K Capture of Be^7 and the Excited State of Li^7

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The fraction of Be^7 *K* capture to the 478 kev excited state of Li^7 has been experimentally determined to be 0.107 ± 0.02. The experimental method consisted in measuring the number of Be^7 atoms by counting neutrons from the $Li^7(pn)Be^7$ reaction, and in observing the subsequent number of 478 kev gammas by use of a counter calibrated by beta-gamma-coincidences from Au^{198}. Implications concerning the character of the 478 kev Li^7 level are discussed.

UNTIL recently it has been usually assumed that the 478 kev excited state of Li^7 was the $P_{\frac{1}{2}}$ branch of a spin multiplet with the ground state being the $P_{3/2}$ branch since the observed total angular momentum of the ground state is $\frac{3}{2}$. Such an assignment was consistent[1,2] with the one published measurement[3†] of the fraction (3 percent–30 percent) of Be^7 *K* captures to the excited state of Li^7. When, however, the total angular momentum of the ground state of B^{10} was measured[4] to be 3 instead of 1, it became difficult to understand why the disintegration of B^{10} by thermal neutrons, $B^{10}(n, \alpha)Li^7$, should leave the Li^7 in the 478 kev excited state in 93 percent of the disintegrations.[5]

To explain the boron disintegration branching, Inglis[6] has postulated that the excited state of Li^7 was a $F_{5/2,7/2}$ spin multiplet. Such an *F* state is hard to reconcile with the above branching of *K* capture in Be^7 if the ground states of Be^7 and Li^7 are to be regarded as primarily *P* states. However, there were large experimental uncertainties in the old branching ratio measurement, and hence an independent and more direct determination of this branching ratio seemed desirable.

Our method for determination of the branching ratio consisted in (1) measuring the number of Be^7 nuclei formed in the $Li^7(p, n)Be^7$ reaction by counting the neutrons in a calibrated neutron counter, and (2) in observing the number of *K* captures to the excited state by counting the 478 kev gammas from the subsequent decay of the excited state.

The calibration of the gamma-counter can be made quite accurate because of the fortunate circumstance that the simple beta-decay of Au^{198} is followed by a single gamma-ray[7–12,*] whose energy of 411.2 kev[11] is nearly the same as the 478 kev gamma from lithium so that only a small correction is required for the change in gamma-counting efficiency as a function of gamma-ray energy. The efficiency (including solid angle) of the gamma-counter was determined in the conventional manner[13] by counting simultaneously the single counts in a beta-counter and the beta-gamma-coincident counts between the beta- and gamma-counters which were located on opposite sides of a $\frac{1}{8}$-inch diameter piece of activated 0.003 inch gold foil. For this geometry, it was shown experimentally that small variations in the position, size and thickness of the gold source had negligible effects on the efficiency determinations. We believe that the calibration of the gamma-counters was good to about 6 percent.

The determination of the number of neutrons (hence Be^7 nuclei) was more difficult, though we may hope for only a 10 percent uncertainty in this factor by making proper choice of neutron detector and bombarding conditions. An energy insensitive shielded "long counter"[14] one meter from the target and at 0° to the proton beam was the neutron detector. This long counter was then calibrated in position by placing a calibrated Ra-Be neutron source at the target. The relative efficiency for counting the Ra-Be neutrons is the same as that for counting 500 kev neutrons according to Fig. 5 of reference 14.

Two different thin (30 kev and 15 kev) lithium targets were bombarded by about 6 microampere hours of 2.3 Mev protons. At this voltage, the neutron energy in the forward direction is about 500 kev and the laboratory angular distribution is very asymmetric. The total neutron flux was obtained by use of Taschek and Hemmindinger's data[15] on the angular distribution at this energy. Since the neutron detector is at 0°, the strong forward bunching of the neutrons makes the integrated

[1] G. Breit and J. Knipp, Phys. Rev. **54**, 652 (1938).
[2] E. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).
[3] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).
† *Note added in proof.*—C. M. Turner, in a recent letter in Phys. Rev. **76**, 148 (1949), reports a preliminary value of 10 to 13 percent for the fraction of Be^7 *K* captures to the excited state of Li^7. This value is in good agreement with the present work.
[4] Gordy, Ring, and Burg, Phys. Rev. **74**, 1191 (1948).
[5] C. W. Gilbert, Proc. Camb. Phil. Soc. **44**, 447 (1948); J. K. Boggild, Kgl. Danske Vid. Sels. Math. Fys. Medd. **23**, 4 (1945).
[6] D. R. Inglis, Phys. Rev. **74**, 1876 (1948).
[7] D. Saxon and R. Heller, Phys. Rev. **75**, 909 (1949).
[8] K. Siegbahn and A. Hedgran, Phys. Rev. **75**, 523 (1949).
[9] E. Jurney, Phys. Rev. **74**, 1049 (1948).
[10] R. Wilkinson and C. Peacock, Phys. Rev. **74**, 1250 (1948).
[11] DuMond, Lind, and Watson, Phys. Rev. **73**, 1392 (1948).
[12] P. Levy and E. Greuling, Phys. Rev. **75**, 819 (1949).

* References 11 and 12 take exception to this statement and report the presence of low intensity 208 kev and 157 kev gamma-rays. However, were the decay scheme advocated by Levy and Greuling to be substantiated, a rough estimate shows that our counter calibration would be changed by about 8 percent. The change would raise our values of $(\lambda^*/\lambda+\lambda^*)$ in Table I by about 8 percent.
[13] A. C. G. Mitchell, Rev. Mod. Phys. **20**, 296 (1948).
[14] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[15] R. F. Taschek and A. Hemmindinger, Phys. Rev. **74**, 373 (1948).

TABLE I. Summary of measurements on the fraction of Be^7 K captures which leave the Li^7 nucleus in the 478 kev excited state.

Lithium Target	No. 1	No. 2	No. 3
Thickness (kv)	90	30	15
Bombarding proton energy in Mev	2.0	2.3	2.3
Total counts (C_n) in neutron detector	1.71×10^6	3.12×10^6	0.691×10^6
Relative efficiency (μ) for detection of neutrons from Ra-Be and from $Li^7(pn)Be^7$	1.04[a]	1.00[a]	1.00[a]
$\alpha=\sigma/4\pi\sigma(0°)$ where $\sigma(0°)$ is the differential cross section of the $Li^7(pn)Be^7$ reaction and σ is the total cross section	0.64[b]	0.34[b]	0.33[b]
Total number of Be^7 atoms, $N_{Be^7}=[\mu C_n\alpha/(\epsilon_n\omega_n)_{RaBe}]$ where $(\epsilon_n\omega_n)_{RaBe}=0.757\pm0.01\times10^{-6}$ is the observed neutron detection efficiency, including solid angle, for the calibrated Ra-Be source	1.50×10^{12}	1.40×10^{12}	0.302×10^{12}
Observed Be^7 gamma-activity, A_{Be^7} (corrected for decay) in counts per sec.	16.8±0.2	16.9±0.2	3.45±0.2
Fraction $(\lambda^*/\lambda+\lambda^*)$ of Be^7 K captures which lead to Li^7 excited: $(\lambda^*/\lambda+\lambda^*)=[A_{Be^7}/N_{Be^7}(\lambda+\lambda^*)(\epsilon\gamma\omega\gamma)_{Be^7}]$ where $\lambda+\lambda^*=\log2/T_{\frac{1}{2}}$ and $T_{\frac{1}{2}}=52.93\pm0.22$ days[c] $(\epsilon\gamma\omega\gamma)_{Be^7}=7.1\pm0.4\times10^{-4}$ = gamma-counting efficiency (including solid angle) for the Be^7 activity $=(478/411)(\epsilon_\gamma\omega_\gamma)_{Au^{198}}=(478/411)(N_{\beta\gamma}/N_\beta)_{Au^{198}}$	0.104±0.006	0.112±0.007	0.106±0.007

[a] From Fig. 5 of reference 14.
[b] From Figs. 2–4 of reference 15.
[c] Reference 16.

neutron flux relatively insensitive to possible uncertainties in the angular distribution at the large angles.

A third lithium target was bombarded by 2.0 Mev protons. At this energy the angular distribution in the laboratory is much more nearly spherically symmetric.[15]

Any neutron induced activity in the 0.010 inch tantalum target backings was shown experimentally to be less than 2 percent of the Be^7 activity and hence negligible for these measurements. It should also be pointed out that no Be^7 activity is lost by recoiling Be^7 nuclei leaving the target. Since the reaction is endothermic, the velocity of the center of mass system is always large compared to Be^7 center of mass velocity, and hence in the laboratory system all Be^7 recoils are toward the tantalum backing.

All measured Be^7 activities were corrected to the initial activities by using Segré and Wiegand's precise value[16] of the half-life, $T_{\frac{1}{2}}=52.93\pm0.22$ days.

Results for the three targets are shown in Table I where the indicated errors are only statistical. The agreement of the data for targets bombarded with different proton energies indicates absence of large errors arising from uncertainties in the angular distribution of the neutrons. The major error in absolute number of neutrons probably is associated with the Ra-Be neutron standard. This Ra-Be source was calibrated last August at the Argonne National Laboratories as emitting 0.998×10^6 neutrons per second. However, in view of the difficulties in absolute flux measurements, we doubt whether our number of Be^7 atoms is known to better than 10 percent.

A mean value from all three targets would therefore give for the fraction (f) of transitions to the excited state, $f=0.107\pm0.02$, where the indicated error now includes an estimate of the uncertainty in both the neutron and gamma-calibration.

[16] E. Segré and C. Wiegand, Phys. Rev. **75**, 43 (1949).

DISCUSSION

Experimentally Be^7 K capture is an "allowed" transition.[2] In the discussion of our experimental data, we will follow Rosenfeld's[17] treatment of allowed transitions on Wigner's approximation. On Wigner's "first approximation" only transitions between the "fine structure" components of a multiplet are "allowed" and all terms have a definite L but not necessarily a definite S. The general expression for the lifetime is

$$1/T_{\frac{1}{2}}=(1/\tau_0\log2)\sum_f|G_{if}|^2I(W_{if}),$$

where τ_0 is the characteristic time constant of beta-decay, G_{if} is the matrix element for the transition from an initial state i to a final state f and $I(W_{if})$ for our case of K capture is

$$I(W_{if})=2\pi(Z_{\text{eff}}/137)^3W_{if}^2,$$

where W_{if} is the difference in energy (in units mc^2) between the initial and final state. $Z_{\text{eff}}=3.7$ for Be.

For Be^7 K capture the sum is taken over the transition to the ground state of Li^7 and to the 478 kev level. The differences in energy between the initial and final states are now known very accurately from the recent absolute voltage determination[18] of the $Li^7(p,n)Be^7$ threshold (±0.1 percent) and the $n-H$ mass difference[19]

[17] L. Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949), Vol. II, Appendix I, p. 377.
[18] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).
[19] Tollestrup, Jenkins, Fowler, and Lauritsen, Phys. Rev. **76**, 181 (1949).

(=0.800±0.004 Mev) and energy of the gamma-ray (478±1.5 kev)[20] from the excited state of Li^7. The resulting W's are given in Table II.

For the assumption of the Gamow-Teller interaction, the matrix elements can be calculated by the usual procedures of atomic spectroscopy.[21] The results are displayed in Table II for various assumptions concerning the character of the states involved.

From Table II it is seen that transitions (2) and (3) are definitely excluded by the present measurements. Transition (1) almost agrees with the present experiment but of course the $P_{\frac{1}{2}}$ assignment to the excited level of Li^7 is in disagreement[6,22] both with the branching of $B^{10}(n\alpha)Li^7$ and with the variation[3] with deuteron energy of the $Li^6(dp)Li^7$ reactions. Transition (4) does not quite satisfy the present experimental data, and furthermore the assumed difference in total angular momentum of the ground states of the mirror nuclei Be^7 and Li^7 is very unlikely according to current ideas of nuclear structure.

The existence of tensor forces may be expected to produce a mixing of states. In transition (5) we assume that the ground states of Be^7 and Li^7 are identical and primarily $P_{3/2}$ but contain an unspecified admixture of $D_{3/2}$. On the further assumption that the excited state is predominantly $D_{5/2}$, we may use the experimentally determined branching ratio to estimate roughly the amount of admixture required. The result is a 25 percent $D_{3/2}$ probability. The approximate character of this result should be emphasized since among other things, the matrix elements may be sensitive to detailed assumptions concerning the respective wave functions. It will be noted that transition (5) is also consistent with the $B^{10}(n\alpha)Li^7$ branching and with the dependence on deuteron energy of the $Li^6(dp)Li^7$ reactions.

It is possible that this large admixture of $D_{3/2}$ may give trouble in understanding the magnetic moment of Li^7. However, the pure $P_{3/2}$ state usually assumed does not in itself predict[23] a value of the magnetic moment in very good agreement with experiment. Furthermore, the neglect of contributions from exchange currents may not be justified. Therefore, perhaps the possibility of a large $D_{3/2}$ admixture warrants further consideration.

Two other hypotheses might reconcile all the experimental data:

(a) Two different excited levels of Li^7 may be involved.

TABLE II. Comparison of possible allowed transitions.

Transition assumed	$\lvert G_{if}\rvert^2$ on GT interaction	W_{if}	Branching ratio $\frac{\lambda^*}{\lambda}=\frac{\lvert G^*\rvert^2 I^*(W)}{\lvert G\rvert^2 I(W)}$	Fraction to excited state $\frac{\lambda^*}{\lambda+\lambda^*}$	τ_0 (sec.)
(1) $P_{3/2}\nearrow P_{1/2}$	4/9	0.725			
$P_{3/2}\searrow P_{3/2}$	5/9	1.66	0.152	0.13	1.44×10^3
(2) $P_{1/2}\nearrow P_{1/2}$	1/9	0.725			
$P_{1/2}\searrow P_{3/2}$	8/9	1.66	0.024	0.023	
(3) $D_{3/2}\nearrow D_{5/2}$	12/15	0.725			
$D_{3/2}\searrow D_{3/2}$	3/15	1.66	0.759	0.43	
(4) $D_{5/2}\nearrow D_{5/2}$	7/15	0.725			
$D_{5/2}\searrow D_{3/2}$	8/15	1.66	0.166	0.14	1.40×10^3
(5) $aP_{3/2}+bD_{3/2}\nearrow D_{5/2}$	$b(12/15)$	0.725			
$aP_{3/2}+bD_{3/2}\searrow aP_{3/2}+bD_{3/2}$	$a^2(5/9)+b^2(3/15)$	1.66	0.120	0.107	1.69×10^3

($a=0.75$; $b=0.25$, chosen to give correct experimental value)

[20] L. G. Elliot and R. E. Bell, Phys. Rev. **74**, 1869 (1948).
[21] For example see Rosenfeld, reference 17, p. 380. In his formula (13) of Section A1.131 replace $2(L-1)$ by $(2L-1)$.
[22] L. R. Hafstad and E. Teller, Phys. Rev. **54**, 681 (1938).
[23] For a summary discussion and references see Rosenfeld, reference 17, p. 413.

(b) The total orbital angular momentum L may not be a good quantum number.††

Hypothesis (a) seems unlikely in view of the recent determinations[20,24] of the equivalence in energy of the excited state independent of the reaction producing it.

An experimental measurement of the angular momentum and magnetic moment of Be^7 would be of great help in choosing between various hypotheses, as also would a measurement of the electric quadrupole moment of Li^7.‡

In Table II is also included a calculation of τ_0, the characteristic time constant of beta-decay, which employs the very accurate data on $I(W)$ and $T_{\frac{1}{2}}$ which is now available.

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†† *Note added in proof.*—This hypothesis is discussed by S. S. Hanna and D. R. Inglis in a recent letter to Phys. Rev. **75**, 1767 (1949).

[24] Rasmussen, Lauritsen, and Lauritsen, Phys. Rev. **75**, 199 (1949); Zaffarano, Kern, and Mitchell, Phys. Rev. **74**, 105 (1948); F. N. D. Kurie and M. Ter-Pogossian, Phys. Rev. **74**, 677 (1948); Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948); Fowler, Lauritsen, and Rubin, Phys. Rev. **75**, 1463, 1471 (1949).

‡ *Note added in proof.*—The sign of the electric quadrupole moment of Li^7 has been recently found (Kusch, Phys. Rev. **76**, 138 (1949)) to be positive instead of negative as expected on past nuclear models. According to recent unpublished calculations of R. Avery and C. Blanchard at the University of Wisconsin, both the magnetic moment and electric quadrupole moment of Li^7 can be accounted for correctly in sign and approximate magnitude by assuming that the ground state of Li^7 is predominately $D_{3/2}$.

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Neutron-Capture Cross Section of 85-Minute Ba^{139}

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Four samples of barium carbonate were irradiated with neutrons at three different times and at three different positions in the heavy water pile. A few days after an irradiation, lanthanum separations were made until no further La^{140} activity could be detected. The lanthanum was discarded. At intervals of 4 to 9 days the La^{140} grown from the Ba^{140} was separated and its number of atoms determined with a calibrated Geiger-Müller counter. The fluxes of thermal neutrons were obtained by experiment as far as possible; the maximum used was 2.0×10^{13} neutrons/cm²/sec. The final value for the capture cross section of Ba^{139} is 4.7 ± 1.2 barns.

I. INTRODUCTION

CROSS SECTIONS for the capture of thermal neutrons by stable elements have been measured in numerous investigations. A nucleus of mass A transforms to one of mass $A+1$ when a neutron is captured. This nucleus is radioactive in some cases and stable in others. Some methods of measuring capture cross sections that require little or no knowledge of scattering cross sections are (1) the activation method, (2) the pile reactivity method, and (3) the mass spectrographic method. The activation method is applicable when the nuclei formed by neutron-capture are radioactive. The number of thermal neutrons captured per second is equal to and in practice obtained from the number of β-disintegrations per second at saturation. This method of measuring capture cross sections has been applied, for instance, by Seren, Friedlander, and Turkel,[1] who discussed it in detail and presented a long list of measurements. When the nucleus of mass $A+1$ is stable, the number of thermal neutrons captured per second has to be determined in some other way such as by the change in the reactivity of a chain-reacting pile.[2] If the capture cross section is high, the mass spectrograph shows a measurable change in the relative abundances of the isotopes before and after a prolonged irradiation.[3] Numerical values of cross sections could be obtained in favorable cases.

The combination of high flux of thermal neutrons in a pile and the activation method permits capture cross sections to be measured even for β-active nuclei. A stable isotope of atomic number Z and mass A is irradiated with neutrons in a pile, producing β-active isotopes of masses $A+1$, $A+2$, $\cdots$ in succession. The amounts of these successive isotopes produced in a given time are in rapidly decreasing orders of magnitude. It is clear that if the neutron flux is sufficiently high, the amount of isotope of mass $A+2$ produced by neutron bombardment can, in many cases, be either directly measured, or obtained from a measurement on

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[1] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).

[2] Anderson, Fermi, Wattenberg, Weil, and Zinn, Phys. Rev. **72**, 16 (1947).

[3] Lapp, VanHorn, and Dempster, Phys. Rev. **71**, 745 (1947). A. J. Dempster, Phys. Rev. **71**, 829 (1947).