Neutrons from the Proton Bombardment of Li^6 and Li^7*

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The $Li^7(p,n)Be^7$ and $Li^6(p,n)Be^6$ reactions were studied at $E_p=10.5$ Mev, by the method of proton recoils in nuclear emulsions. The $Li^7(p,n)Be^7$ spectra at 30° and 90° show the known states of Be^7 at 0, 0.43, and 4.53 Mev. The cross section for formation of the ground state at 90° (lab) is 3.2 mb/sterad (±30%). The $Li^6(p,n)Be^6$ spectra at 30°, 60°, 90°, and 135° show ground-state groups with $Q=-5.05\pm0.2$ Mev. This leads to $(M-A)$ for $Be^6=20.13\pm0.2$ Mev. $Be^6(0)$ is thus unbound with respect to (He^4+2p) by 1.35 Mev. The cross section for formation of $Be^6(0)$ at 90° (lab) is 0.5 mb/sterad (±30%). At 90°, there is also indication of a sharp excited state at $E_x=1.5\pm0.2$ Mev. The lifetimes of $Be^6(0)$ and $Be^6(1.5$ Mev) are $\gtrsim 4\times10^{-21}$ sec and $>7\times10^{-21}$ sec, respectively. These results are discussed in terms of the other available information on the $A=6$ isobars.

I. INTRODUCTION

THIS is the fourth[1-3] in a series of papers describing studies of the level structure of the $T_z=-1$ $[T_z=N-Z/2]$ nuclei. These nuclei are proton rich and are either difficult or impossible to reach with other than neutron producing reactions.[4] For this reason their level structure is usually very poorly known.

The $Li^6(p,n)Be^6$ reaction has been investigated previously at $E_p=9.6\pm0.1$ Mev by Bogdanov *et al.*[5] This group used a time-of-flight method with a single-channel fast neutron spectrometer to obtain neutron spectra at several angles from targets of separated Li^6 and isotopic lithium on lead backings. Bogdanov *et al.* observed the groups corresponding to the ground and first excited states of Be^7 (unresolved) and to the state at 4.53 Mev.[4] In addition, using the enriched targets, they observed neutron groups corresponding to the ground state of Be^6: $Q_0=-5.2\pm0.2$ Mev; mass excess $M-A=20.3\pm0.2$ Mev.[6] The ground state was found to be quite sharp, $\Gamma<0.3$ Mev. Bogdanov and his collaborators did not observe any excited states of Be^6.

We decided to study the $Li^6(p,n)Be^6$ reaction again to confirm the results of Bogdanov *et al.*[5] on the mass and life-time of the Be^6 ground state and to try to locate excited states of Be^6. The $Li^7(p,n)Be^7$ reaction was studied at the same time, primarily to obtain information about the plate resolution in this experiment, the energy of the incident proton beam, and the general background.

* Work supported by the National Science Foundation and the U. S. Atomic Energy Commission.

[1] C^{10}: F. Ajzenberg and W. Franzen, Phys. Rev. **95**, 1531 (1954).

[2] N^{12}: Ajzenberg-Selove, Bullock, and Almqvist, Phys. Rev. **108**, 1284 (1957).

[3] O^{14}: F. Ajzenberg and W. Franzen, Phys. Rev. **94**, 409 (1959).

[4] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

[5] Bogdanov, Vlasov, Kalinin, Rybakov, and Sidorov, Soviet J. Atomic Energy **3**, 987 (1957).

[6] All masses except Be^6 are taken from A. H. Wapstra, Physica **21**, 367 (1955).

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. The Exposure of the Plates

The source of the incident protons was the 60-inch Brookhaven National Laboratory cyclotron. The detection of the outgoing neutrons from the $Li^6(p,n)Be^6$ and $Li^7(p,n)Be^7$ reactions was by means of Ilford C-2 nuclear emulsions, 400 microns thick, placed at several angles to the incident beam of protons.

The neutron background in the experimental area was extremely high when the standard beam tube arrangement was used. It was found necessary to build an aluminum beam tube approximately nine feet long and made up of three sections. The first section 4 feet long, was connected to the exit port of the cyclotron at the shielding wall. This section contained two collimators, a $\frac{1}{2}$-inch wide carbon cylinder with a $\frac{1}{4}$-inch diameter hole followed by a 6-inch long polystyrene cylinder with a $\frac{3}{8}$-inch hole. Carbon was used, of course, because of the high threshold of the $C^{12}(p,n)N^{12}$ reaction ($Q=-18.24$ Mev). Another carbon collimator was also placed inside the permanent cyclotron beam tube just before the ball valve located at the exit port. The second aluminum section, 6 inches long, contained the target holder. The third section, closed at one end, was connected at the other to the second section through a short insulated cylinder. The closed end was lined for a distance of 6 inches with a carbon cylinder having an inner hole 1 inch in diameter and 5 inches long. The proton beam was thus stopped about 4 feet from the target, and from the plates. Additional shielding was provided by slabs of paraffin and borax packages blocking interstices in the shielding wall at the exit port.

The first two targets used were thin Li^6-oxide layers deposited on 5-mil platinum and 10-mil tantalum backings. The background in both cases was extremely high and the plates were fogged to an unmanageable degree. We then exposed plates to the neutrons emitted when the proton beam hit thin (0.1 mil to 0.25 mil) foils of aluminum, tantalum, and gold, in order to discover the

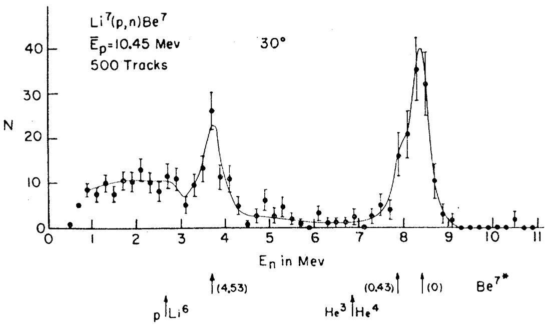

FIG. 1. $Li^7(p,n)Be^7$ data at 30° (in the laboratory system). N is the corrected number of neutrons per 100-kev interval. E_n is the neutron energy. The calculated positions of the Be^7 ground state and the states at 0.43 and 4.53 Mev are indicated by arrows. The binding energies of a proton, a He^3, and an α particle in Be^7 are also shown.

most satisfactory type of backing material. In all three cases the background was high. The targets we finally used were self supporting foils of Li^6 and isotopic lithium which turned out to be trouble free and very simple to prepare.

Thin self-supporting foils of isotopic lithium metal and lithium metal enriched[7] to 99.3% of Li^6 were obtained by the use of a standard jeweler's press equipped with stainless steel rollers. The rolling[8] of the foils, and their subsequent storing, both took place with copious quantities of mineral oil (Nujol). The thicknesses of both the Li^6 and Li^7 foils were the same, 8×10^{-3} cm. Just before their use, the foils were cleaned[9] in a mixture of hexane and 10% methyl alcohol (the latter etches the surfaces of the lithium foil leaving it perfectly silvery) and then oxidized by allowing a stream of oxygen to hit the foil. This last step prevents the lithium from absorbing nitrogen. The threshold of the $O^{16}(p,n)F^{16}$ reaction is very high ($Q=-16.41$ Mev) while that of the $N^{14}(p,n)O^{14}$ reaction would give neutrons in an inconvenient energy range ($Q=-5.93$ Mev). The targets

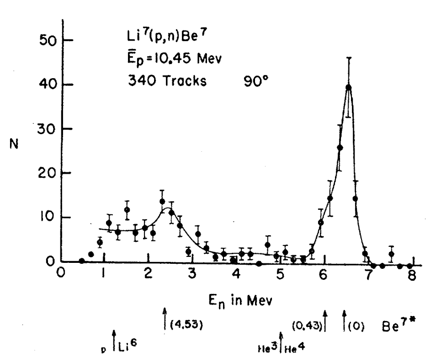

FIG. 2. $Li^7(p,n)Be^7$ data at 90° (see also caption of Fig. 1).

[7] The enriched lithium was furnished by the Stable Isotopes Division of the U. S. Atomic Energy Commission, Oak Ridge, Tennessee.
[8] J. B. Reynolds and K. Standing, Phys. Rev. **101**, 158 (1956).
[9] We are grateful to Professor R. I. Walter for this suggestion.

were mounted in a brass ring placed at the center of the second beam tube section.

The nuclear emulsions were placed 6 inches from the target and at several angles to the incident beam and after exposure were processed and scanned in a standard manner.[10] The total exposure was 1500 microcoulombs for the Li^6 target and 500 microcoulombs for the isotopic lithium target as measured by a current integrator connected to the third section of the beam tube (uncertainty approximately 5%).

The BNL cyclotron is not generally used for nuclear spectroscopic studies and there is no accurate means of determining the energy of the beam. It is primarily for this reason that we exposed plates to neutrons from the $Li^7(p,n)Be^7$ reaction. Since the Q-value of this reaction is very accurately known ($E_{\text{thresh}}=1.8812\pm0.0009$ kev[11]), the proton energy can be determined. As discussed

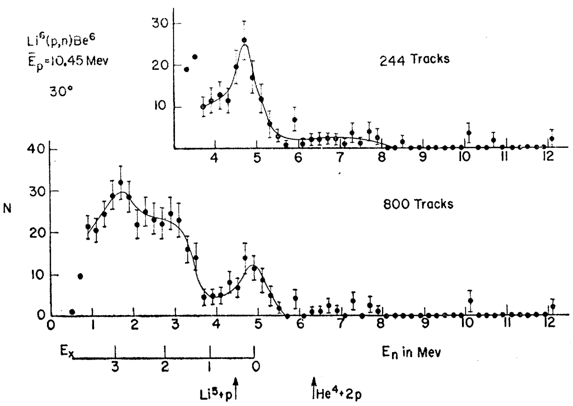

FIG. 3. $Li^6(p,n)Be^6$ data at 30° (in the laboratory system). N is the corrected number of neutrons per 100-kev interval. E_n is the neutron energy. The inset shows the ground-state group with somewhat better statistics. The scale marked E_x indicates the excitation in Be^6 corresponding to a given E_n. The binding energies of the (He^4+2p) and (Li^5+p) systems in Be^6 are also shown. Note that the ground state of Li^5 has a width of ~1.5 Mev.

below, we found the mean energy of the protons to be 10.45 ± 0.1 Mev.

B. The $Li^7(p,n)Be^7$ Data

Figure 1 shows the data at 30° and Fig. 2 at 90° to the incident beam. The ordinate represents the relative number of neutrons per 100-kev interval, that is the number of proton recoil tracks having energies in such an interval, corrected for geometry and variation of the neutron-proton scattering cross section with energy. At both angles the high-energy group of neutrons is due to the unresolved combination of the ground state of Be^7 and the 0.43-Mev level. The peaks are asymmetric and the contribution of the 0.43-Mev level in both cases clearly appears to be less than that of the ground state.

[10] Rubin, Ajzenberg-Selove, and Mark, Phys. Rev. **104**, 727 (1956).
[11] R. O. Bondelid and C. A. Kennedy, Naval Research Laboratory Report—5083, 1958 (unpublished).

The lower energy peak, at both angles, is due to the Be^7 state[12] at 4.53±0.02 Mev. The background neutrons are probably primarily from the following causes: the breakup into (He^3+He^4) and (Li^6+p) and, at 30°, the 1-Mev broad state at 6.35 Mev in Be^7.

These results were obtained to determine the incident proton energy. In computing this energy, we used the average neutron energy corresponding to the three groups. In the case of the unresolved (0) and (0.43-Mev) states a decomposition of the peak was necessary. This was not too difficult because of the asymmetry of the peak and the lower intensity of the 0.43-Mev group. The weighted mean incident proton energy was calculated to be 10.45 Mev with a standard deviation of 0.06 Mev. While the weighting was in favor of the ground state because of better statistics and a better known Q-value, the agreement between the computed $\bar{E}_p$ from all six groups at the two angles was good.[13] The value of $\bar{E}_p$ derived from these data and used in the next reaction was taken to be 10.45±0.1 Mev. This proton energy,

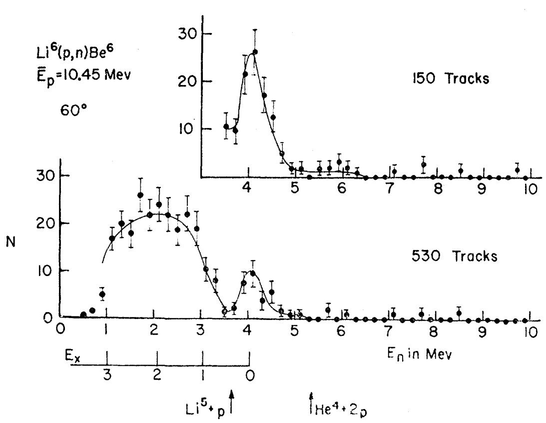

FIG. 4. $Li^6(p,n)Be^6$ data at 60° (see also caption of Fig. 3).

the mean energy, is the full energy of the beam less half the energy required to cross the isotopic lithium target which had a thickness equivalent to an energy loss of 150 kev for ~10-Mev protons. The full energy of the beam was, therefore, 10.53 Mev but we use the mean energy obtained above in the next section also because the foils of isotopic lithium and of Li^6 had the same thickness (within 10%).

C. The $Li^6(p,n)Be^6$ Data

Figures 3–6 show the data at 30°, 60°, 90°, and 135° to the incident beam. In each case the high-energy group is due to the ground state of Be^6. The insets in the first two figures show the ground-state group with better

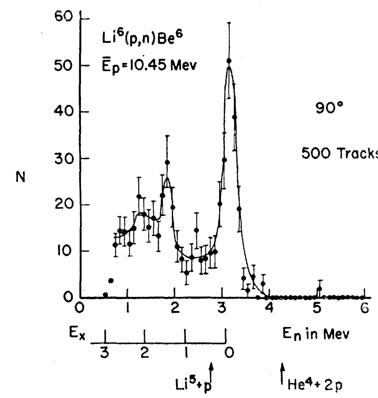

FIG. 5. $Li^6(p,n)Be^6$ data at 90° (see also caption of Fig. 3).

statistics, obtained by scanning the plates, discriminating against lower energy events.

1. The Mass of Be^6

Assuming $\bar{E}_p=10.45$ Mev, we find the following Q-values for the ground-state reaction: at 30°, $Q=-5.26$ Mev; at 60°, $Q=-5.01$ Mev; at 90°, $Q=-5.00$ Mev; at 135°, $Q=-5.07$ Mev. The results at the three larger angles are in excellent agreement. The result at 30° might be fortuitous or might be due to an error in determining the position of the plate, or to an error in determining the average neutron energy of the peak because of its relatively poor resolution. The weighted (in favor of the two back angles) value of $Q=-5.05$ Mev with a standard deviation of 0.1 Mev. Taking into account the uncertainty in the proton energy, we find $Q=-5.05\pm0.2$ Mev in good agreement with the value of -5.2 ± 0.2 Mev obtained by Bogdanov *et al.*[5]

The atomic mass excess of Be^6, using the Wapstra values[6] for Li^6, H^1, and n is then 20.13±0.2 Mev and the atomic mass of Be^6 is 6.02162±0.0002 amu, using the DuMond conversion value 931.141±0.010 Mev=1 amu. This gives 0.44 Mev as the binding energy of (Li^5+p) and indicates that $Be^6(0)$ is unbound with respect to (He^4+2p) by 1.35 Mev.

2. Excited States of Be^6

At 135°, only the ground state could be observed. At the other three angles, a scale is plotted showing the

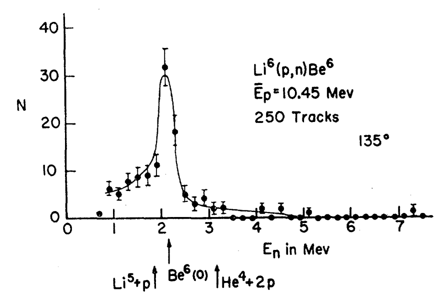

FIG. 6. $Li^6(p,n)Be^6$ data at 135°. The position of the ground state of Be^6 is shown by an arrow (see also caption of Fig. 3).

[12] P. D. Miller and G. C. Phillips, Phys. Rev. **112**, 2048 (1958).

[13] At both angles the 4.53-Mev group appeared at a relatively lower energy than expected from the positions of the other two states. The small difference, ~0.05 Mev, might be fortuitous or else might indicate a somewhat higher excitation energy than 4.53 Mev.

excitation in Be^6 as a function of decreasing neutron energy. The 90° data are the only ones which indicate the possible existence of a sharp excited state of Be^6 below $E_x \sim 3.3$ Mev: $Q=-6.53$ Mev, $E_x=1.5\pm0.2$ Mev. The data at 30° and 60° do not exclude this level but certainly do not support its existence. The situation is, of course, complicated by the fact that all[14] states of Be^6 are unstable with respect to decay into two bodies Li^5 and p, which increases their widths and provides a background of neutrons of heterogeneous energies from $Li^6+p \rightarrow Li^5+p+n$. The small width of the Be^6 ground state, discussed below, and the low neutron background between the ground-state peak and the energy corresponding to $Li^6+p \rightarrow He^4+2p+n$ indicates that the three-body breakup in this reaction is inhibited, as it appears to be in other similar reactions.[4]

The 1.5-Mev excited state energetically can freely decay into Li^5+p. The small width of this presumably $J=2^+$ state might be explained by the fact that p-wave protons would be necessary.

3. *Widths and Lifetimes*

In the $Li^7(p,n)Be^7$ data, the experimental widths of the neutron groups corresponding to the sharp states of Be^7 at 0 and 0.43 Mev are estimated to be $\sim$400 kev. These values are approximately 100 kev larger than the calculated neutron group widths for neutrons of the various energies involved. The calculations take into account a number of factors the most important of which are range straggling[15] which varies from 100 to 200 kev over the energy range, the width of the proton beam, $\sim$100 kev, and the thickness of the target. The inhomogeneity of the emulsion is not taken into account, and this probably accounts in part for the difference between the calculated and the experimental widths.

Since the thicknesses of the target, the proton beams, and the emulsions used were the same in both exposures, it is possible to estimate upper limits to the true widths of the ground and 1.5-Mev states of Be^6 from the neutron group widths. At 90° and 135°(lab) the experimental ground-state neutron group widths were $\sim$350 kev. On the basis of the Be^7 results, a width of $\sim$320 kev is calculated for a sharp state. Therefore the width of $Be^6(0) \lesssim 150$ kev, and the mean life of the ground state of Be^6, τ_0, is $\gtrsim 4\times10^{-21}$ sec ($\tau_0 \sim \hbar/\Gamma_0$). This may be compared with the value of $\tau_0 > 2\times10^{-21}$ sec found by Bogdanov *et al.*[5]

At 90°(lab) the width of the neutron group to the 1.5-Mev state is estimated to be $\sim$300 kev. On the basis of the type of calculation described earlier, a sharp state would have a neutron group width of $\sim$330 kev. Therefore the 1.5-Mev excited state seems to be quite sharp. We estimate its width at $<$100 kev, and therefore its mean life, τ_1, is $>7\times10^{-21}$ sec ($\tau_1 \sim \hbar/\Gamma_1$).

4. *Background*

As may be seen by comparing the Li^6 and the Li^7 results, the general room background was extremely low. The neutron energies corresponding to the reactions $O^{18}(p,n)F^{18}$ ($Q=-2.450$), $N^{14}(p,n)O^{14}$ ($Q=-5.930$ Mev), and $C^{13}(p,n)N^{13}$ ($Q=-3.005$ Mev) at the four angles were computed. There appears to be very little or no contributions from these reactions.

D. Cross Sections

The cross section for formation of the ground+first-excited state of Be^7 at $E_p=10.45$ Mev was computed[16] to be 4 mb/steradian at 90°(laboratory system) [99°(c.m.)] with an uncertainty of 30%.[17] The contribution of the 0.43-Mev state is estimated to be (19±4%). This gives a cross section for the ground state alone of 3.2 mb/steradian (±30%).

The cross section for formation of the ground state of Be^6 at $E_p=10.45$ Mev was found to be 0.5 mb/steradian at 90°(lab) [104°(c.m.)] with an uncertainty of 30%.

The ratio of the cross section of the $Li^7(p,n)Be^7(0)$ reaction to the $Li^6(p,n)Be^6(0)$ reaction at 90°(lab) is thus 6.4±3.

At $E_p=9.6$ Mev, Bogdanov *et al.*[5] find that the cross section of the combined ground and first excited states of Be^7 is approximately 7 mb/sterad at 99°(c.m.), and that the cross section for $Be^6(0)$ is $\sim$0.3 mb/sterad at 104°(c.m.). Our results are in fairly good agreement with these taking our quoted errors into account.

The plates at 90° were particularly clear in both the Li^6 and Li^7 exposures. At the other angles the plates were heavily fogged and in spots difficult to scan. We may have missed some tracks at those angles and for this reason we prefer not to quote cross sections at angles other than 90°. In a general way, the shape of the angular distribution agrees with the results of Bogdanov *te al.*[5] obtained at $E_p=9.6$ Mev. We find the lowest intensity of the Be^6 ground-state group to be at 72°(c.m.) [60°(lab)]. At our energy, however, the highest intensity occurs at 104°(c.m.) [90°(lab)], where the cross section is approximately three times that at 72°. The ratio obtained by Bogdanov *et al.*[5] for these two angles is approximately 1.5.

III. Be^6 AND THE $A=6$ ISOBARIC TRIAD

The first $T=1$ state in the $T_z=0$ member of the $A=6$ triad, Li^6, is located at 3.56 Mev (see Fig. 7). It has $J=0^+$. The most convincing evidence[18] for $T=1$ stems

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[14] This includes the ground state, despite the positive binding energy, 0.44 Mev, of Li^5+p, because of the $\sim$1.5 Mev width of the Li^5 ground state.

[15] A. G. Rubin, Ph.D. thesis, Boston University, 1957 (unpublished).

[16] L. Rosen, Nucleonics 11, No. 8, 38 (1953).

[17] This uncertainty includes 10% statistical error, 10% uncertainty in the thickness of the targets, 5% uncertainty in the number of incident protons. The cross section value also takes into account attenuation of the neutrons in the emulsion.

[18] The level evidence is discussed in reference 4.

from the fact that this state is not observed in either the scattering of deuterons from He^4 or in $Li^6(d,d')Li^{6*}$. The J^π assignment is derived principally from studies of the $Be^9(p,\alpha\gamma)Li^6$ reaction. From charge independence considerations, the masses of He^6 and Be^6, corrected[19] for Coulomb effects and the $n-H^1$ mass difference, should also be $\sim$3.6 Mev greater than the mass of $Li^6(0)$. Using the Wapstra[6] masses of He^6 and Li^6, the atomic mass difference He^6-Li^6 is 3.536 Mev, a value which is at most in error by 40 kev. When this mass difference is corrected in the manner described above, the isobaric mass difference is found to be 4.1 Mev, 0.5 Mev *greater* than the energy of the first $T=1$ level at 3.56 Mev in Li^6. From the results discussed in this paper $Be^6(0)-Li^6(0)=4.27$ Mev. The isobaric mass difference is then 3.1 Mev, a value 0.5 Mev *less* than the energy of the 3.56-Mev level in Li^6. These deviations do not need, of course, to reflect on the validity of the hypothesis of charge independence: for instance, the Coulomb calculation was based on the crude model of a uniformly charged nucleus.[20] However, it should be pointed out that this model gives more consistent results for all the other light nuclei.[19] The isobaric mass difference of the two mirror nuclei ${}_2He^6$ and ${}_4Be^6$ which should be 0, from charge symmetry, is thus approximately 1 Mev, the largest deviation in the light mirror nuclei.[21]

The second $T=1$ states are located at 1.71 Mev in He^6 ($J=2^+$), probably at 5.35 Mev in Li^6 [$Li^6(5.35)-Li^6(3.56)=1.79$ Mev] and, from the data presented in this paper, probably at 1.5 ± 0.2 Mev in Be^6. A shift of a couple of hundred kev in the positions of the excited state from $He^6\to Be^6$ is not surprising in view of the different degree of binding of the states, for instance.

[19] See, for instance, T. Lauritsen and F. Ajzenberg-Selove, *American Institute of Physics Handbook* (McGraw-Hill Book Company, Inc., New York, 1957), Sec. 8-e.

[20] A sophisticated discussion of Coulomb energy corrections is given by B. C. Carlson and I. Talmi, Phys. Rev. **96**, 436 (1956).

[21] With the exception of $F^{20}-Na^{20}$, but the present value for the mass of Na^{20} may be seriously in error.

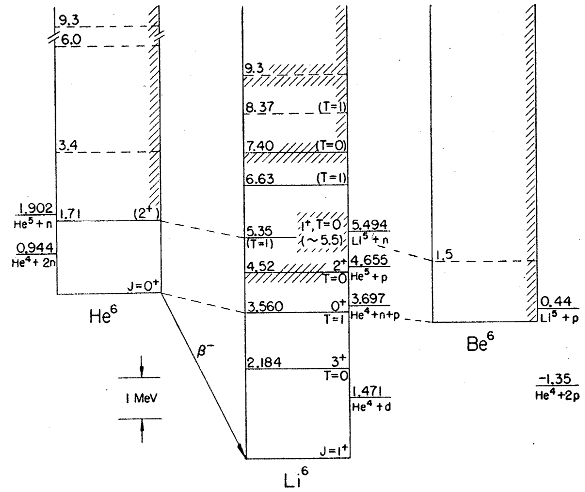

FIG. 7. The mass-6 isobaric triad. The data for He^6 and Li^6 are taken from F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959). The data for Be^6 is that presented in this paper. The levels connected by dashed lines are believed to be the analog isobaric states. Corrections have been made for Coulomb energy differences and the $n-p$ mass difference. [See the discussion in the text and T. Lauritsen and F. Ajzenberg-Selove, *American Institute of Physics Handbook* (McGraw-Hill Book Company, Inc., New York, 1957), Sec. 8-e.]

The evidence for higher $T=1$ states in He^6 and Li^6 is not too good and, as discussed in this paper, we have not observed any states in Be^6, other than the 1.5-Mev state, for $E_x\lesssim3.3$ Mev.

IV. ACKNOWLEDGMENTS

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