964).

[2] G. T. Garvey, J. Cerny, and R. H. Pehl, Phys. Rev. Letters 12, 726 (1964).

[3] J. Cerny, R. H. Pehl, and G. T. Garvey, Phys. Letters 12, 234 (1964).

[4] F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instr. Methods 31, 1 (1964).

[5] S. Meshkov and C. W. Ufford, Phys. Rev. 101, 734 (1956).

[6] V. V. Balashov, At. Energ. (USSR) 9, 48 (1960) [translation: Soviet J. At. Energy 9, 544 (1961)].

[7] W. M. Fairbairn, Nucl. Phys. 45, 437 (1963).

[8] D. H. Wilkinson, Phys. Rev. Letters 13, 571 (1964).

[9] This error of 150 keV is considerably larger than the errors on the masses of the analog Li^{7*} and Be^{7*} states and is our estimate of the accuracy of a Coulomb energy correction in such light nuclei.

[10] In a note added in proof in reference 4, a particle identifier spectrum was shown with a group marked $He^7(P)$. This was, in fact, submitted as $He^7(?)$. The possibility that the particular group could be He^7 was based on its lifetime given in Chart of the Nuclides (Knolls Atomic Power Laboratory, General Electric Company, Schnectady, New York, 1964), 7th ed., which is herein shown to be erroneous.

[11] Nucl. Sci. Abstr. 14, 2893 (1960).

[12] V. I. Goldanskii, Nucl. Phys. 19, 482 (1960). See also A. I. Baz, V. I. Goldanskii, and Ya. B. Zeldovich, Usp. Fiz. Nauk 3, 211 (1961) [translation: Soviet Phys.—Usp. 3, 729 (1961)].

[13] V. I. Goldanskii, Zh. Eksperim. i Teor. Fiz. 38, 1637 (1960) [translation: Soviet Phys.—JETP 11, 1179 (1960)].

[14] Calculations in the mass-8, $T = 2$ system based on this He^8 mass give for C^8 a mass excess of 36.4 ± 0.8 MeV, which agrees with the predictions of reference 12 (<38 MeV in the C^{12} system), and implies that C^8 is unbound.

[15] Ya. B. Zeldovich, Zh. Eksperim. i Teor. Fiz. 38, 1123 (1960) [translation: Soviet Phys.—JETP 11, 812 (1960)].

[16] O. V. Lozhkin and A. A. Rimskii-Korsakov, Zh. Eksperim. i Teor. Fiz. 40, 1519 (1961) [translation: Soviet Phys.—JETP 13, 1064 (1961)].

[17] B. M. K. Nefkens, Phys. Rev. Letters 10, 243 (1963).

[18] D. Kurath, Phys. Rev. 101, 216 (1957); J. B. French and A. Fujii, Phys. Rev. 105, 652 (1957); L. F. Chase, R. G. Johnson, F. J. Vaughn, and E. K. Warburton, Phys. Rev. 127, 859 (1962).

[19] V. Ajdačić, M. Cerino, B. Lalović, G. Paić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters 14, 444 (1965).