REVIEWS OF MODERN PHYSICS VOLUME 34, NUMBER 2 APRIL, 1962

Compilation of Hyperfragment Binding Energies

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I. INTRODUCTION

EXTENSIVE data relating to the Λ-binding energies in the "light hypernuclei" (mass number $A \leqslant 5$) are at present available. Detailed information regarding heavier hypernuclear species is however still sparse. Indeed, not only are the binding energies known with considerably less precision, but the experimental situation regarding the possible existence of certain species is still open to discussion.

The purpose of this note is to present new results on π^--mesonic decays of "heavy hypernuclei" ($A>5$) and at the same time to report on an up-to-date compilation of binding-energy data for all hypernuclear species. A preliminary report of this work has been given elsewhere.[1]

II. SOURCE OF DATA

The data which have been considered originate from two main sources: the π^--mesonic-decay events located in the stacks of The Enrico Fermi Institute for Nuclear Studies–Northwestern University collaboration[2–4] (group I) and the analogous events which have been analyzed in various other laboratories and collected from the literature[5–14] (group II). The statistics in group I are further classified according to whether the data were already reported in our previous publication on binding energies[2] (group Ia) or have been analyzed subsequently[1,3,4] (group Ib).

The binding energy B_Λ has been based in all cases upon the value $Q_\Lambda = (37.58 \pm 0.15)$ Mev for the kinetic energy released in the charged decay of the free Λ.[15] Analysis of the new events proceeded as discussed in reference 2 except that, in addition, some events in group Ib were identified from the joint study of the decay and production kinematics.[4]

It is, however, relevant here to mention that no π-p-r-decay mode was accepted having a recoil range <3 μm, while for other decay modes (with the exception of π-r decays), the shorter recoil had to be >2 μm.

The selection of the events which ultimately made up group Ib has been somewhat arbitrary. Whereas all $A>5$ events of unique identity were analyzed for their B_Λ, only a few of the lighter hyperfragments were retained for this purpose. These included the relatively rare events representing $_\Lambda H^3$ and $_\Lambda He^4$ as well as non-π-r decays of $_\Lambda H^4$ and non-π-p-r decays of $_\Lambda He^5$. Because of this, it should be emphasized that the relative frequencies in this sample of hypernuclides are not significant. Moreover, the acceptance criteria imposed on the event configuration, to obtain particularly reliable identifications, introduce additional biases as mentioned earlier.[2] Corrected data referring to the branching ratios in the π^--decay modes of the $A \leqslant 5$ hypernuclides have already been presented.[3]

Further details regarding the exposure, calibration, and scanning of the various emulsion stacks may be found in the preceding references. Because of the variety of stacks used (although in most cases an adequate density calibration was made), it is desirable to have some method of checking on the internal consistency of the B_Λ data. In this regard, one may rely on a comparison of B_Λ for $_\Lambda He^5$ obtained in groups I and II, respectively, since this species is sufficiently abundant and its binding energy well enough known that it may conveniently serve as a reference standard.

* Research supported by the U. S. Air Force Office of Scientific Research, Contract No. 49(638)-209.

† Research supported by the National Science Foundation and by the U. S. Atomic Energy Commission through Argonne National Laboratory subcontract.

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TABLE I. Binding energies from uniquely identified, mesonic decay. Group Ia consists of events in reference 2, whereas Group Ib represents events from reference (4) together with those from the present work. It should be emphasized that these events have been particularly selected for B_Λ determinations. The frequency of particular decay modes is strongly biased and the given breakdown of decay modes should *not*, therefore, be used for estimating decay-branching ratios.

Decay mode	Group Ia $\bar{B}_\Lambda$	Group Ia No. of events	Group Ib $\bar{B}_\Lambda$	Group Ib No. of events	Average $\bar{B}_\Lambda$	Average No. of events
${}_\Lambda H^3 \to \pi^- + He^3$	-0.28 ± 0.4	4	0.26 ± 0.8	1	-0.17 ± 0.36	5
$\pi^- + H^1 + H^2$	0.12 ± 0.7	1	...	...	0.12 ± 0.7	1
$\pi^- + n + 2H^1$	0.79 ± 0.8	1	...	...	0.79 ± 0.8	1
${}_\Lambda H^4 \to \pi^- + He^4$	2.52 ± 0.23	19	2.34 ± 0.5	4	2.49 ± 0.21	23
$\pi^- + n + He^3$	1.61 ± 0.6	2	2.06 ± 0.6	3	1.84 ± 0.43	6
$\pi^- + H^1 + H^3$	1.77 ± 0.31	5	0.90 ± 0.7	1	1.63 ± 0.29	6
$\pi^- + 2H^2$	2.21 ± 0.7	1	2.58 ± 0.7	1	2.40 ± 0.5	2
$\pi^- + n + H^1 + H^2$	...	...	1.01 ± 0.7	1	1.01 ± 0.7	1
${}_\Lambda He^4 \to \pi^- + H^1 + He^3$	2.37 ± 0.17	13	2.69 ± 0.30	4	2.45 ± 0.15	17
$\pi^- + 2H^1 + H^2$	3.09 ± 0.7	1	...	...	3.09 ± 0.7	1
${}_\Lambda He^5 \to \pi^- + H^1 + He^4$	3.06 ± 0.10	60	...	...	3.06 ± 0.10	60
$\pi^- + H^2 + He^3$	...	...	3.01 ± 0.5	1	3.01 ± 0.5	1
${}_\Lambda He^7 \to \pi^- + Li^7$	...	...	4.41 ± 1.5	1	4.41 ± 1.5	1
$\pi^- + H^1 + He^6$	...	...	5.15 ± 0.7	1	5.15 ± 0.7	1
$\pi^- + H^3 + He^4$	3.04 ± 0.7	1	...	...	3.04 ± 0.7	1
$\pi^- + n + H^2 + He^4$	...	...	2.91 ± 0.9	2	2.91 ± 0.9	2
${}_\Lambda Li^7 \to \pi^- + Be^7$ [a]	(6.08)	9	(6.82)	6	(6.38)	15
$\pi^- + H^1 + Li^6$	5.56 ± 0.46	2	...	...	5.56 ± 0.46	2
$\pi^- + He^3 + He^4$	5.47 ± 0.6	1	5.80 ± 0.6	1	5.64 ± 0.43	2
${}_\Lambda Li^8 \to \pi^- + 2He^4$	6.34 ± 0.54	5	6.57 ± 0.42	8	6.50 ± 0.33	13
${}_\Lambda Li^9 \to \pi^- + n + 2He^4$	$7.4\ \pm1.6$	3	8.00 ± 0.9	1	7.87 ± 0.79	4
${}_\Lambda Be^9 \to \pi^- + H^1 + 2He^4$	6.38 ± 0.35	3	...	...	6.38 ± 0.35	3
${}_\Lambda B^{11} \to \pi^- + He^3 + 2He^4$	9.93 ± 0.6	1	...	...	9.93 ± 0.6	1
${}_\Lambda B^{12} \to \pi^- + 3He^4$	9.55 ± 0.6	1	9.90 ± 0.6	1	9.75 ± 0.42	2
${}_\Lambda C^{13} \to \pi^- + N^{13}$	...	...	$10.8\ \pm0.5$	1	$10.8\ \pm0.5$	1

[a] Several hypernuclear species may contribute to simulate this decay mode.

III. RESULTS AND DISCUSSION

Table I summarizes the data for events in group I. In this table, the old data (group Ia) are separated from the new (group Ib), and, in addition, the events are broken down into the various decay modes for a given species. The discrepancy in the relative frequencies between the two columns of this table is striking evidence of the selection bias alluded to earlier.

Table II presents our events of group I together with other events from the literature. In this case, B_Λ is not specified for individual decay modes of a given species. A comparison of B_Λ for ${}_\Lambda He^5$, given in the first two columns of the table, readily attests to the internal consistency of the data, and the weighted average of groups I and II is given in the final column. In performing this grand average, we have not included those π-r decays of Table I which are shown in parentheses under ${}_\Lambda Li^7 \to \pi^- + Be^7$. As already pointed out in reference 2, it is possible that species other than ${}_\Lambda Li^7$ may be present in this class of events; indeed, a more detailed investigation of them utilizing the kinematics at production has uncovered examples[4] which are not ${}_\Lambda Li^7$. Consequently, these events are not listed in Table II.

A few comments are in order concerning B_Λ for the isospin doublet ${}_\Lambda H^4$ and ${}_\Lambda He^4$. Of particular interest is the extent of the difference Δ in their B_Λ. If any significance is to be attached to this difference, it is important that the B_Λ of ${}_\Lambda H^4$ or of ${}_\Lambda He^4$ not be subject to systematic errors which are comparable with Δ or else that they both be subject to identical systematic errors. Thus, for example, an error in Q_Λ, although it introduces an error in both the B_Λ of ${}_\Lambda H^4$ and ${}_\Lambda He^4$, nevertheless leaves their difference unchanged. On the other hand, there are possible sources of systematic error which can affect Δ, particularly any error (*e.g.*, in the energy derived from the observed range) which is a function of the energy release, since the majority of ${}_\Lambda H^4$ events (π-r type) have an energy release which is significantly different from that encountered for ${}_\Lambda He^4$. Evidence bearing on such an effect may be obtained by comparing the binding energy for the single species ${}_\Lambda H^4$ calculated using first the π-r and next the non-π-r events in which no neutrons are

TABLE II. Binding energies from uniquely identified mesonic decays.

Identity	Group II[a] B_Λ (Mev)	Group II[a] σ_{av}[c] (Mev)	Group II[a] No. of events	Group I[b] B_Λ (Mev)	Group I[b] σ_{av}[c] (Mev)	Group I[b] No. of events	Average B_Λ (Mev)	Average σ_{av}[c] (Mev)	Average No. of events
$_\Lambda H^3$	0.39	0.25	18	0.01	0.30	7	0.23	0.20	25
$_\Lambda H^4$	2.10	0.11	58	2.12	0.15	37	2.11	0.09	95
$_\Lambda He^4$	2.40	0.13	22	2.48	0.15	18	2.44	0.10	41
$_\Lambda He^5$	3.12	0.08	73	3.06	0.10	61	3.10	0.06	134
$_\Lambda He^7$	3.0	0.8	1	3.83	0.41	5	3.66	0.36	6
$_\Lambda Li^7$ non π-r	5.39	0.30	5	5.60	0.30	4	5.50	0.17	9
$_\Lambda Li^8$	6.38	0.28	9	6.50	0.33	13	6.44	0.21	22
$_\Lambda Li^9$	7.5	0.6	2	7.87	0.79	4	7.68	0.48	6
$_\Lambda Be^8$	6.38	0.50	2	...	...	...	6.38	0.50	2
$_\Lambda Be^9$	6.52	0.26	6	6.40	0.35	3	6.50	0.21	9
$_\Lambda B^{11}$	...	...	...	9.9	0.6	1	9.9	0.6	1
$_\Lambda B^{12}$	11.2	0.6	1	9.75	0.42	2	10.23	0.35	3
$_\Lambda C^{13}$	...	...	...	10.8	0.5	1	10.8	0.5	1

[a] Group II contains surveyed data from references 5–14.
[b] Group I contains surveyed data from references 2–4. Group Ib events are from the present report.
[c] Possible systematic errors (± 0.2 Mev) have not been included.

emitted. Doing this, we find $B_\Lambda=(2.33\pm 0.14)$ Mev and $B_\Lambda=(2.02\pm 0.15)$ Mev, respectively, indicating that the possibility of such an error cannot be ruled out. However, any real discrepancy of this kind may also be due to the possible identification bias which is discussed subsequently. To minimize effects which may be sensitive to a difference in the energy release, one could compare the binding energies of $_\Lambda H^4$ and $_\Lambda He^4$ calculated from the $\pi-p-r-$decay modes only, where the energy release is the same for both cases. One finds for 23 π-p-r decays of $_\Lambda H^4$, $B_\Lambda=(2.00\pm 0.15)$ Mev, whereas on the basis of 38 π-p-r decays of $_\Lambda He^4$, $B_\Lambda=(2.42\pm 0.12)$ Mev. However, even these values may be shifted relative to each other because of a possible systematic error caused by identification biases. The π-p-r decays of $_\Lambda H^4$ and $_\Lambda He^4$ could, in fact, occasionally be confused with those of $_\Lambda H^3$ and $_\Lambda He^5$, respectively, due to measurement errors and the range-straggling of the recoils. The effect of this contamination would be to lower the measured B_Λ for $_\Lambda H^4$ and increase that for $_\Lambda He^4$. The magnitude of this effect cannot be estimated with our present sample, so we can at this time place only an upper limit on Δ, viz:

$$B_\Lambda({}_\Lambda He^4)-B_\Lambda({}_\Lambda H^4)\leqslant(0.42\pm 0.20)\text{ Mev.}$$

However, with increased statistics it should, in principle, be possible to correct for this possible source of bias.

Particular difficulty is encountered in attempting to distinguish between

$$_\Lambda Li^8\to\pi^-+2He^4 \qquad (1)$$

and

$$_\Lambda Li^9\to\pi^-+2He^4+n, \qquad (2)$$

when the momentum unbalance of the visible particles is relatively small (i.e., possible neutron emission with momentum $\lesssim 40$ Mev/c). For such configurations, the visible-energy release for both species is very similar, differing only ~ 2 Mev. Only when the neutron momentum in (2) significantly exceeds the upper limit of the momentum spread due to measurement errors and straggling can the two species be readily distingusihed. This is shown graphically in Fig. 1, as has already been indicated[4] using fewer events. The problem is essentially identical to that of detecting possible examples of $_\Lambda He^6\to\pi^-+p+He^4+n$ amongst events of the type $_\Lambda He^5\to\pi^-+p+He^4$ previously discussed in reference 2.

It is not inconceivable that some of the events with $\Delta P\lesssim 40$ Mev/c identified as $_\Lambda Li^8$ could indeed represent $_\Lambda Li^9$ decays involving neutron emission. Such a possibility can be investigated in more detail when larger statistics are available, e.g., by determining whether the distribution of visible-energy release for these events is skew with a tail on the side of low-energy release. If it exists, the effect of such a bias would be to make the quoted B_Λ value for $_\Lambda Li^8$ and $_\Lambda Li^9$ slightly larger than the true value.

The relative energies in the center-of-mass system of the two α particles coming from either the decay of $_\Lambda Li^8$ or $_\Lambda Li^9$ have been determined for the events of Fig. 1 and are contained in the histogram shown in

Fig. 2. This distribution may indicate to what extent the decay of $_\Lambda Li^8$ may be thought of as proceeding through the unbounded Be^{8*} either in its ground state or in its low-lying, excited state and may contribute information on the spin of $_\Lambda Li^8$. Although the statistics are still very limited, the observed distribution seems to deviate from a phase-space expectation for the $_\Lambda Li^8$ events. In fact, the grouping of events in the interval 3–5 Mev raises the possibility that the decay of $_\Lambda Li^8$ may be proceeding through the 2^+ excited state Be^{8*} which lies ~ 3 Mev above the ground state. If, as appears likely,[16] the s-wave channel in Λ decay is dominant, one would not expect this level to be reached from an initial state $J(_\Lambda Li^8)=0$,[17] thereby leaving the possibilities $J(_\Lambda Li^8)=1$ or 2. The present situation does not, however, rigorously rule out $J(_\Lambda Li^8)=0$, because the final nuclear state 2^+ can be reached then via the p-wave Λ-decay interaction. The apparent absence of transitions to the ground state of Be^8, as seen from Fig. 2, may seem rather surprising if $J(_\Lambda Li^8)=0$ or 1. A check amongst the nonuniquely identified events indicates that none of them could represent transitions to the ground state of Be^8. One cannot exclude, however, that some examples of the latter may have been missed due to their rather inconspicuous configuration.

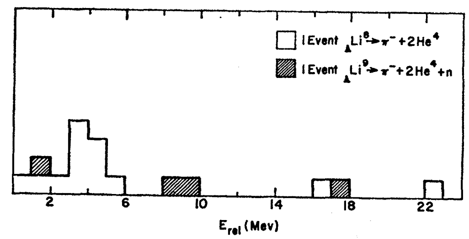

FIG. 2. Distribution of relative energy (E_{rel}) of the two α particles from the π^--mesonic decays of $_\Lambda Li^8$ and $_\Lambda Li^9$.

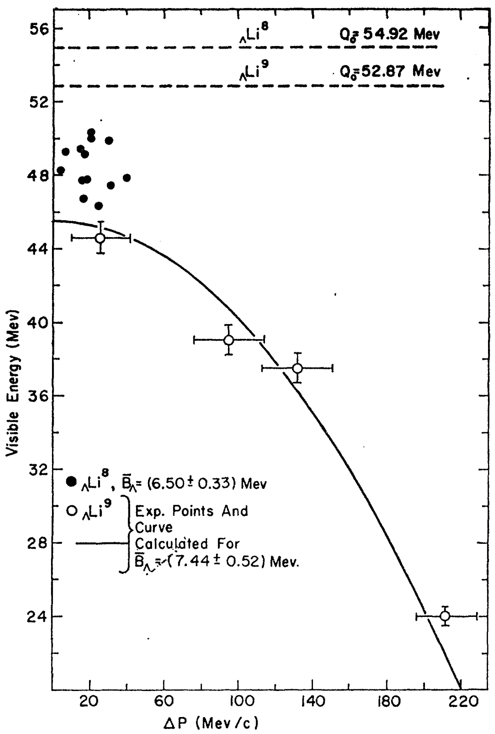

FIG. 1. Visible-energy release vs momentum unbalance for $_\Lambda Li^8 \to \pi^- + 2He^4$ and $_\Lambda Li^9 \to \pi^- + 2He^4 + n$ decays. Dashed lines represent the energy release (Q_0) corresponding to $B_\Lambda = 0$ for both decays.

With better statistics, a study of the angular distribution of the decay products may distinguish between the above-mentioned possibilities.

ACKNOWLEDGMENTS

We should like to thank Professor M. M. Block and Professor L. M. Brown at Northwestern University and Professor R. H. Dalitz and Professor V. L. Telegdi at The Enrico Fermi Institute for Nuclear Studies for many helpful discussions.

The data from Group I all originated from stacks exposed to the 300-Mev/c, separated K^- beam at the Berkeley Bevatron during 1957. We are greatly indebted to Dr. E. J. Lofgren and the Bevatron staff for their cooperation in securing these exposures.

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