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Lifetimes of Hypernuclei, $_\Lambda H^3$, $_\Lambda H^4$, $_\Lambda He^5$ †

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Presented in this report are lifetime estimates for hypernuclei $_\Lambda H^3$, $_\Lambda H^4$, and $_\Lambda He^5$ based upon data obtained from an emulsion stack exposed to 2.3- and 2.5-BeV/c K^- mesons. These lifetimes are: $\tau(_\Lambda H^3)=(0.9_{-0.4}{}^{+2.2})\times10^{-10}$ sec (3 in-flight and one at-rest decays; $_\Lambda H^3\rightarrow He^3+\pi^-$); $\tau(_\Lambda H^4)=(1.8_{-0.7}{}^{+2.5})\times10^{-10}$ sec (3 in-flight and 4 at-rest decays; $_\Lambda H^4\rightarrow He^4+\pi^-$); $\tau(_\Lambda He^5)=(1.4_{-0.5}{}^{+1.9})\times10^{-10}$ sec (3 in-flight and 25 at-rest decays; $_\Lambda He^5\rightarrow He^4+p+\pi^-$). Also one decay in flight and nine decays at rest of $_\Lambda He^4\rightarrow He^3+p+\pi^-$ were observed in a total estimated time of 1.50×10^{-10} sec. Included in the observation times for $_\Lambda He^4$ and $_\Lambda He^5$ are contributions from nine ambiguous decays at rest of $_\Lambda He^{4,5}\rightarrow He^{3,4}\rightarrow p+\pi^-$.

I. EXPERIMENTAL ARRANGEMENT

THE lifetimes of the light hypernuclei ($A\leq5$) have been the subject of a number of experimental investigations[1–5] and are discussed theoretically by Dalitz and Rajasekharan.[6] The best established lifetime is that of $_\Lambda H^3$ from an experiment with a helium bubble chamber.[1] Less well known is the lifetime of $_\Lambda H^4$ which is based upon systematic studies in a propane bubble chamber,[2] and in emulsion.[3] Only preliminary estimates are presently available for the helium hypernuclei and these pertain to mixed samples of $_\Lambda He^4$ and $_\Lambda He^5$.[4,5]

Presented here are additional data on the lifetimes of $_\Lambda H^3$, $_\Lambda H^4$, and $_\Lambda He^5$ obtained from an emulsion stack consisting of 166, 6 in.$\times$5-in.$\times$600-μ Ilford K-5 pellicles exposed at the Brookhaven AGS to K^- mesons at 2.3 BeV/c (80 percent), and 2.5 BeV/c (20 percent). The beam composition at the stack was $K:\mu:\pi=6.9:2.6:0.5$ and the total flux was 8×10^5 particles.

Two different scanning procedures were employed. In both procedures, denoted henceforth as A and B, the dark prongs of stars found by area scanning were followed in the original plate and a selected number of forward going flat prongs with ionization greater than $7\times$minimum were followed out of the plate to their endings. In the A scanning, prongs of an estimated 30 000 beam stars were examined under low magnification (150$\times$) and a total of 2100 prongs were followed out of the plate, also under low magnification. All secondaries and scatterings were examined under high magnification (650$\times$) for possible associated light tracks.[7] In the B scanning, 26 000 beam stars were examined and 8789 prongs were followed out of the plate, all under high magnification (650$\times$). Special attention was given to the search for associated light tracks at every scattering point.

II. LIFETIMES OF THE HYDROGEN HYPERNUCLEI

Owing to the difficulty of identifying in-flight decays through other modes, lifetimes are based entirely upon the following decays:

$$_\Lambda H^3\rightarrow He^3+\pi^-$$
$$_\Lambda H^4\rightarrow He^4+\pi^-.$$

A total of nine in-flight and nine at-rest two-body decays were found, of which six of the in-flight events came from the B scanning. Five of the nine in-flight events were found outside of the parent star plate with comparable rates per prong followed for the two scannings.

It is expected however, in accordance with previous emulsion experience,[3] that the actual scanning efficiency for such events is much greater with the B method. This is because the direction of the helium recoil does not deviate largely from the direction of the hypernucleus as can be seen in the camera lucida[8] drawing of a typical event shown in Fig. 1. Consequently, the hydrogen lifetimes are obtained only from events found in the B scanning.

The analysis of in-flight two-body decays involves both a comparison of the transverse momenta of the decay particles, and also a binding energy determination for each of the hypothesized identifications; $_\Lambda H^3$ and $_\Lambda H^4$. These binding energies are then compared with the established values; $B_\Lambda(_\Lambda H^3)=0.21\pm0.20$ MeV, and $B_\Lambda(_\Lambda H^4)=2.11\pm0.10$ MeV, given by Crayton *et al.*[9] The latter often proved to be the more sensitive test in those cases where the helium recoil angle θ_R (taken with

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[1] M. M. Block, R. Gessaroli, J. Kopelman, S. Ratti, M. Schneeberger, L. Grimellini, T. Kikuchi, L. Lendinara, L. Monari, W. Becker, and E. Harth, *Proceedings of the International Conference on Hyperfragments at St. Cergue* (CERN, Geneva, 1963), p. 63.
[2] L. R. Fortney, presented by W. J. Fry at the International Conference on Hyperfragments at St. Cergue, Switzerland, March 1963 (unpublished).
[3] N. Crayton, D. H. Davis, R. Levi Setti, M. Raymund, O. Skjeggestad, G. Tomasini, R. G. Ammar, L. Choy, W. Dunn, M. Holland, J. H. Roberts, and E. H. Shipley, *Proceedings of the 1962 International Conference on High Energy Physics at CERN* (CERN, Geneva, 1962), p. 460.
[4] R. G. Ammar, W. Dunn, and M. Holland, Phys. Letters 3, 340 (1963).
[5] Y. W. Kang, N. Kwak, J. Schneps, and P. A. Smith, Phys. Rev. Letters 10, 302 (1963).
[6] R. H. Dalitz and G. Rajasekharan, Phys. Letters 1, 58 (1962).
[7] The blob density in this stack, at minimum ionization is 21 per 100 μ.
[8] We are indebted to the high-energy physics group at the U. S. Naval Research Laboratory for making available to us their camera lucida equipment.
[9] N. Crayton, R. Levi Setti, M. Raymund, O. Skjeggestad, D. Abeledo, R. G. Ammar, J. H. Roberts, and E. N. Shipley, Rev. Mod. Phys. 34, 186 (1962).

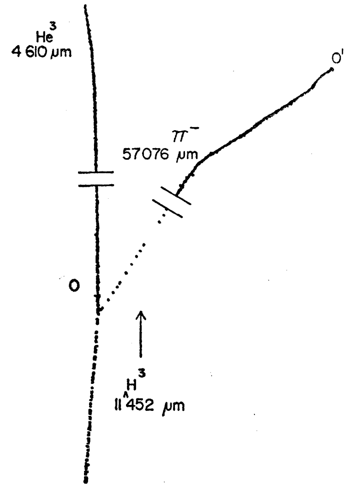

FIG. 1. Camera lucida drawing of event 1-95-1.

TABLE I. $_\Lambda H^3$ two-body decays in flight.[a]

Event	Range of hyper-nucleus (μ)[b]	Binding energy (MeV) Assuming $_\Lambda H^3$	Binding energy (MeV) Assuming $_\Lambda H^4$	Flight time (10^{-10} sec)	Momentum at decay (MeV/c)	θ_R (deg)
1-95-1	11 567	-0.2 ± 1.2	11.5 ± 1.2	1.14	938	7.0
1-98-3	400	3.3 ± 0.6	18.7 ± 0.6	0.07[c]	256	13.8
1-122-4	1600	-3.2 ± 2.9	-11.6 ± 2.9	0.20	763	9.0

[a] Events found in the B scanning.
[b] Ranges normalized to standard emulsion density 3.815 g cm^{-3}.
[c] The potential time available was 2.1×10^{-11} sec.

respect to the direction of the hypernucleus) is small or is difficult to measure owing to large dip angles of the tracks involved. In fact, the binding energy method is the only one available when one of the two final momenta is not well known as for example in event 1-22-4 where the decay pion interacts in flight. The analysis of event 1-136-3, in which both decay particles interact in-flight, is based upon an ionization and multiple scattering determination of the pion momentum. The mass of this hypernucleus, as determined from its ionization and multiple scattering, is 3780±870 MeV. Data for individual two-body decays in-flight are given in Tables I and II.

The lifetime of $_\Lambda H^3$ is based upon three decays in flight and one decay at rest whose flight time is 5.2×10^{-11} sec. The connecting track of event 1-98-3 is such (dip angle >20°) that it would not have been followed out of the plate and would have been missed had it not occurred in the same plate as the parent star. The other two in-flight decays would have been observed to come to rest in the stack. The $_\Lambda H^3$ lifetime is deduced from these data using the Bartlett S-function[10,11] with the result,

$$\tau(_\Lambda H^3)=(0.9_{-0.4}^{+2.2})\times10^{-10}\text{ sec}.$$

The lifetime of $_\Lambda H^4$ is based upon four decays at rest and three decays in flight, all of which would have been observed to come to rest. The total observation time is 5.44×10^{-10} sec and the lifetime is

$$\tau(_\Lambda H^4)=(1.8_{-0.7}^{+2.5})\times10^{-10}\text{ sec}.$$

III. LIFETIMES OF THE HELIUM HYPERNUCLEI

A camera lucida drawing of an in-flight decay of a helium hypernucleus via the pion-proton-recoil (πpr) mode is shown in Fig. 2. Such events invariably involve two dark prongs, the proton and the recoil, and can readily be seen under low magnification. Therefore, the lifetimes of helium hypernuclei are based on πpr decays found in scanning A as well as B.

A total of forty-three at-rest, and four in-flight decays of this kind have been found. For at-rest events in which the range of the recoil is greater than three microns, the analysis is based upon a comparison of the recoil range and the momentum of the pion-proton system as described elsewhere.[12,13] The identification of events having recoil ranges less than or equal to three microns is based upon their binding energies. In Fig. 3 points corresponding to the quantities $(\Delta B_\Lambda)_5$ and $(\Delta B_\Lambda)_4$ are plotted for each event in this category and for events with longer recoils which are still ambiguous between $_\Lambda He^4$ and $_\Lambda He^5$. The quantities $(\Delta B_\Lambda)_4$ and $(\Delta B_\Lambda)_5$ are, respectively, the absolute differences between the binding energies of the event, assuming

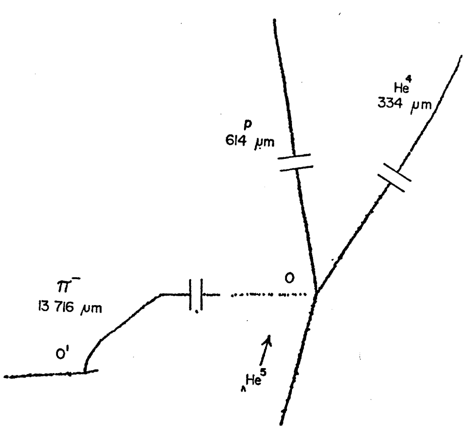

FIG. 2. Camera lucida drawing of event 1-88-2.

TABLE II. $_\Lambda H^4$ two-body decays in flight.[a]

Event	Range of hyper-nucleus (μ)[b]	Binding energy (MeV) Assuming $_\Lambda H^3$	Binding energy (MeV) Assuming $_\Lambda H^4$	Flight time (10^{-10} sec)	Momentum at decay (MeV/c)	θ_R (deg)
1-103-1	3110	-14.5 ± 0.9	0.5 ± 0.9	0.76	388	24.0
1-133-1	2781	-12.8 ± 0.8	1.8 ± 0.8	0.69	426	12.0
1-136-3	13 961	-6.1 ± 2.7	3.1 ± 2.7	1.40	1177	6.2

[a] Events found in the B scanning.
[b] Ranges normalized to standard emulsion density 3.815 g cm^{-3}.

[10] M. S. Bartlett, Phil. Mag. 44, 249 (1953).
[11] C. Castagnoli, G. Cortini, and C. Franzinetti, Suppl. Nuovo Cimento 10, 1 (1958).
[12] W. E. Slater, Suppl. Nuovo Cimento 10, 1 (1958).
[13] P. H. Steinberg, Ph.D. thesis, Northwestern University, Evaston, 1959 (unpublished).

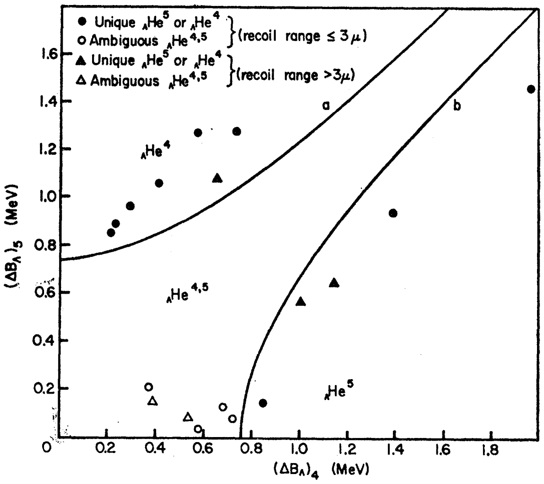

FIG. 3. $(\Delta B_{\Lambda})^5$ versus $(\Delta B_{\Lambda})_4$ plot for $_{\Lambda}He^{4,5}$ $(\pi p r)$ events. The boundary a represents the probability ratio of 3:1 favoring $_{\Lambda}He^4$ and b represents the probability ratio of 3:1 favoring $_{\Lambda}He^5$.

$_{\Lambda}He^4$ and then $_{\Lambda}He^5$ and the corresponding values based upon a survey of all previous data.[9] It is important to point out that the mean binding energy (3.25±0.11) MeV, of nineteen $_{\Lambda}He^5$ decays, uniquely identified by recoil range versus momentum comparison, is perfectly consistent with the value (3.10±0.07) MeV, given in Ref. 9. All binding energies are based upon careful stack calibrations and no systematic effects are apparent.

In Fig. 3 the boundaries a and b represent, respectively, the probability ratio of 3:1 favoring $_{\Lambda}He^4$ and $_{\Lambda}He^5$ (using a standard deviation of 0.5 MeV for the binding energy). Events above a are identified as $_{\Lambda}He^4$ and below b, as $_{\Lambda}He^5$.

In general, it is not possible to distinguish between decays occurring at momenta less than 60 MeV/c and decays at rest. This can be seen in Fig. 4 where the vector sum of momenta of the decay particles ΔP is plotted against the angle between ΔP and the direction of the hypernucleus at decay. In deducing lifetimes therefore, the moderation time 0.31×10^{-12} sec, corresponding to 60 MeV/c, is deleted from the moderation time of each event.

The corrected observation times for the at-rest events are given in Table III. The four decays in-flight are analyzed kinematically by comparing the helium recoil range with the momentum as inferred from momentum balance. On this basis all four events are uniquely identified, three as $_{\Lambda}He^5$ and one as $_{\Lambda}He^4$. Data for these events are given in Table IV. In every case the decay

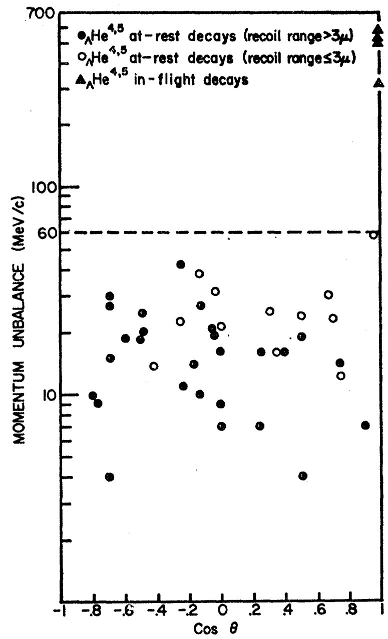

FIG. 4. Distribution of momentum unbalance ΔP versus $\cos\theta$ where θ is the angle between ΔP and the hyperfragment direction for helium hypernuclei. For ambiguous $_{\Lambda}He$ events ΔP is computed assuming $_{\Lambda}He^5$.

TABLE III. Total observation times for at-rest decays of helium hypernuclei.

Hypernucleus	Number of events	Total observation time (10^{-12} sec)
$_{\Lambda}He^5$	25[a]	322.7
$_{\Lambda}He^4$	9[b]	124.0
$_{\Lambda}He^{4,5}$	9[c]	85.5

[a] Included are three events which are ambiguous between $_{\Lambda}He^5$ and $_{\Lambda}He^7$. These events account for 5% of the total observation time.
[b] Including three events which are ambiguous between $_{\Lambda}He^4$ and $_{\Lambda}H^4$. These events account for 16% of the observation time.
[c] Included are three events with incomplete pion tracks.

TABLE IV. $_{\Lambda}He^4$ and $_{\Lambda}He^5$ decays in-flight.

Event	Identity	Range of hypernucleus (μ)[a]	Inferred momentum of recoil (MeV/c)	Recoil momentum from range: Assuming $_{\Lambda}He^4$ (MeV/c)	Assuming $_{\Lambda}He^5$ (MeV/c)	Flight time (10^{-12} sec)	Momentum at decay (MeV/c)
1-84-2	$_{\Lambda}He^5$	153	386±25	285	345	3.3	299
1-87-1	$_{\Lambda}He^5$	641	462±54	350	430	15.8	511
1-88-2	$_{\Lambda}He^5$	95	471±34	383	472	2.6	559
1-149-1	$_{\Lambda}He^4$	155	374±50	410	510	3.9	522

[a] Ranges normalized to standard emulsion density 3.875 g cm.$^{-3}$

occurred in the same plate as the parent star and would have been observed to come to rest.

In deducing the lifetime of ${}_{\Lambda}He^5$, the total observation time for ambiguous at-rest events was subdivided between ${}_{\Lambda}He^4$ and ${}_{\Lambda}He^5$ in the same proportions as these hypernuclei occur in the unique category. Such a subdivision has also been employed by Ammar *et al.*[4]

The lifetime of ${}_{\Lambda}He^5$ is given by

$$\tau({}_{\Lambda}He^5) = (1.4_{-0.5}{}^{+1.9}) \times 10^{-10}\ \text{sec},$$

and one decay of ${}_{\Lambda}He^4$ was observed in a total observation time of 1.50×10^{-10} sec.

IV. DISCUSSION

The lifetime of ${}_{\Lambda}H^3$ is of considerable interest especially in view of the short lifetime values presently available.[1,2] The value given by Block *et al.*,[1] $(1.05_{-0.18}{}^{+0.20}) \times 10^{-10}$ sec, is considerably below the free Λ lifetime, which is surprising in view of the light binding of the hypernucleus. Dalitz and Rajasekharan[6] give a theoretical lifetime for ${}_{\Lambda}H^3$ of $(1.8 \pm 0.1) \times 10^{-10}$ sec, corresponding to spin, $J = \frac{1}{2}$. The present experiment is consistent with a low value for the lifetime but with a large statistical uncertainty.

Data from the present experiment are combined with those of Crayton *et al.*,[3] and the Bartlett method is used to obtain a lifetime for ${}_{\Lambda}H^4$ of

$$\tau({}_{\Lambda}H^4,\ \text{Compilation}) = (1.35_{-0.28}{}^{+0.58}) \times 10^{-10}\ \text{sec}.$$

Both sets of data are obtained from emulsion studies and are subject to the same experimental biases. Both studies are based upon decays in flight of the type ${}_{\Lambda}H^4 \rightarrow He^4 + \pi^-$ which are easy to miss in the scanning, and the lifetime given is expected to be an overestimate. This result is nevertheless consistent with the value obtained from the formula

$$\Gamma = (\Gamma_{\pi^-})(1 + R_0 + Q), \qquad (1)$$

where R_0 is the decay ratio (π^0 mesonic)/(π^- mesonic), and Q is the decay ratio (nonmesonic)/(π^- mesonic). Using experimental values for R_0 and Q, given by Block *et al.*,[1] and theoretical π^- decay rate Γ_{π^-}, given by Dalitz and Rajasekharan,[6] one obtains total decay rates[14] for ${}_{\Lambda}H^4$, as

$$\Gamma({}_{\Lambda}H^4,\ J=0) = (6.4 \pm 0.7) \times 10^9\ \text{sec}^{-1},$$

and

$$\Gamma({}_{\Lambda}H^4,\ J=1) = (2.0 \pm 0.5) \times 10^9\ \text{sec}^{-1}.$$

The compiled experimental value,

$$\Gamma({}_{\Lambda}H^4,\ \text{experimental}) = (7.4 \pm 2.2) \times 10^9\ \text{sec}^{-1},$$

clearly favors the spin assignment, $J = 0$, which is in agreement with the conclusion derived from the large branching ratio $(\pi^- + He^4)/(\text{all } \pi^- \text{ modes})$, observed for ${}_{\Lambda}H^4$.[1,15]

The present data on helium hypernuclei are combined with previously reported data[4,5] to obtain a lifetime,

$$\tau({}_{\Lambda}He^{4,5},\ \text{compilation}) = (1.33_{-0.28}{}^{+0.52}) \times 10^{-10}\ \text{sec}$$

for undifferentiated ${}_{\Lambda}He^{4,5}$. The decay rate of ${}_{\Lambda}He^4$ is calculated from (1) using experimental values[1] for R_0 and Q, and the theoretical Γ_{π^-} for $J = 0$.[6] The decay rate of ${}_{\Lambda}He^5$ is based on $R_0 = \frac{1}{2}$, as required by the $\Delta I = \frac{1}{2}$ rule and $Q = 1.8 \pm 0.5$ adopted by Dalitz[16] from emulsion data. The results,

$$\Gamma({}_{\Lambda}He^4) = (4.4 \pm 0.4) \times 10^9\ \text{sec}^{-1},$$
$$\Gamma({}_{\Lambda}He^5) = (3.9 \pm 0.6) \times 10^9\ \text{sec}^{-1},$$

are both below

$$\Gamma({}_{\Lambda}He^{4,5},\ \text{experimental}) = (7.5 \pm 2.1) \times 10^9\ \text{sec}^{-1},$$

obtained from the above compiled experimental lifetime. These discrepancies may not be significant in view of the large statistical error in the experimental value. However, one notes that these discrepancies and the discrepancy for ${}_{\Lambda}H^3$ are both in the same direction. This perhaps raises doubts concerning the reliability of the theoretical estimates for these π^- mesonic decay rates.

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We wish to express our gratitude to the BNL bubble chamber group and AGS staff for their invaluable assistance in the exposure of the stack, and the BNL photography department for their aid in the processing of the stack.

[14] The free Λ decay rate used is taken from M. M. Block, R. Gessaroli, S. Ratti, L. Grimellini, T. Kikuchi, L. Lendinara, L. Monari, E. Harth, W. Becker, W. M. Bugg, and H. Cohn, Phys. Rev. **130**, 766 (1963). The error on the calculated Γ includes experimental errors in R_0, Q, and Γ_Λ, and the uncertainty in Γ_{π^-} arising from the error in the experimental ratio $p^2/(p^2+s^2)$ for the free decay $\Lambda \rightarrow p + \pi^-$ (see Ref. 6).

[15] R. G. Ammar, R. Levi Setti, W. E. Slater, S. Limentani, P. E. Schlein, and P. H. Steinberg, Nuovo Cimento **19**, 20 (1961).

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