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THE OBSERVATION OF T=3/2 LEVELS IN Li$^7$-Be$^7$ AND THE UNCHARACTERIZED NUCLEI He$^7$, B$^7$ AND He$^8$

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March 1965
THE OBSERVATION OF $T = 3/2$ LEVELS IN Li$_7$ - Be$_7$ AND THE UNCHARACTERIZED NUCLEI He$_7$, B$_7$ AND He$_8$.

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The location and properties of the hitherto unestablished $T = 3/2$ levels in the $T_Z = \pm 1/2$ 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 $T = 3/2$ states.

As has previously been shown, the $^{12}$Be$_7$($p,t$) 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 seven 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. 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 $T = 1/2$ 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 $^1S$, $T = 1$ pick-up of two neutrons, while the ($p$,He$_3$) transitions can occur by pick-up 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 $T = 3/2$ states in Li$^7$ and Be$^7$, assuming the
close independence of nuclear forces, proceed from identical initial to final
states through only $1s$, $T = 1$ pick-up 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 Ref. 1). Indeed, Fig. 2
shows that the transitions to the pair of previously unobserved "mirror" levels
at $11.13 \pm 0.05$ MeV in Li$^7$ and $10.79 \pm 0.04$ MeV in Be$^7$ are identical, consider-
ing the background subtraction and statistical errors. Therefore, these two
states can be assigned a $T = 3/2$ isospin. Their excitation energies are close
to the theoretical estimates for the lowest $T = 3/2$ state$^5,6$ in Li$^7$—the first
three $T = 3/2$ states are predicted to be $3/2^- (10.9^5, 10.1^6)$; $1/2^- (\approx 12.4^5,6)$,
and $5/2^- (13.7^5, 13.2^6$ 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 Ref. 3). Due to angular momentum conservation, this also restricts
our transitions to be to the $3/2^-$ states. These two $T = 3/2$ 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 $T = 1/2$ and $T = 3/2$ states, esti-
mat ed by Wilkinson$^8$ for the 1$p$ shell; and with a probable Thomas-Ehrman
shift.

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

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

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

To estimate the mass of $\text{He}^8$, we can use the arguments reported by Goldanskii, namely that the difference between the binding energies of the fourth and third neutrons of the $1p_{3/2}$ 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 $\text{He}^7$ 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 $\text{He}^6 + 2n$, the mass excess of which is $33.74$ MeV, $\text{He}^8$ should be stable to neutron emission by at least $1.3$ MeV.

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

These results for $\text{He}^8$ can be used to limit the mass excess of the tetranucleon $n^4$, which has recently "regained" stability with the apparent discovery that the trinucleon $n^3$ is bound by about $1$ MeV. Our $\text{He}^8$ mass and the observed $\beta$-decay require a mass excess of more than $29.2$ MeV for $n^4$; if Goldanskii's treatment 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 $T = 3/2$ level energies and widths in $\text{Li}^7$ and $\text{Be}^7$ implies that $\text{He}^7$ 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 $\text{He}^8$ is bound, decaying by $\beta$-emission with a maximum energy of the order of $10.1 \pm 0.4$ MeV.
FOOTNOTES AND REFERENCES

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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 Ref. 4, a particle identifier spectrum was shown with a group marked He$^7$(P). This was in fact submitted as He$^7$?6. The possibility that the particular group could be He$^7$ was based on its lifetime given in Ref. 11, which is herein shown to be erroneous.
11. Chart of the Nuclides, Knolls Atomic Power Laboratory, USAEC, 7th ed.

15. Calculations in the mass 8, T = 2 system based on this He mass give for C\(^8\) a mass excess of 36.4 ± 0.8 MeV, which agrees with the predictions of Ref. 13 (< 38 MeV in the C\(^{12}\) system), and implies that C\(^8\) is unbound.


FIGURE CAPTIONS

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

Fig. 2. Angular distributions for the \(T = 3/2\) 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.
Fig. 1

Be\(^9\) (p, t) Be\(^7\)

32.5 deg
43.7 MeV

Be\(^9\) (p, He\(^3\)) Li\(^7\)

32.5 deg
43.7 MeV
\[ \frac{d\sigma}{d\Omega} (p, t) \] and \[ \frac{k_t}{k_{He^3}} \times \frac{d\sigma}{d\Omega} (p, He^3) \]

- Be\(^9\) (p, t) Be\(^7\) (10.79 MeV)
- Be\(^9\) (p, He\(^3\)) Li\(^7\) (11.13 MeV)

\( \theta_{c.m.} \) (deg)

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Fig. 2
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