EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/80-200
November 7, 1980

DELAYED NEUTRON EMISSION PROBABILITIES OF ^{9}Li and ^{11}Li

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ABSTRACT

The P_n values for ^{9}Li and ^{11}Li were determined to be (50 ± 4)% and (95 ± 8)%, respectively, by a beta-neutron coincidence technique. The P_n values of $^{27-31}$Na, $^{93-98}$Rb and $^{145-146}$Cs, which had been deduced by normalization to the older P_n value for ^{9}Li, should thus be raised by the factor 1.43. The beta decay branch to the 320 keV first excited state of ^{11}Be was found to be (9.2 ± 0.7)%. The fraction of one neutron emission leading to excited states of ^{10}Be was deduced to be (41 ± 4)%. The half-life of ^{11}Li was remeasured to be (8.83 ± 0.12)ms.

Radioactivity : ^{9,11}Li from U or Ta (^{3}He,X) on-line mass separation; measured βn-coin . ^{9,11}Li deduced P_n. ^{11}Li measured $T_{\frac{1}{2}}$, βγ-coin. ^{9,11}Li deduced log ft. Natural targets.

Geneva, October 1980
Submitted to Nuclear Physics A

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1. INTRODUCTION

The delayed neutron emission probabilities, P_n, of individual nuclides are of primary interest for the understanding of the gross properties of the decay process and for its implications in the astrophysical r-process. Many experiments of this kind have been performed, although they are difficult because of the low production cross section and the short half-lives of the delayed neutron precursors. Because of the inherent difficulty of neutron detection, the known P_n value of an accessible nucleus is often used to determine the ratio of the efficiencies of the neutron and beta detectors. For example, the P_n values for ^{11}Li, and many Na, Rb and Cs isotopes [1,2] have been deduced by using the adopted value[3] for ^{9}Li (35 ± 5)% by Chen et al.[4]. Our new measurement of the ^{9}Li P_n value gives (50 ± 4)% and increases the other results correspondingly.

The P_n value of ^{9}Li was first estimated by Alburger[5] to be (75 ± 15)% from an analysis of the beta spectrum obtained in plastic scintillator. This value was used in the decay scheme proposed by Macefield, Wakefield and Wilkinson[6]. However, in the latest measurement, Chen et al.[4] used a ΔE-E telescope to detect the arrival of a ^{9}Li nucleus and afterwards recorded the charged particle spectrum in the E counter. The assumption was that for each neutron there would be two alpha particles depositing their energy in the E detector. A peak due to the alphas from the first excited 2^+ state of ^{8}Be was clearly seen, below which there were some statistically uncertain peaks, and a rising continuum at pulse heights below 150 keV. One of the small peaks was interpreted as due to alphas from the 0^+ ground state of ^{8}Be and the continuum as due to beta particles. Recent measurements of the neutron spectrum[7] confirm that there is a decay branch to the ^{8}Be ground state. However, the alphas from the break-up of ^{8}Be share a total kinetic energy of only 92 keV and with a pulse height defect they could have been lost in the beta continuum. Thus, they would not have been included in the alpha spectrum and the derived[4] P_n value would have become too low. In fact it was the gamma measurement of ^{11}Li reported here, which proved to be inconsistent with the published P_n value and prompted us to remeasure the P_n of ^{9}Li. The P_n value of ^{11}Li is of particular interest because of the recent discoveries that it is a beta delayed two neutron[8] and three neutron[9] emitter.

2. EXPERIMENTAL TECHNIQUES

The lithium isotopes were produced by the 900 MeV ^{3}He beam from the CERN SC irradiating uranium carbide or tantalum targets in combination with a thermal ion source at the ISOLDE facility. The 60 keV ion beam from the separator was deposited on a movable aluminized mylar tape. The beta detector which consisted of a 1 mm thick 24 x 16 mm^2 plastic scintillator (Ne 102) mounted on a 30 mm phototube was placed in a metal cylinder right behind the tape at the collection position.

The 4π neutron counter[9,10)] consisted of eight ^{3}He proportional counters imbedded in paraffin-wax in concentrical geometry around the cylinder containing the beta detector. The walls of the cylinder consisted of brass (5 mm) and steel (2 mm). The neutron detection efficiency was determined with a 1.9 kg sample of ^{238}U to be (14 ± 1)%. The variation of the neutron detection efficiency with energy, which has not been measured, is in the present work the largest source of systematic error.

The gamma detector was a coaxial Ge(Li) crystal with 17% standard efficiency. The beta-gamma coincidence data were obtained by using the beta signal to open a 5 μs linear gate on the gamma signal, which in this case gave a negligible random rate. The gamma detection efficiency was determined to about 5% accuracy with calibrated sources placed at the point of sample collection in the cylinder.

Since the residence time of a neutron in the paraffin moderated detector is exponentially distributed with a mean life time of about 100 μs, the neutron-beta coincidence measurements were performed by starting a clock with the beta signal and stopping it with the neutron signal. The data were fitted to an exponential plus a constant value where the latter accounted for the random background at the low coincidence rates of about 10 s^{-1} used here. From beta-gamma coincidence measurements on ^{26}Na, the beta detection efficiency was determined to be (40 ± 3)% and the gamma efficiency was checked for the 1.8 MeV gamma ray.

3. RESULTS

3.1 Li

From two beta-neutron coincidence measurements on ^{9}Li the P_n value was determined to be (50 ± 4)%. The statistical uncertainty is four times smaller; the error shown comes mainly from the uncertainty in the efficiency of the neutron detector. Ten other sets of singles measurements were made, which with the determined beta detection efficiency also yield values of P_n. Eight of these were relative neutron to beta saturation yields and two used a pulsed ion beam to determine neutron- and beta-decay curves to verify that the activity was due to ^{9}Li. These measurements gave also a P_n value of 50% with an equally small statistical error, but the uncertainty in the beta detection efficiency gave a larger systematic error. Table 1 presents the P_n values measured by Roeckl et al. [1,2)] renormalized to a ^{9}Li P_n value of 50% instead of 35%.

Since the ground state of ^{9}Be is the only non-neutron emitting state (see Fig. 1), the beta decay branch to the ground state is thus also (50 ± 4)%.

3.2 ^{11}Li

For ^{11}Li, the half-life was redetermined by neutron measurements to be (8.83 ± 0.12) ms. Combining this with the previous result$^{1)}$ of (8.5 ± 0.2) ms, we recommend a best value of (8.7 ± 0.1) ms.

When counting the betas of ^{11}Li in the saturation mode one has to take into account the contribution from the 14 s ^{11}Be daughter in equilibrium (see Fig. 2). Assuming that the ^{11}Li decay to the ^{11}Be ground state is negligible, then all the ^{11}Be yield must come from beta decay to the 320 keV state, which is the only excited neutron bound state. If the probability of beta decay to this state is denoted P_γ, then the beta count rate in saturation should be proportional to $1+P_\gamma$. Taking this into account the beta-gamma coincidence measurement gave a value for P_γ equal to (9.2 ± 0.7)%. The ^{11}B gamma ray at 2.12 MeV was also visible. Taking its abundance per ^{11}Be decay$^{4)}$ as 33%, then the ^{11}Be decays per ^{11}Li decay in saturation came to (9 ± 2)%, in agreement with P_γ. From this one can calculate that the one standard deviation upper limit on $P_{g.s.}$ is 2%. The 3.368 MeV gamma ray from the first excited state of ^{10}Be, populated following neutron emission was seen. The experimental value, which is the probability of emission divided by $(1+P_\gamma)$, was found to be (32.0 ± 2.5)%. Using the determined value of P_γ the probability of the 3.3 MeV gamma ray thus becomes (35 ± 3)%.

Recently, Détraz et al.$^{12)}$ have also studied the gamma decay of ^{11}Li. They normalized their yields to the beta singles rate, or to ion counting done before and after the data collection. For P_γ they found (5.2 ± 1.4)%, a value a factor of 1.8 ± 0.5 smaller than the one measured here. From a comparison of their 2.12 MeV and 320 keV gamma rays they could also set an upper limit of 2% for $P_{g.s.}$. For the 3.3 MeV gamma ray in ^{10}Be they reported an intensity of (21 ± 6)%, again a factor of 1.7 ± 0.5 smaller than the present value. Détraz et al.$^{12)}$ also reported intensities for some of the gamma rays in ^{10}Be, feeding the 3.3 MeV level which we did not attempt to resolve from our spectrum.

For the ^{11}Li beta-neutron coincidence measurement, the tape was moved every two seconds (with interruption of counting) in order to reduce the contribution of the ^{11}Be daughter to an almost negligible amount. The results gave a value for P_n equal to (96 ± 8)%, of which the statistical error was 5% and the rest of the error came from the uncertainty in the neutron detection efficiency. A one per cent correction was made to this number because ^{11}Li is a multiple neutron emitter, and once a neutron stops the clock in the coincidence measurements, the other neutrons from that event cannot be detected.

Six sets of singles measurements were also performed, four of which were relative beta-neutron saturation yields, one used the tape transport again to remove the ^{11}Be daughter, and one obtained beta and neutron decay curves. The average value of P_n was 93% with about the same statistical error as in the coincidence measurement, but with a larger systematic error. We adopt a best P_n value of (95 ± 8)%. The renormalized value from the measurements of Roeckl et al.[1]) given in Table 1 agrees with this new value.

Previously ^{11}Li had been reported[9]) to be a multiple neutron emitter. The relative probabilities of two neutron and three neutron emission were given to be*)

$$P_{2n}/P_{1n} = 0.048 \pm 0.005$$

$$P_{3n}/P_{1n} = 0.022 \pm 0.002. \tag{1}$$

From this one obtains :

$$P_n/P_{1n} = 1 + 2\ P_{2n}/P_{1n} + 3\ P_{3n}/P_{1n} = 1.16 \pm 0.01. \tag{2}$$

By assuming that the Li + t disintegration mode as well as the ground state beta decay are negligible one can state that :

$$1 - P_\gamma = P_{1n} + P_{2n} + P_{3n}.$$

Using the values for two and three neutron emission given in equation (1) one obtains :

$$(1 - P_\gamma)/P_{1n} = 1.07 \pm 0.005. \tag{3}$$

Combining this with equation (2) one finds that the relationship between P_n and P_γ is given by :

$$P_n/(1 - P_\gamma) = 1.08 \pm 0.01. \tag{4}$$

Our results presented above give for this ratio the value 1.05 ± 0.08, which shows consistency between our neutron and gamma measurements.

With these assumptions, one may calculate a more accurate value for P_n from the measured value of P_γ by using equation (4). This gives a ^{11}Li P_n value of (98 ± 1)%, and by using equations (2) and (4), the following multi-neutron emission probabilities are obtained :

$$P_{1n} = (85 \pm 1)\%$$

$$P_{2n} = (4.1 \pm 0.4)\%$$

$$P_{3n} = (1.9 \pm 0.2)\%$$

From the intensity of the 3.3 MeV gamma ray in ^{10}Be and the P_{1n} value the fraction of one neutron emission leading to excited states of ^{10}Be becomes (41 ± 4)%.

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*) Note that the probability of emission of i neutrons is denoted P_{in} so that the usual P_n value is given by $P_n = \sum_i iP_{in}$.

4. DISCUSSION

The new set of P_n values changes considerably the comparative half-lives for the allowed beta transitions in ^{9,11}Li. Taking the ^{9}Li and ^{11}Li Q_β and $T_{\frac{1}{2}}$ values to be 13.61 MeV$^{3)}$, 178.3 ms$^{3)}$ and 20.76 MeV$^{13)}$, 8.7 ms, respectively, one obtains a log ft value of 5.32 for the ^{9}Li decay to the ground state and 5.59 for the ^{11}Li decay to the first excited state. The ^{9}Li number is in good agreement with the shell model calculations of 5.05 by Cohen and Kurath$^{14)}$ and 5.54 by Hauge and Maripuu$^{15)}$. For the ^{11}Li allowed decay, however, the calculated values are 4.61 by Cohen and Kurath$^{14)}$ and 4.83 by Boyakina$^{16)}$, which are almost a factor of ten faster than observed. Although ^{11}Li is the fastest beta decaying isotope published Barker and Hickey$^{17)}$ have pointed out that, indeed, the half life is surprisingly long. Wilkinson and Alburger$^{18)}$ pointed out that the ^{11}Be ground state most likely had even parity, contrary to what had been expected previously. One elegant experiment, which helped to prove this conclusively was carried out by Deutsch et al.$^{19)}$, who showed that direct muon capture in ^{11}B identifies the expected $P_{\frac{1}{2}}$ level ($\frac{1}{2}^-$) at 320 keV above the $\frac{1}{2}^+$ ground state, The crossing of the two states is consistent with an extrapolation of their positions in the nuclei ^{12}B and ^{13}C $^{20)}$ and it can be understood in terms of a strong deformation of ^{11}Be (Fig. 3). We note in this connection that the nucleon numbers 4,6 and 10 favour deformed shapes and that strongly deformed states occur at relatively low excitation energy in $^{16}_{8}$O. If ^{11}Li is also deformed, we would expect a $\frac{1}{2}^-$ ground state assignment instead of $3/2^-$ as assumed in ref. 17).

The present limit on the ^{11}Li beta decay to the ^{11}Be ground state, $P_{g.s.} < 2\%$, gives a log ft greater than or equal to 6.3 for the $(3/2,1/2)^- \rightarrow \frac{1}{2}^+$ first forbidden transition. In the compilation by Raman and Gove$^{20)}$ one finds a similar transition for ^{15}C ($\frac{1}{2}^+$) $\rightarrow$ ^{15}N ($\frac{1}{2}^-$) with a log ft of 6.0. Thus, since the allowed decay of ^{11}Li to the 320 keV state is so slow, it is possible that the forbidden decay to the ground state is not negligible, and could be present in an amount up to our experimental limit

We wish to acknowledge fruitful discussions with Claude Dêtraz, Marcelle Epherre, John C. Hardy, Michel Langevin and Ernst Roeckl.

Table 1

Renormalized P_n values (%)

^{11}Li *a)*	87 ± 10
^{27}Na *a)*	0.11 ± 0.04
^{28}Na *a)*	0.8 ± 0.2
^{29}Na *a)*	22 ± 3
^{30}Na *a)*	47 ± 5
^{31}Na *a)*	43 ± 11
^{93}Rb *b)*	1.8 ± 0.2
^{94}Rb *b)*	12.1 ± 1.3
^{95}Rb *b)*	12.2 ± 1.3
^{96}Rb *b)*	19 ± 2
^{97}Rb *b)*	39 ± 4
^{98}Rb *b)*	19 ± 3
^{145}Cs *b)*	17 ± 2
^{146}Cs *b)*	20 ± 2

a) From ref. 1)

b) From ref. 2)

FIGURE CAPTIONS

Figure 1 : The decay scheme of ^{9}Li from ref. 3) and this work.

Figure 2 : The decay scheme of ^{11}Li from ref. 3) and this work. The P_n value is greater than the shown sum of the beta branches to the neutron emitting states because of multiple neutron emission.

Figure 3 : Spectrum of single particle orbits in a spheroidal potential. The orbits are labelled by the asymptotic quantum numbers $[Nn_3\ \Lambda\Omega]$ where the parity is $(-1)^N$. The ^{11}Be ground state corresponds to the crossing between $[101\frac{1}{2}]$ and $[220\frac{1}{2}]$. If ^{11}Li is deformed, the ground state will be $[110\frac{1}{2}]$. (From ref. 21).)

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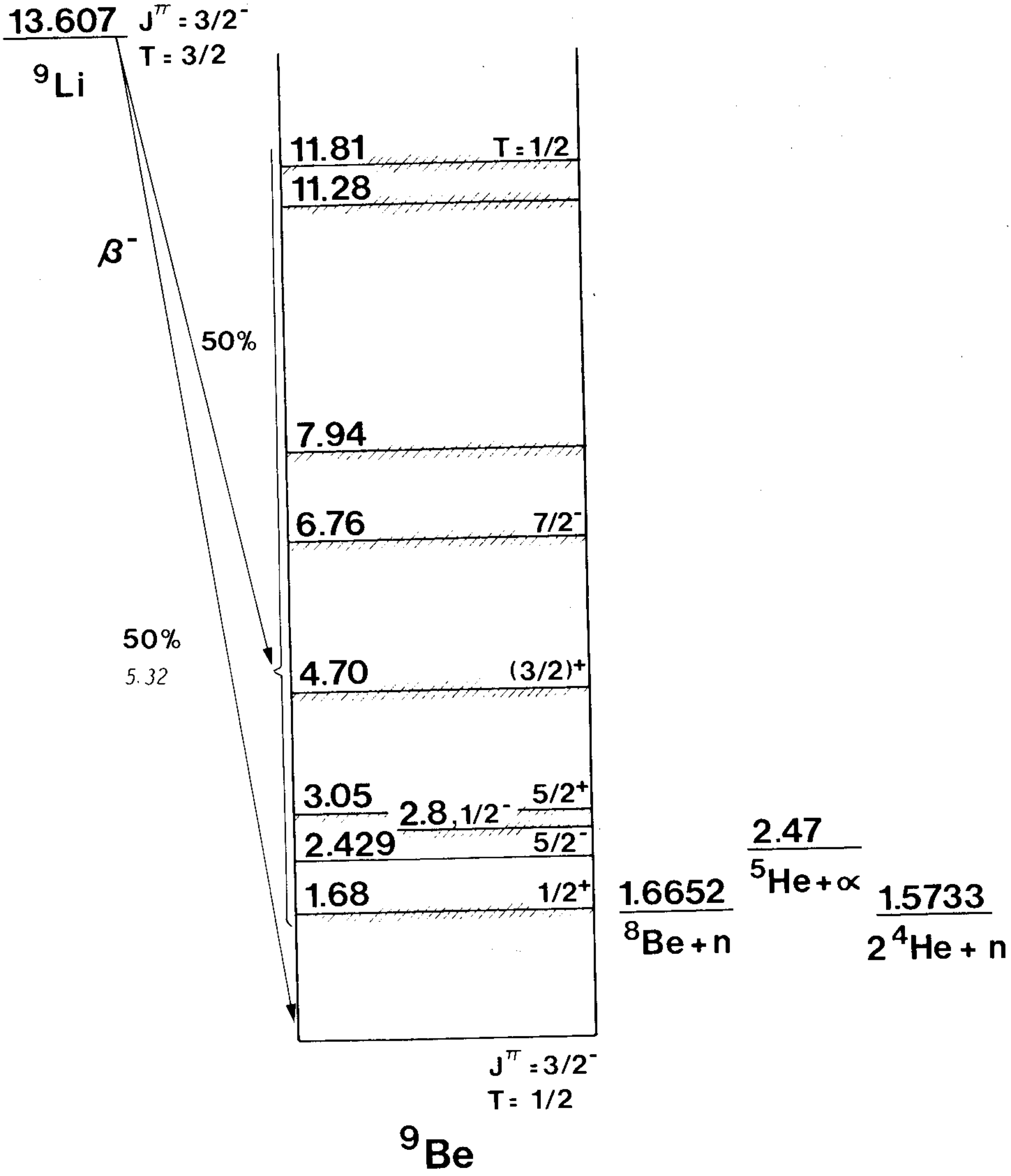
13.607 $J^\pi = 3/2^-$
T = 3/2
^{9}Li
β^-
50%
50%
5.32
11.81 T = 1/2
11.28
7.94
6.76 7/2$^-$
4.70 (3/2)$^+$
3.05 5/2$^+$
2.8, 1/2$^-$
2.429 5/2$^-$
1.68 1/2$^+$
1.6652
^{8}Be + n
2.47
^{5}He + α
1.5733
2 ^{4}He + n
$J^\pi = 3/2^-$
T = 1/2
^{9}Be

Fig. 1

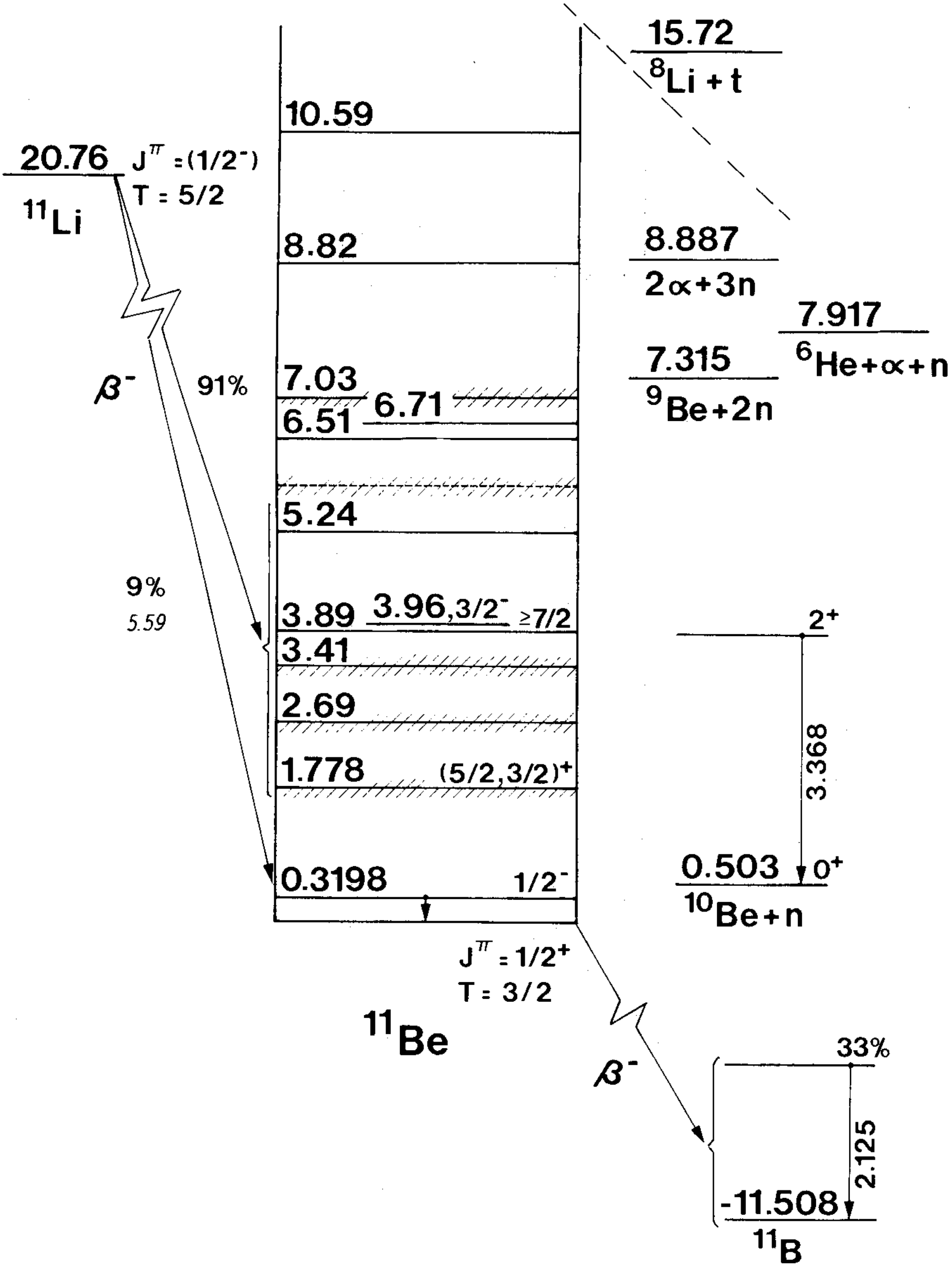
15.72
^{8}Li + t
10.59
20.76
J$^\pi$ = (1/2$^-$)
T = 5/2
^{11}Li
8.82
8.887
2α+3n
7.917
^{6}He+α+n
7.315
^{9}Be+2n
β$^-$
91%
7.03
6.71
6.51
5.24
9%
5.59
3.89
3.96,3/2$^-$
≥7/2
3.41
2.69
1.778
(5/2,3/2)$^+$
2$^+$
3.368
0.3198
1/2$^-$
0.503
0$^+$
^{10}Be+n
J$^\pi$ = 1/2$^+$
T = 3/2
^{11}Be
β$^-$
33%
2.125
-11.508
^{11}B

Fig. 2

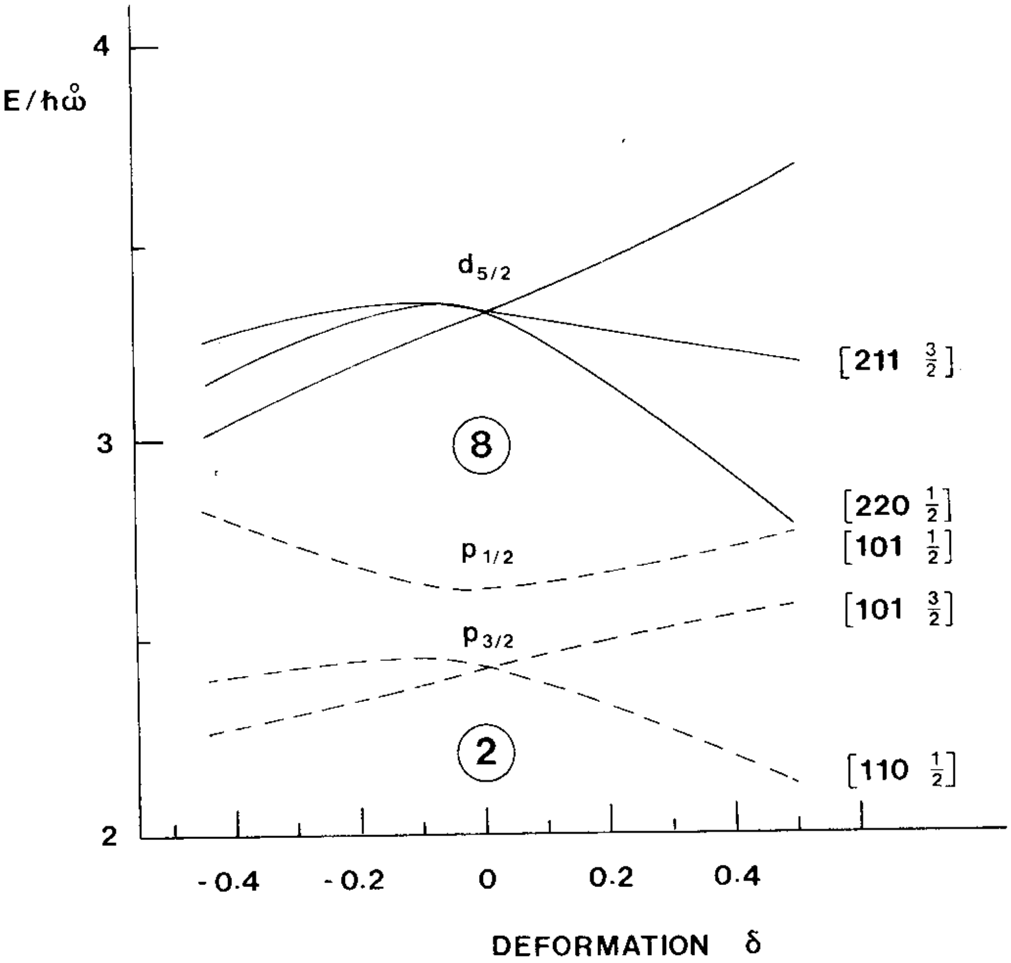
4
E/ħω̊
3
2
d5/2
p1/2
p3/2
8
2
[211 3/2]
[220 1/2]
[101 1/2]
[101 3/2]
[110 1/2]
-0.4
-0.2
0
0.2
0.4
DEFORMATION δ

Fig. 3