cian. The experimental situation has also to be improved for $\theta^* < 70°$.

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Lifetimes of Light Hyperfragments. II*

R. E. PHILLIPS† AND J. SCHNEPS

Department of Physics, Tufts University, Medford, Massachusetts 02155

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We have continued our studies of the lifetimes of light hyperfragments. Our analysis is based on a total sample of 1476 mesonic decays of hyperfragments, of which 77 decayed in flight. The values we found for the mean lives are the following: $\tau({}_\Lambda H^3) = (2.85_{-1.05}^{+1.27}) \times 10^{-10}$ sec, using both two-body and three-body decays; $\tau({}_\Lambda H^4) = (2.68_{-1.07}^{+1.66}) \times 10^{-10}$ sec, using only three-body decays; $\tau({}_\Lambda He^4) = (2.28_{-1.29}^{+2.33}) \times 10^{-10}$ sec; $\tau({}_\Lambda He^5) = (2.51_{-0.73}^{+1.90}) \times 10^{-10}$ sec; and $\tau({}_\Lambda He^{4,5}) = (2.43_{-0.43}^{+0.60}) \times 10^{-10}$ sec for the combined mean life of all the ${}_\Lambda He^4$ and ${}_\Lambda He^5$ events. The last lifetime quoted contains only a statistical error. The others, in addition, contain in their errors the effects due to uncertainties in our knowledge of the bias for two-body events and of the separation of ambiguous three-body events. All the results are in good agreement with theoretical calculations of hyperfragment lifetimes.

I. INTRODUCTION

THE data presented in this paper represent the continuation of a program to determine the lifetimes of light hyperfragments in nuclear emulsion by observing their mesonic decays, both at rest and in flight. Earlier results on ${}_\Lambda H^3$, ${}_\Lambda H^4$, ${}_\Lambda He^4$, and ${}_\Lambda He^5$ were reported in 1965 in a paper[1] which we shall hereafter refer to as I. The status of experimental and theoretical work on hyperfragment lifetimes was also reviewed in that paper. At that time, the only serious discrepancy which existed between theoretical and experimental values concerned the lifetime of ${}_\Lambda H^3$. Recently, there have been reported two new measurements of the lifetime of ${}_\Lambda H^3$, one by Keyes *et al.*[2] and one by the present authors,[3] which appear to have reconciled this discrepancy.

The new data reported here were obtained from a stack of nuclear emulsions exposed to a 1.1-GeV/c K^- beam at the Bevatron. We obtained a total of 1218 π^--mesonic decays in this stack, of which 59 were in flight. We combined these with the 258 mesonic decays reported in I, of which 18 were in flight, making a total sample of 1476 mesonic decays (77 in flight) on which we based our analysis. Although the results concerning ${}_\Lambda H^3$ have already been reported in Ref. 3, we also include them here in greater detail, with some refinements in the calculations and amplification of the discussion.

II. EXPERIMENTAL PROCEDURE

A. Exposure and Processing

A stack of 160 Ilford $K5$ nuclear emulsion pellicles, each 6×8 in. and of 600-μ thickness, was exposed to a 1.1-GeV/c K^- beam from the Bevatron. Approximately 3×10^6 K^- mesons were incident on the central portion of the stack, covering about 30 pellicles. The rest of the stack served to bring energetic decay particles to rest so that they could be followed to the end of their range.

After exposure, each pellicle was cut in half for ease of handling. A coordinate grid was then lightly printed on the surface of each half pellicle for the purpose of locating events. The pellicles were then mounted on glass plates and processed according to standard procedures.[4]

B. Scanning

The scanning procedure was the same as that used in I. That is, the plates were area-scanned under low magnification (100×) for stars produced by an incident K^- meson. Each grey or dark track leading from such a star was followed until it ended or left the pellicle. Any secondary star found was examined under high magnification (1000×) in order to reveal a possible light meson track which may have been missed under low power. In addition, all apparent scatterings were ex-

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* Supported by the U. S. Atomic Energy Commission.

† Present address: M.I.T. Instrumentation Laboratory, Cambridge, Mass.

[1] Y. W. Kang, N. Kwak, J. Schneps, and P. A. Smith, Phys. Rev. **139**, B401 (1965).

[2] G. Keyes, M. Derrick, T. Fields, L. G. Hyman, J. G. Fetkovich, J. McKenzie, B. Riley, and I. T. Wang, Phys. Rev. Letters **20**, 819 (1968).

[3] R. E. Phillips and J. Schneps, Phys. Rev. Letters **20**, 1383 (1968).

[4] W. H. Barkas, *Nuclear Research Emulsions* (Academic Press Inc., New York, 1963).

amined under high magnification at least two times (by different scanners) in order to find possible π-meson tracks. No secondary star was considered if the projected length of the prong producing it was less than $20\,\mu$.

C. Measurements

The measurements of the ranges, dip angles, and azimuthal angles of hyperfragments and their decay tracks were carried out according to standard procedures.

In about 10% of the events, the decay π meson left the stack before coming to rest. In all but a very few of these events, it was possible to identify the track as that of a π meson and determine its energy by measurements of grain density, multiple scattering, or both. In the case of a few decays in flight, where the secondary tracks are likely to be longer than for rest decays, it was possible to distinguish between proton, deuteron, or triton interpretations for a track by measuring the integrated gap length.

We also made use of measurements of the widths of hyperfragment and decay particle tracks in order to assist in the determination of hyperfragment charge. For decays at rest we used exactly the same procedure as described in I, measuring the average width between 20 and 40 μ from the end of a stopping track. For some of the decays in flight (because of their longer secondary tracks), we measured track widths at greater residual ranges (50–400 μ) in order to obtain better sensitivity.

III. HYPERFRAGMENT ANALYSIS

A. Event Identification

The kinematic analysis of each event was performed by the computer program SIFT,[5] which was also used in I. It tries all possible identities for each of the decay tracks and also tries fits with neutral particles and short invisible recoils. In the majority of events, several possible interpretations were found to fit the data. The following set of rules was used to eliminate from consideration as many of these interpretations as possible:

(1) Eliminate interpretations with poor momentum balance and poor agreement with known binding energies.

(2) Eliminate those interpretations which require a neutron or short invisible recoil which is parallel to a visible track (within 10 deg).

(3) Eliminate those flight interpretations for which the following conditions all hold: The hyperfragment and any decay track are parallel; the continuation time (time it would have taken to come to rest after decay) is short; and the appearance of the track does not exclude a decay at rest, providing, of course, there were acceptable rest interpretations.

(4) For cases which still have remaining interpretations of different charge, measure the width of the hyperfragment track, its decay recoil, or both. This measurement was not decisive in all cases, but for a substantial number of events did serve to eliminate some interpretations from consideration.

Rule (1) served to separate most of the heavier hyperfragments from the hydrogen and helium events. Rule (4) also assisted in this and along with Rule (2) served to further separate hydrogen from helium events. Rule (3) eliminated some superfluous flight interpretations.

To see how rule (2) functions, suppose that a less massive identity than the true identity were assigned to some particular track. To balance momentum an additional neutron moving in the same direction would be added to the visible decay particles by SIFT. If the binding energy of this incorrect interpretation were approximately correct then the interpretation would be considered possible. A large number of events fell into the ambiguous category

$$_{\Lambda}\mathrm{H}^3 \rightarrow \pi^- p p n\,,$$
$$_{\Lambda}\mathrm{He}^{4,5} \rightarrow \pi^- p \mathrm{He}^{3,4}\,.$$

In those cases where the neutron was emitted within 10 deg of a proton we felt justified in eliminating the $_{\Lambda}\mathrm{H}^3 \rightarrow \pi^- p p n$ from consideration on the basis of rule (2), since the probability for this is quite small.

In addition, as in I, we did not accept as decays in flight events with momentum below 60 MeV/c.

B. Statistical Separation of Ambiguous Rest Events

In order to determine the lifetimes, we chose to consider only the most common decay modes which did not involve a neutral particle. These are

$$_{\Lambda}\mathrm{H}^3 \rightarrow \pi^- + \mathrm{He}^3\,,$$
$$_{\Lambda}\mathrm{H}^3 \rightarrow \pi^- + p + \mathrm{H}^2\,,$$
$$_{\Lambda}\mathrm{H}^4 \rightarrow \pi^- + \mathrm{He}^4\,,$$
$$_{\Lambda}\mathrm{H}^4 \rightarrow \pi^- + p + \mathrm{H}^3\,,$$
$$_{\Lambda}\mathrm{H}^4 \rightarrow \pi^- + \mathrm{H}^2 + \mathrm{H}^2\,,$$
$$_{\Lambda}\mathrm{He}^4 \rightarrow \pi^- + p + \mathrm{He}^3\,,$$
$$_{\Lambda}\mathrm{He}^5 \rightarrow \pi^- + p + \mathrm{He}^4\,.$$

The two-body events can always be identified uniquely. However, for the three-body rest events, even after the application of the procedures described above for identifying individual events, we were still left with a large number which had more than one possible interpretation. There were two categories of such ambiguous events to be dealt with. One involves events which have both a $_{\Lambda}$H and a $_{\Lambda}$He interpretation. To separate these statistically, we compared the range distributions. The other category contains events which have two or more interpretations with the same charge. There are two major classes; $_{\Lambda}\mathrm{H}^{3,4} \rightarrow \pi^- + p + \mathrm{H}^{2,3}$

[5] P. A. Smith, Tufts University report (unpublished).

TABLE I. Uniquely identified hyperfragments.[a,b]

Decay mode	Number of events	Decay mode	Number of events
${}_{\Lambda}\mathrm{H}^3 \to \pi^-\mathrm{He}^3$	34	${}_{\Lambda}\mathrm{He}^7 \to \pi^-\mathrm{H}^3\mathrm{He}^4$	6
${}_{\Lambda}\mathrm{H}^3 \to \pi^-p\mathrm{H}^2$	13	${}_{\Lambda}\mathrm{He}^7 \to \pi^-\mathrm{Li}^6 n$	7
${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$	7	${}_{\Lambda}\mathrm{He}^7 \to \pi^-\mathrm{H}^2\mathrm{He}^4 n$	2
${}_{\Lambda}\mathrm{H}^4 \to \pi^-\mathrm{He}^4$	128	${}_{\Lambda}\mathrm{Li}^7 \to \pi^-p\mathrm{Li}^6$	36
${}_{\Lambda}\mathrm{H}^4 \to \pi^-p\mathrm{H}^3$	15	${}_{\Lambda}\mathrm{Li}^7 \to \pi^-\mathrm{He}^3\mathrm{He}^4$	7
${}_{\Lambda}\mathrm{H}^4 \to \pi^-\mathrm{H}^2\mathrm{H}^2$	5	${}_{\Lambda}\mathrm{Li}^7 \to \pi^-p\mathrm{H}^2\mathrm{He}^4$	9
${}_{\Lambda}\mathrm{H}^4 \to \pi^-\mathrm{He}^3 n$	19		
		${}_{\Lambda}\mathrm{Li}^8 \to \pi^-\mathrm{He}^4\mathrm{He}^4$	28
${}_{\Lambda}\mathrm{He}^4 \to \pi^-p\mathrm{He}^3$	21	${}_{\Lambda}\mathrm{Li}^8 \to \pi^-p\mathrm{H}^3\mathrm{He}^4$	2
${}_{\Lambda}\mathrm{He}^4 \to \pi^-pp\mathrm{H}^2$	5		
${}_{\Lambda}\mathrm{He}^4 \to \pi^-pppn$	2	${}_{\Lambda}\mathrm{Li}^9 \to \pi^-\mathrm{He}^4\mathrm{He}^4 n$	7
${}_{\Lambda}\mathrm{He}^5 \to \pi^-p\mathrm{He}^4$	33	${}_{\Lambda}\mathrm{Le}^{10} \to \pi^-\mathrm{H}^3\mathrm{Li}^7$	1
${}_{\Lambda}\mathrm{He}^5 \to \pi^-pp\mathrm{H}^3$	1		
		${}_{\Lambda}\mathrm{Be}^9 \to \pi^-p\mathrm{He}^4\mathrm{He}^4$	5

[a] Events reported in I not included.
[b] Includes both rest and flight events.

TABLE II. Categories of ambiguous rest events containing hydrogen and helium interpretations.[a]

Category	Number of events	Category	Number of events
(1) ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^-p\mathrm{H}^{3,4}$	407	(9) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{H}^{3,4} \to \pi^-p\mathrm{H}^{2,3}$	3
(2) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^-p\mathrm{He}^{3,4}$	71	(10) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{H}^{3,4} \to \pi^-p\mathrm{H}^{2,3}$ ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^-p\mathrm{He}^{3,4}$	1
(3) ${}_{\Lambda}\mathrm{H}^{3,4} \to \pi^-p\mathrm{H}^{2,3}$	81		
(4) ${}_{\Lambda}\mathrm{H}^4 \to \pi^-p\mathrm{H}^3$ ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^-p\mathrm{He}^{3,4}$	19	(11) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{H}^4 \to \pi^-p\mathrm{H}^3$	5
(5) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{H}^4 \to \pi^-p\mathrm{H}^3$ ${}_{\Lambda}\mathrm{He}^4 \to \pi^-p\mathrm{He}^3$	6	(12) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{H}^{3,4} \to \pi^-p\mathrm{H}^{2,3}$ ${}_{\Lambda}\mathrm{He}^4 \to \pi^-p\mathrm{He}^3$	2
(6) ${}_{\Lambda}\mathrm{H}^{3,4} \to \pi^-p\mathrm{H}^{2,3}$ ${}_{\Lambda}\mathrm{He}^4 \to \pi^-p\mathrm{He}^3$	8	(13) ${}_{\Lambda}\mathrm{H}^3 \to \pi^-ppn$ ${}_{\Lambda}\mathrm{H}^4 \to \pi^-p\mathrm{H}^3$	15
(7) ${}_{\Lambda}\mathrm{H}^{3,4} \to \pi^-p\mathrm{H}^{2,3}$ ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^-p\mathrm{He}^{3,4}$	3	(14) ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^-p\mathrm{He}^{3,4}$ ${}_{\Lambda}\mathrm{Li}^7 \to \pi^-p\mathrm{Li}^6$	4
(8) ${}_{\Lambda}\mathrm{H}^4 \to \pi^-p\mathrm{H}^3$ ${}_{\Lambda}\mathrm{He}^4 \to \pi^-p\mathrm{He}^3$	5		

[a] Events reported in I not included.

which must be separated into ${}_{\Lambda}\mathrm{H}^3$ and ${}_{\Lambda}\mathrm{H}^4$; and ${}_{\Lambda}\mathrm{He}^{4,5} \to \pi^- + p + \mathrm{He}^{3,4}$ which must be separated into ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$. To separate these events we used a method which compared the average measured binding energy of the ambiguous events with the average binding energies of the unique events.

In order to determine the binding energies of the unique classes of events, we needed samples of unique events in which each event was chosen independently of its measured binding energy. For this we reanalyzed all our three-body events with a ${}_{\Lambda}\mathrm{H}$ or ${}_{\Lambda}\mathrm{He}$ interpretation using the selection criteria of Mayeur *et al.*[6] in place of our rule (1). Under their criteria an interpretation can be accepted as unique only if the range of the recoil is greater than a certain value and only if this interpretation and no other has its momentum balanced within two standard deviations. The minimum values used for the recoil ranges were $R_{\mathrm{H}^2}=6\,\mu$; $R_{\mathrm{H}^3}=6\,\mu$; $R_{\mathrm{He}^3}=10\,\mu$; and $\mathrm{R}_{\mathrm{He}^4}=6\,\mu$. We modified their criteria by using four standard deviations on the momentum balance instead of two. The reasons for this were first that we had evidence, from studying the distribution of residual momenta of our three-body events, that our errors were underestimated by a factor of almost 2; and second, four standard deviations is a more stringent condition than two, and although it gives us fewer unique interpretations, we could be certain that they contained essentially no contamination.

Summarizing, rules (1)–(4) were first applied to all the events, and then the more stringent criteria described above were applied to the three-body ${}_{\Lambda}\mathrm{H}$ and ${}_{\Lambda}\mathrm{He}$ events. Following this procedure we obtained altogether 394 uniquely identified hyperfragments. The number of these hyperfragments in each decay mode is shown in Table I. In Table II are shown the numbers of hyperfragments in the various categories of ambiguous rest events.

The separation into hyperfragments of different charge was made, as remarked before, on the basis of range distributions. Figure 1 shows the range distributions of ${}_{\Lambda}\mathrm{H}^3$, ${}_{\Lambda}\mathrm{H}^4$, ${}_{\Lambda}\mathrm{He}^4$, and ${}_{\Lambda}\mathrm{He}^5$ obtained after using

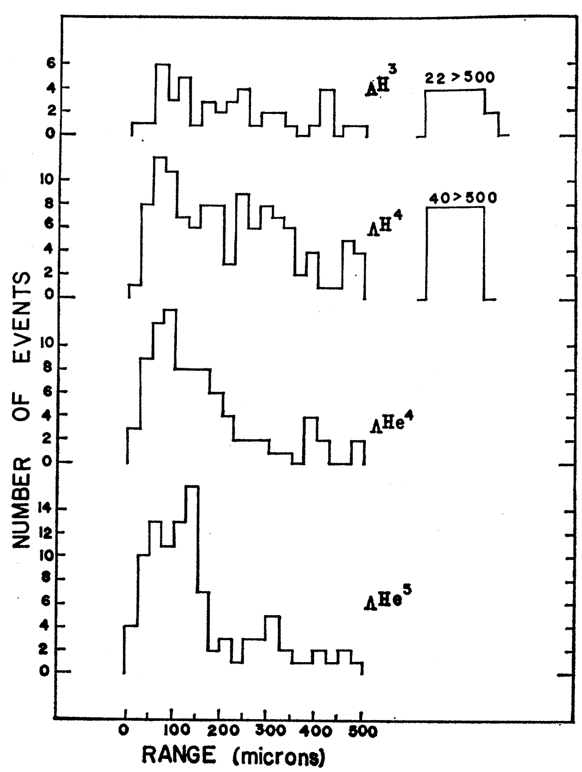

FIG. 1. Range distributions of uniquely identified hyperfragments.

[6] C. Mayeur, J. Sacton, P. Vilain, G. Wilquet, D. O'Sullivan, D. Stanley, P. Allen, D. H. Davis, E. R. Fletcher, D. A. Garbutt, J. E. Allen, V. A. Bull, A. P. Conway, and P. V. March, Nuovo Cimento 43A, 180 (1966).

rules (1)–(4). Note that there are no ${}_{\Lambda}\mathrm{He}$ events with range greater than 500 μ. Figure 2 shows the range distributions of the different categories of ambiguous events.

Since the number of events in the ambiguous categories was generally small, no effort was made to fit the ${}_{\Lambda}\mathrm{H}$ and ${}_{\Lambda}\mathrm{He}$ distributions to the ambiguous ones in a rigorous way. The separation was made by comparing the number of events in the tail of the distributions (range greater than 500 μ) to the number of events in the peak. All events in the tail of the distributions of ambiguous events along with a proportionate number of events in the peak were assigned to ${}_{\Lambda}\mathrm{H}$, and the rest to ${}_{\Lambda}\mathrm{He}$. Part A of Table III shows the results of this division.

The division of the ambiguous categories ${}_{\Lambda}\mathrm{H}^{3,4}$ and ${}_{\Lambda}\mathrm{He}^{4,5}$ was made as follows, taking ${}_{\Lambda}\mathrm{He}^{4,5}$ as the example: We first determined the mean binding energies for ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ using our unique events. Then the mean value of the binding energy of all the ambiguous events was determined, first as if they were all ${}_{\Lambda}\mathrm{He}^4$, and then as if they were all ${}_{\Lambda}\mathrm{He}^5$. The values obtained, $\hat{B}_4$ and $\hat{B}_5$, can be expressed as follows:

$$\hat{B}_4 = f_4 B_4 + f_5(B_5 + \bar{F}), \tag{1}$$

$$\hat{B}_5 = f_4(B_4 - \bar{F}') + f_5 B_5, \tag{2}$$

where B_4 and B_5 are the binding energies of ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ as determined from our unique events, f_4 and f_5 are the fractions of ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ contained in the ambiguous category. $\bar{F}$ is the average value of the shift in the binding energy due to calculating a true ${}_{\Lambda}\mathrm{He}^5$ as if it were ${}_{\Lambda}\mathrm{He}^4$, and $-\bar{F}'$ is the average value of this shift when calculating a true ${}_{\Lambda}\mathrm{He}^4$ as if it were ${}_{\Lambda}\mathrm{He}^5$.

For a given ${}_{\Lambda}\mathrm{He}^5$ calculated as ${}_{\Lambda}\mathrm{He}^4$ the shift in binding energy is

$$F(R) = T_4(R) - T_3(R), \tag{3}$$

and for a given ${}_{\Lambda}\mathrm{He}^4$ calculated as ${}_{\Lambda}\mathrm{He}^5$ the shift is

$$-F(R) = T_3(R) - T_4(R), \tag{4}$$

where $T_3(R)$ and $T_4(R)$ are the kinetic energies of He^3 and He^4 recoils of range R. Then we see $\bar{F} = F(R)$ averaged over the range spectrum of the recoils from ${}_{\Lambda}\mathrm{He}^5$ and $\bar{F}' = F(R)$ averaged over the range spectrum of the recoils from ${}_{\Lambda}\mathrm{He}^4$.

The range spectra of the recoils in the two cases are not expected to be very different, differing at most in their mean values by a few microns. Furthermore, $F(R)$ is a quite slowly varying function over the region of R which is of interest. Therefore, to a very good approximation, within 5%, $\bar{F} = \bar{F}'$. Using this, we can solve Eqs. (1) and (2) for $\bar{F}$, f_4, and f_5 (noting also that $f_4 + f_5 = 1$).

From our unique ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ events we determined the corresponding binding energies. They turned out to be

$$B_4 = 2.10 \pm 0.17 \text{ MeV},$$
$$B_5 = 2.87 \pm 0.11 \text{ MeV}.$$

For the ambiguous events we found

$$\hat{B}_4 = 2.69 \pm 0.05,$$
$$\hat{B}_5 = 2.62 \pm 0.05.$$

Solving Eqs. (1) and (2), we then obtain

$$\bar{F} = 0.07,$$
$$f_4 = 0.29 \pm 0.11,$$
$$f_5 = 0.71 \pm 0.11.$$

For the ${}_{\Lambda}\mathrm{H}^{3,4}$ case we use the same procedure, writing

$$\hat{B}_3' = f_3' B_3' + f_4'(B_4' + \bar{F}'), \tag{5}$$

$$\hat{B}_4' = f_3'(B_3' - \bar{F}') + f_4' B_4'. \tag{6}$$

From our unique ${}_{\Lambda}\mathrm{H}^3$ and ${}_{\Lambda}\mathrm{H}^4$ events we obtained

$$B_3' = 0.35 \pm 0.41 \text{ MeV},$$
$$B_4' = 1.86 \pm 0.30 \text{ MeV},$$

and from the ambiguous events we found

$$B_3' = 1.08 \pm 0.14,$$
$$B_4' = 1.04 \pm 0.14.$$

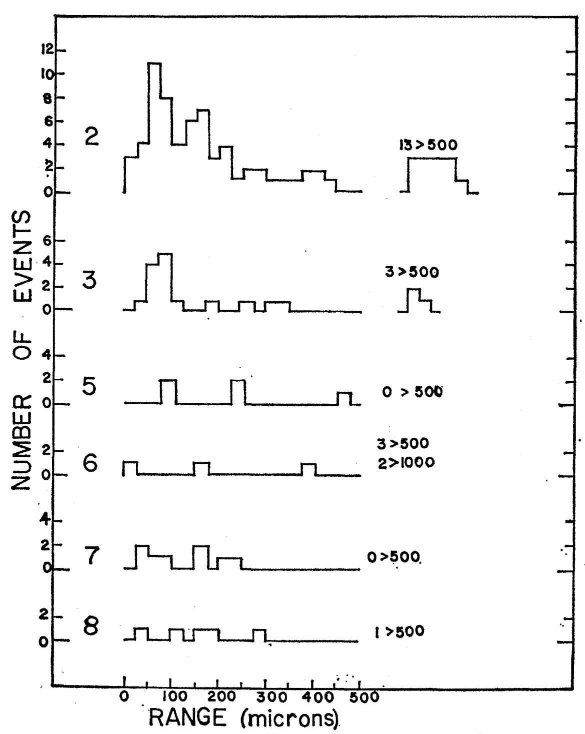

FIG. 2. Range distributions of ambiguous categories of hyperfragments. The numbers appearing before each distribution correspond to the number for the given category of ambiguous events as indicated in Table II.

TABLE III. The division of ambiguous rest events. Part A shows events divided on the basis of range distributions, part B those divided on the basis of binding energy, and part C the few remaining events which were divided on the basis of previous abundance.[a]

Category	Number	${}_{\Lambda}H^3 \to \pi ppn$	${}_{\Lambda}H^{3,4} \to \pi pH^{2,3}$	${}_{\Lambda}H^3 \to \pi pH^2$	${}_{\Lambda}H^4 \to \pi pH^3$	${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	${}_{\Lambda}H^4 \to \pi pHe^3$	${}_{\Lambda}He^5 \to \pi pHe^4$
(A)								
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	71	16±4				55±7		
${}_{\Lambda}H^4 \to \pi pH^3$; ${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	19				9±3	10±3		
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}H^4 \to \pi pH^3$; ${}_{\Lambda}He^4 \to \pi pHe^3$	6						6±2	
${}_{\Lambda}H^{3,4} \to \pi pH^{2,3}$; ${}_{\Lambda}He^4 \to \pi pHe^3$	8		8±3					
${}_{\Lambda}H^{3,4} \to \pi pH^{2,3}$; ${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	3					3±2		
${}_{\Lambda}H^4 \to \pi pH^3$; ${}_{\Lambda}He^4 \to \pi pHe^3$	5				1±1		4±2	
Totals (A)	112	16±4	8±3	0	10±3	68±8	10±3	0
(B)			└──→	4±2	4±2	└──→	20±7	48±7
${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	407						118±44	289±44
${}_{\Lambda}H^{3,4} \to \pi pH^{3,4}$	81			43±18	38±18			
(C)								
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}H^4 \to \pi pH^3$	15	5			10			
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}H^{3,4} \to \pi pH^{2,3}$	3	0.5		1.25	1.25			
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}H^{3,4} \to \pi pH^{2,3}$; ${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	1			0.1	0.1		0.2	0.6
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}H^4 \to \pi pH^3$; ${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$	5	0.1			0.5		1.3	3.1
${}_{\Lambda}H^3 \to \pi ppn$; ${}_{\Lambda}H^{3,4} \to \pi pH^{2,3}$; ${}_{\Lambda}He^4 \to \pi pHe^3$	2	0.1		0.2	0.2		1.5	
${}_{\Lambda}He^{4,5} \to \pi pHe^{3,4}$; ${}_{\Lambda}Li^7 \to \pi pLi^6$	4						0.9	2.1
Totals	630	22±4		48±18	64±18		152±44	343±44

[a] Events reported in I not included.

These values then yield

$$\bar{F}'=0.04,$$

$$f_3'=0.53\pm0.22,$$

$$f_4'=0.47\pm0.22.$$

In making this division of the ambiguous ${}_{\Lambda}He^{4,5}$ and ${}_{\Lambda}H^{3,4}$ events, note that we used for the ${}_{\Lambda}He^4$, ${}_{\Lambda}He^5$, ${}_{\Lambda}H^3$, and ${}_{\Lambda}H^4$ binding energies the values obtained from our own unique events, rather than using more accurate determinations such as those reported by Gajewski *et al.*[7] The purpose of this was to eliminate the effects of any unknown systematic errors which might have occurred in the determination of our binding energies.

The division of ambiguous events according to the binding energy method is shown in part B of Table III.

Finally, there were a small number of ambiguous events, 30, which could not be divided by use of the above methods. As a first approximation these were divided so as to have the same relative abundance as they have in parts A and B of Table III. The categories of events of this type and their division are shown in part C of Table III.

C. Flight Events

Since the lifetime is particularly sensitive to the number of decays in flight, we used every possible means to uniquely identify the flight events. That is, in addition to momentum balance in the kinematic analysis we also made use of known binding energies, and if necessary we also made measurements of individual tracks as described in Sec. II C. In Table IV we list all the flight events individually with a summary of the pertinent information concerning each event. Table V summarizes the over-all breakdown of events for both the rest and the flight cases.

Various assumptions on how the ambiguous flight events divide are discussed in Sec. IV, where we calculate lifetimes.

D. Biases

In determining lifetimes it is important to know, for each decay mode used, whether there is any scanning

[7] W. Gajewski, C. Mayeur, J. Sacton, P. Vilain, G. Wilquet, D. Harmsen, R. Levi-Setti, M. Raymund, J. Zakrzewski, D. Stanley, D. H. Davis, E. R. Fletcher, J. E. Allen, V. A. Bull, A. P. Conway, and P. V. March, Nucl. Phys. **B1**, 105 (1967).

TABLE IV. Summary of decays in flight.[a,b]

Event No.	Identity	R	P	t	T	T_m
73517345K	$_\Lambda H^3 \to \pi^- He^3$	210.4	95	9.5	···	31.6
78255915K		1632.5	187	47.8	···	50.9
84718144		61.2	590	2.0	29.2	108.0
88190912		3900.4	181	92.1	···	95.6
89777911		137.6	259	3.6	6.1	21.5
91437554K		328.1	397	7.3	20.4	43.8
71574715K	$_\Lambda H^3 \to \pi^- p H^2$	214.5	340	6.6	···	12.5
71835553K		2035.2	677	28.9	42.1	206.0
72631302		485.2	344	12.5	···	17.6
75690531K		409.7	498	7.8	10.7	91.5
78073944		87.0	328	0.9	25.3	35.2
83470715		1096.6	292	29.4	43.8	57.7
86954723		142.7	234	4.0	···	17.9
90275935		52.5	648	1.1	6.1	160.9
70473145K	$_\Lambda H^4 \to \pi^- He^4$	271.3	153	14.5	···	16.9
71695151K		79.6	112	5.2	···	6.1
73417746		100.3	275	3.0	···	6.2
75256936K		259.0	622	5.2	···	96.1
75812535		615.5	235	23.5	···	28.9
79652515		350.4	387	10.1	13.0	27.3
81271314K		665.4	89	32.4	···	31.2
86590113K		1055.8	643	20.3	70.0	93.0
86732124K		2563.7	475	59.3	···	76.0
87757124K		215.3	453	5.3	28.0	36.6
65375113	$_\Lambda H^4 \to \pi^- He^3 n$	238.6	331	8.0	···	29.3
71270745	1st solution	264.3	387	7.7	28.0	32.6
	2nd solution		667	4.8	9.4	113.0
69959700	$_\Lambda H^4 \to \pi^- dd$	118.9	130	6.1	···	9.1
72554912	$_\Lambda H^4 \to \pi^- p H^3$	270.6	204	12.8	···	18.9
77235164		209.0	232	9.0	10.3	21.5
78238711K		76.6	318	2.3	···	12.3
81859722		30.2	378	0.2	2.3	24.2
82318924		540.5	336	17.7	19.1	20.7
87775155K		709.2	876	10.5	11.6	194.0
88771103K		160.9	683	1.6	3.0	116.0
90394515		741.8	70	33.9	···	34.0

Event No.	Identity	R	P	t	T	T_m
	$_\Lambda H^{3,4} \to \pi^- p H^{2,3}$					
72796511	if $_\Lambda H^3$	79.1	260	2.2	···	5.3
	if $_\Lambda H^4$		314	2.3	···	5.8
77915955K	if $_\Lambda H^3$	643.3	435	14.4	16.7	46.4
	if $_\Lambda H^4$		524	15.2	17.9	51.0
82397944	if $_\Lambda H^3$	61.2	796	0.7	8.1	249.0
	if $_\Lambda H^4$		976	1.2	12.4	284.0
83752535K	if $_\Lambda H^3$	701.7	134	28.2	···	30.9
	if $_\Lambda H^4$		147	29.3	···	31.6
84150702K	if $_\Lambda H^3$	486.0	238	16.7	17.5	31.4
	if $_\Lambda H^4$		302	16.8	17.7	36.8
70957932	$_\Lambda He^4 \to \pi^- p He^3$	258.4	543	5.6	···	13.2
73358732K		231.9	434	5.6	···	7.6
81876361K		156.9	250	5.3	···	7.0
69254751	$_\Lambda He^5 \to \pi^- p He^4$	21.2	668	0.1	···	20.6
70778954K		169.3	259	6.5	···	9.2
82092934		217.0	274	8.1	···	10.8
87615936		147.8	363	4.6	···	6.8
	$_\Lambda He^{4,5} \to \pi^- p He^{3,4}$					
74911336	if $_\Lambda He^4$	114.8	471	2.5	···	14.7
	if $_\Lambda He^5$		552	2.5	···	11.1
75179713	if $_\Lambda He^4$	102.3	275	3.2	···	4.1
	if $_\Lambda He^5$		315	3.4	···	4.4
75572515K	if $_\Lambda He^4$	68.0	163	2.6	···	3.4
	if $_\Lambda He^5$		169	2.6	···	3.5
76870725	if $_\Lambda He^4$	693.7	889	9.8	···	16.2
	if $_\Lambda He^5$		1040	10.2	···	17.5
79079121	if $_\Lambda He^4$	267.4	398	7.0	···	8.7
	if $_\Lambda He^5$		448	7.4	···	9.3
83231713K	if $_\Lambda He^4$	1344.8	453	28.2	···	29.9
	if $_\Lambda He^5$		503	29.9	···	32.0
84714161K	if $_\Lambda He^4$	101.1	488	1.9	···	3.5
	if $_\Lambda He^5$		555	1.9	···	3.7
88395143	if $_\Lambda He^4$	200.7	603	3.7	···	14.6
	if $_\Lambda He^5$		717	4.0	···	14.0
89035300	if $_\Lambda He^4$	26.3	335	0.1	···	6.6
	if $_\Lambda He^5$		381	0.2	···	7.4
89474715K	if $_\Lambda He^4$	90.0	384	2.1	···	3.4
	if $_\Lambda He^5$		452	2.1	···	3.6
82833541	$_\Lambda Li^8 \to \pi^- He^4 He^4$	299.7	575	8.8	···	10.6

[a] Events reported in I not included.
[b] R is range of hyperfragment to point of decay in μ; P is momentum of hyperfragment at point of decay in MeV/c; t is time of flight after subtracting time spent in first 20 μ (projected) of flight, in units of 10^{-12} sec; T is potential time after subtracting time spent in first 20 μ (projected); T_m is moderation time if hyperfragment had not decayed.

bias against finding decays in flight in comparison to those at rest or vice versa.

For the three-body modes we used, π^-+p+recoil, there is no *a priori* reason to expect an appreciable bias against either decays in flight or at rest. Both should be easy to recognize. As a check on this we second scanned a portion of our stack and compared the scanning efficiencies for finding three-body rest and flight decays. The result of this was an efficiency of 85% for rest decays based on 150 events; and 100% for flight decays based on seven events. We conclude from this that the scanning biases are comparable in the two cases, and therefore do not take them into account when calculating the lifetimes.

On the other hand, for the two-body decays which we considered using, $_\Lambda H^3 \to \pi^- + He^3$ and $_\Lambda H^4 \to \pi^- + He^4$, it is necessary to proceed with caution because, in our type of scanning, biases might be expected for both rest and flight events. In order to use these events we must have some knowledge of the extent of these biases.

We consider the rest events first. In practice the events are usually found by observing a hook at the end of a stopping track. This hook corresponds to the He^3 or He^4 recoil, which has a range of about 8μ. The π meson is usually found after the hook has been seen, and often it is necessary to study the event under high power in order to find it. For events in which the recoil has a large dip angle, and therefore a short projected range, we would expect there to be a bias against finding hooks. This bias might be expected to become severe for projected ranges less than about 3 μ. Further, for events which have a small dip angle, so that the π-meson track, as well as the recoil, is very flat, we may also expect some bias. This is because a light track which is flat is generally more difficult to see than one which is moderately dipping.

We can study these biases by looking at the distribution of the sine of the dip angle of the recoils. If there are no biases this distribution should be flat. In Fig. 3 we show these distributions for $_\Lambda H^4$ and $_\Lambda H^3$, respectively. In both cases we see that events have been missed for both very small and very large dip angles. If we assume that the distributions are essentially flat between the values 0.2–0.8 of the sine of the dip angle, then we find that the fraction of events missed was 26.4% for $_\Lambda H^4$ and 24.3% for $_\Lambda H^4$. Assuming these fractions to be essentially the same for the two cases, and combining them, we find the fraction missed is $(26\pm4)\%$ for the two-body decays at rest.

Estimation of the bias against finding flight events is more difficult because there are fewer of them. There are two reasons for expecting a bias. First, these events are found by scanning for apparent scatterings. As the scattering angle becomes smaller the fraction of events missed will become larger. Thus there will be bias against events where the recoil is emitted at a small angle with respect to the hyperfragment direction of flight. Second, after a scattering was found, it was examined very carefully under high power by two different scanners to see if a π meson was emitted. Nevertheless, if the π meson were very lightly ionizing it might still be missed. We therefore expect some bias for events of this type.

In the case of $_\Lambda H^4$ many of the π mesons are expected to be appreciably below twice minimum ionizing in most events, whereas for $_\Lambda H^3$ the emitted π^- are lower in energy and produce a darker track comparable to the ionization of the π^- from three-body decays which are seen with good efficiency. Therefore, we expect no difficulty in finding the π^- tracks from $_\Lambda H^3$ decays. We have evidence that, in fact, an appreciable number of π^- mesons from $_\Lambda H^4$ decays were missed. This consists in the following: First, if the lifetimes of $_\Lambda H^3$ and $_\Lambda H^4$ were about the same, we should expect roughly the same ratio of $_\Lambda H^4$ to $_\Lambda H^3$ two-body flight events as we find for rest events, that is $119/28\approx4$. Taking into account possible differences in these lifetimes and other

TABLE V. Results of hyperfragment identification for $_\Lambda H$ and $_\Lambda He$.[a]

Decay mode	Rest unique	Rest ambiguous	Total rest	Flight unique	Flight ambiguous
$_\Lambda H^3 \rightarrow \pi^- He^3$	28	0	28	6	0
$_\Lambda H^3 \rightarrow \pi^- ppn$	7	22	29	...	...
$_\Lambda H^3 \rightarrow \pi^- pH^2$	5	48	53	8	{ 5
$_\Lambda H^4 \rightarrow \pi^- pH^3$	7	64	71	8	
$_\Lambda H^4 \rightarrow \pi^- He^4$	119	0	119	10	0
$_\Lambda H^4 \rightarrow \pi^- H^2H^2$	3	0	3	1	0
$_\Lambda H^4 \rightarrow \pi^- He^3n$	17	0	17	2	0
$_\Lambda He^4 \rightarrow \pi^- pppn$	2	...	2	...	...
$_\Lambda He^4 \rightarrow \pi^- ppH^2$	5	...	5	...	...
$_\Lambda He^4 \rightarrow \pi^- pHe^3$	18	152	170	3	{ 10
$_\Lambda He^5 \rightarrow \pi^- pHe^4$	29	343	372	4	
$_\Lambda He^5 \rightarrow \pi^- ppH^3$	1	...	...		

[a] Events reported in I not included.

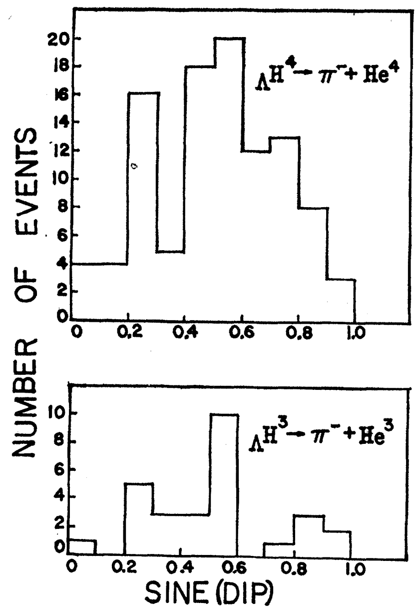

FIG. 3. Distributions of the sine of the dip angle of the recoil for $_\Lambda H^3$ and $_\Lambda H^4$ two-body decays.

minor factors we might expect this ratio to be between 3 and 5. In fact the ratio we found for the flight events was $10/6=1.7$. This indicates that perhaps 40–60% of the $_\Lambda H^4$ events were missed. Further, we had evidence that the efficiency for detecting the light π^- tracks from $_\Lambda H^4$ was scanner-dependent, whereas this was not the case for the darker π^- tracks from $_\Lambda H^3$. Since we had no good way to estimate this type of bias against $_\Lambda H^4$ we decided we could not use the two-body $_\Lambda H^4$ events for a lifetime determination.

For the $_\Lambda H^3$ events we must now consider the problem of the bias against finding events where the angle between the direction of the recoil and the direction of flight of the hyperfragment is small. We can estimate this bias by the following procedure:

(1) We choose an angle above which we expect the bias to be negligible. We choose 10 deg for this.

(2) We calculate, as a function of the momentum at decay of the hyperfragments the fraction of events which will have angles under 10 deg (assuming the decay angular distribution is isotropic in the c.m. frame of reference).

(3) Using the observed momentum distribution at production of our $_\Lambda H^3$ events, and assuming a value for the lifetime, we calculate the momentum distribution at decay of the flight events. The result turns out to be very insensitive to the value assumed for the lifetime within the range from 1 to 3×10^{-10} sec.

(4) Combining the results of the last two steps, we obtain the fraction of all our decays in flight that should have angles under 10 deg. This turns out to be 0.39.

(5) We then see how many of our actual flight events had angles above 10 deg and how many were below. For

this we make use of the six events reported in this paper plus three reported in I. Of these nine events eight were above 10 deg and one was below. From the result of step (4) we should have expected $8/(1/0.39-1)=5$ events below 10 deg. Thus for all flight events we find the fraction missed to be $4/13=0.31$.

Of course, the value 0.31 is a rather crude estimate since we are dealing with a small number of events. Including the standard statistical errors we find the fraction missed to be $0.31_{-0.20}^{+0.15}$, that is, it is between 0.11 and 0.46.

We also considered the possibility that the choice of 10 deg in step (1) was too small. Therefore we repeated the calculations using 15 deg and 20 deg. The results were essentially the same as for 10 deg, indicating that our choice was reasonable.

In addition, we point out that the missed two-body events will tend to have a higher momentum than those which were found, and this must be taken into account when calculating the lifetime. This effect will be discussed further in Sec. IV.

It turns out that despite the uncertainties in the biases for both rest and flight events, we can obtain useful information on the $_{\Lambda}H^3$ lifetime from the two-body decays.

Finally, for our rest events, having separated the ambiguous three-body events and having corrected for bias in the case of two-body events, we can obtain branching ratios for $_{\Lambda}H^3$ and $_{\Lambda}H^4$. We find for the ratio R_3, $({}_{\Lambda}H^3 \rightarrow \pi^- + He^3/{}_{\Lambda}H^3 \rightarrow \text{all } \pi^-)$, $R_3=0.34\pm0.06$. For the corresponding quantity for $_{\Lambda}H^4$ we find $R_4=0.63 \pm0.06$. These values are in good agreement with previous determinations. For example, for R_3, Ammar *et al.*,[8] Block *et al.*,[9] and Keyes *et al.*[2] have, respectively, found the values $0.39_{-0.07}^{+0.12}$, 0.39 ± 0.07, and 0.38 ± 0.09. For R_4 Block *et al.*[9] found 0.68 ± 0.04 and Ammar *et al.*[10] found $0.67_{-0.05}^{+0.06}$. The agreement of our values with these is a check on the over-all validity of our methods of treating the rest events.

IV. LIFETIMES

We determine lifetimes by means of the Bartlett maximum-likelihood method as discussed, for example, by Franzinetti and Morpurgo[11] (see the Appendix). There are two ways in which we could, in principle, analyze our data. The first would make use of all events, both in flight and at rest. The second would make use only of the flight events. An advantage of the second method would be that it could be done using only uniquely identified events. Unfortunately, however, it is not practical to use only flight events in a nuclear emulsion experiment. The reason for this is that the potential time for seeing a decay is about a factor of 10 times less than the lifetime. Under these conditions it is impossible to make a meaningful lifetime determination, and we are therefore constrained to use the first method. However, in this method we cannot make use of only those events which have a unique interpretation, because we cannot assume, for a given species, that the fraction of events which yield a unique interpretation is the same for both the rest and flight categories. Therefore we must use all events, making a statistical separation of the ambiguous ones. The way in which we statistically separated the rest events was described in Sec. III B.

TABLE VI. Summary of total moderation times of rest events for the hyperfragment decay modes used. The total includes the time for unique events plus the time for the fraction of ambiguous events assigned to the given mode.[a]

Decay mode	Total moderation time (10^{-2} sec)
$_{\Lambda}H^3 \rightarrow \pi^- He^3$	887
$_{\Lambda}H^3 \rightarrow \pi^- p H^2$	990
$_{\Lambda}H^4 \rightarrow \pi^- p H^3$	1247
$_{\Lambda}H^4 \rightarrow \pi^- H^2 H^2$	35
$_{\Lambda}He^4 \rightarrow \pi^- p He^3$	1335
$_{\Lambda}He^5 \rightarrow \pi^- p He^4$	2889

[a] Events reported in I not included.

In applying the maximum-likelihood method to a given hyperfragment species, the crucial data needed for the rest events turn out to be only the total moderation time of all the events. This is easily obtained by summing up the individual times for the unique events and by assigning an appropriate fraction of the ambiguous events to this species. A summary is shown in Table VI.

On the other hand, for the flight events each individual flight time and potential time enters separately into the calculation. Thus, even if we could make a statistical separation of the ambiguous flight events, we must consider how to include them in a maximum-likelihood calculation. That is, to each possible interpretation of an ambiguous event there corresponds a certain weight, and so basically the question is how to include a fraction of an event in the maximum-likelihood method, which in normal usage is set up to treat integer numbers of events. We show in the Appendix how we do this.

A. $_{\Lambda}H^3$ and $_{\Lambda}H^4$

We first calculate the lifetime of $_{\Lambda}H^3$ using only two-body decays. We include the three flight and four rest events of I as well as the six flight and 28 rest events reported here. Our procedure for doing this is as follows. We determine a lifetime directly from the 41 events and then apply two corrections. The first takes into account

[8] R. G. Ammar, W. Dunn, and M. Holland, Nuovo Cimento **26**, 840 (1963).

[9] M. M. Block, R. Gessaroli, J. Kopelman, S. Ratti, M. Schneeberger, L. Grimellini, T. Kikuchi, L. Lendinara, L. Monari, W. Becker, and E. Harth, in *Proceedings of the International Conference on Hyperfragments, St. Cergue, Switzerland, 1963* (CERN, Geneva, 1964), p. 147.

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

[11] C. Franzinetti and G. Morpurgo, Nuovo Cimento Suppl. **6**, 577 (1957).

the fact that the bias against rest events was found to be 26%, whereas that for flight events was 31%. This correction is a 3% reduction in the lifetime value. The second takes account of the fact, previously mentioned, that the bias against flight decays is not uniform, as is implicit in our lifetime calculation, but depends on the hyperfragment momentum. Knowing the momentum distribution of our hyperfragments at production, the bias as a function of momentum, and the type of sample we have (that is, what fraction of all events decay in flight and what fraction of the flight events would have left the pellicle of origin had they not decayed), we can calculate the size of this correction quite accurately. It turns out that it corresponds to a 10% increase in the lifetime value. The net result of the two corrections is a 6.5% increase in the lifetime value. Including these corrections, our result for the mean life τ is

$$\text{two-body: } \tau({}_\Lambda H^3) = (2.13_{-0.68}^{+1.17}) \times 10^{-10} \text{ sec.}$$

The error quoted is purely the statistical error as obtained from the maximum-likelihood calculation. To see what the effect of the biases against finding both rest and flight events are, we make use of the estimates of these biases obtained in Sec. III D. That is, the fraction of rest events missed is 0.26 ± 0.04 and the fraction of flight events missed is $0.31_{-0.20}^{+0.15}$. We then obtain the following limits:

two-body:

$$(1.58_{-0.40}^{+0.60}) < \tau({}_\Lambda H^3) < (2.52_{-0.81}^{+1.36}) \times 10^{-10} \text{ sec.}$$

We next calculate the ${}_\Lambda H^3$ and ${}_\Lambda H^4$ lifetimes using three-body events of the type ${}_\Lambda H^{3,4} \to \pi^- + p + H^{2,3}$ and ${}_\Lambda H^4 \to \pi^- + H^2 + H^2$. In addition to the events reported in this paper we include the two flight and 14 rest ${}_\Lambda H^3$ events and the one flight and six rest ${}_\Lambda H^4$ events reported in I.

The main problem here is including the ambiguous events. We showed how to separate the ambiguous rest events in Sec. III B. The results as shown in Table III were that 48 ± 18 of them were ${}_\Lambda H^3$ and 64 ± 18 were ${}_\Lambda H^4$. Adding these to the 13 unique ${}_\Lambda H^3$ and 18 unique ${}_\Lambda H^4$ events, and also adding in the rest events from I, we obtain finally 75 ± 18 ${}_\Lambda H^3$ and 85 ± 18 ${}_\Lambda H^4$ rest events.

To determine the average moderation time per rest event for the 48 ± 18 ${}_\Lambda H^3$, and also for the 64 ± 18 ${}_\Lambda H^4$, we did not directly use the range distribution of the ambiguous events, since it contains a mixture of ${}_\Lambda H^3$ and ${}_\Lambda H^4$ hyperfragments. Instead, we also made use of the range distributions of the two-body ${}_\Lambda H^3$ and ${}_\Lambda H^4$ events which contain no contamination.

TABLE VII. ${}_\Lambda H^3$ mean-life values (10^{-10} sec) for three-body events for various combinations of assumptions (i)–(vi), concerning the division of ambiguous events, given in the text.

Assumption	(i)	(ii)	(iii)
(iv)	$3.84_{-1.32}^{+2.40}$	$4.68_{-1.74}^{+3.36}$	$6.26_{-2.58}^{+3.60}$
(v)	$3.16_{-1.08}^{+1.98}$	$3.84_{-1.42}^{+2.76}$	$5.12_{-2.20}^{+4.58}$
(vi)	$2.48_{-0.86}^{+1.54}$	$3.00_{-1.12}^{+2.16}$	$3.99_{-1.64}^{+3.56}$

TABLE VIII. ${}_\Lambda H^4$ mean-life values (10^{-10} sec) for three-body events for various combinations of assumptions (i)–(vi) concerning the division of ambiguous events, given in the text.

Assumption	(i)	(ii)	(iii)
(iv)	$2.52_{-0.86}^{+1.58}$	$2.16_{-0.70}^{+1.20}$	$1.87_{-0.58}^{+0.94}$
(v)	$3.15_{-1.08}^{+1.96}$	$2.68_{-0.86}^{+1.50}$	$2.31_{-0.70}^{+1.16}$
(vi)	$3.77_{-1.30}^{+2.34}$	$3.20_{-1.02}^{+1.78}$	$2.75_{-0.82}^{+1.38}$

Including the events from I we have 10 unique ${}_\Lambda H^3$ flight events, 10 unique ${}_\Lambda H^4$ flight events, and five flight events ambiguous between ${}_\Lambda H^3$ and ${}_\Lambda H^4$. With so few events it is pointless to attempt a statistical separation. The best assumption that can be made is that the ambiguous events divide in the same way as the unique events of the same type. Thus, each ambiguous flight event is weighted 10/19 ${}_\Lambda H^3$ and 9/19 ${}_\Lambda H^4$.

Using the separations of ambiguous events indicated, we find the following:

three-body:

$$\tau({}_\Lambda H^3) = (3.84_{-1.42}^{+2.76}) \times 10^{-10} \text{ sec},$$

three-body:

$$\tau({}_\Lambda H^4) = (2.68_{-0.86}^{+1.50}) \times 10^{-10} \text{ sec}.$$

Again, the errors shown are only statistical errors. To illustrate the effects of the uncertainties in dividing the ambiguous events, we calculate various extreme values based on combinations of the following set of hypotheses:

(i) All of the ambiguous flight events are ${}_\Lambda H^3$.

(ii) The ambiguous flight events divide in the same way as the unique ones.

(iii) All of the ambiguous flight events are ${}_\Lambda H^4$.

(iv) The number of ambiguous rest events which are ${}_\Lambda H^3$ (${}_\Lambda H^4$) is one standard deviation greater (less) than the determined value.

(v) The number of ambiguous rest events which are ${}_\Lambda H^3$ (${}_\Lambda H^4$) is equal to the determined value.

(vi) The number of ambiguous rest events which are ${}_\Lambda H^3$ (${}_\Lambda H^4$) is one standard deviation less (greater) than the determined value.

The results are shown in Tables VII and VIII.

Finally, to make the most use of our data we combine the two-body and three-body ${}_\Lambda H^3$ events, including the corrections for two-body bias mentioned before. We then obtain for the lifetime:

two-body and three-body:

$$\tau({}_\Lambda H^3) = (2.85_{-0.75}^{+1.14}) \times 10^{-10} \text{ sec.}$$

The uncertainty in this result due to biases in the two-body case is expressed by the following limits:

two-body and three-body:

$$(2.24_{-0.54}^{+0.83}) < \tau({}_{\Lambda}H^3) < (3.12_{-0.81}^{+1.18}) \times 10^{-10}\ \text{sec}.$$

The effect of the uncertainty in the division of ambiguous three-body events is illustrated in Table IX.

The methods we have used to illustrate the effects of the different types of uncertainties on the lifetimes are somewhat cumbersome. To obtain an over-all picture of the effects of the errors we calculate a single combined error on τ in the following manner. We define four types of error: $\Delta\tau_s$, the statistical error; $\Delta\tau_b$, the error due to the biases in the two-body case; $\Delta\tau_r$, the error due to uncertainty in the separation of ambiguous rest events; and $\Delta\tau_f$, the error due to uncertainty in the separation of ambiguous flight events. We then define the combined error $\Delta\tau$ as

$$\Delta\tau = [(\Delta\tau_s)^2 + (\Delta\tau_b)^2 + (\Delta\tau_r)^2 + (\Delta\tau_f)^2]^{1/2}.$$

We can then express our results as follows, where the error indicates the combined error:

two-body:

$$\tau({}_{\Lambda}H^3) = (2.13_{-0.87}^{+1.24}) \times 10^{-10}\ \text{sec};$$

three-body:

$$\tau({}_{\Lambda}H^3) = (3.84_{-1.78}^{+3.16}) \times 10^{-10}\ \text{sec};$$

two-body and three-body:

$$\tau({}_{\Lambda}H^3) = (2.85_{-1.05}^{+1.27}) \times 10^{-10}\ \text{sec};$$

three-body:

$$\tau({}_{\Lambda}H^4) = (2.68_{-1.07}^{+1.66}) \times 10^{-10}\ \text{sec}.$$

The significance of the combined error is probably not too different from that of a standard deviation. In our judgment we have somewhat overestimated the size of the errors, particularly in the separation of ambiguous events.

B. ${}_{\Lambda}$He^4 and ${}_{\Lambda}$He^5

In the case of ${}_{\Lambda}He^4$ and ${}_{\Lambda}He^5$, we use only the three-body decays of the type ${}_{\Lambda}He^{4,5} \to \pi^- + p + He^{3,4}$. Including the data from I, we have a total of 5 ${}_{\Lambda}He^4$ flight events, 9 ${}_{\Lambda}He^5$ flight events, and 11 ${}_{\Lambda}He^{4,5}$ ambiguous flight events. Using the separation of ambiguous rest events as given in Table III, and including the events from I, we have a total of 206 ± 44 ${}_{\Lambda}He^4$ rest events and 452 ± 44 ${}_{\Lambda}He^5$ rest events. We determine the ${}_{\Lambda}He^4$ and ${}_{\Lambda}He^5$ lifetimes in exactly the same way as we determine the ${}_{\Lambda}H^3$ and ${}_{\Lambda}H^4$ three-body lifetimes. The results are

$$\tau({}_{\Lambda}He^4) = (2.28_{-0.67}^{+1.13}) \times 10^{-10}\ \text{sec},$$
$$\tau({}_{\Lambda}He^5) = (2.51_{-0.51}^{+0.74}) \times 10^{-10}\ \text{sec}.$$

The errors shown are only the statistical errors and, as we did before, to show the effects of the uncertainty in separating ambiguous events we calculate a variety of extreme values. These are shown in Table X for ${}_{\Lambda}He^4$ and Table XI for ${}_{\Lambda}He^5$.

Again, in the same way as we did for the hydrogen hyperfragments, we obtain a combined error on the lifetime for the two cases: The results are then

$$\tau({}_{\Lambda}He^4) = (2.28_{-1.29}^{+2.33}) \times 10^{-10}\ \text{sec},$$
$$\tau({}_{\Lambda}He^5) = (2.51_{-0.73}^{+1.90}) \times 10^{-10}\ \text{sec}.$$

We note that the combined error is considerably larger than the statistical error in both cases. The main reason for this is the large number of ambiguous flight decays. Thus the attempt to obtain separate ${}_{\Lambda}He^4$ and ${}_{\Lambda}He^5$ lifetimes is not very successful, in that the errors due to uncertainties in the methods used are considerably greater than the difference in the two lifetimes. Because of this, and also because the predicted lifetimes for ${}_{\Lambda}He^4$ and ${}_{\Lambda}He^5$ are quite similar, we thought it useful to calculate a combined ${}_{\Lambda}He^{4,5}$ lifetime, using all the events. This result, in which only a statistical error occurs, is

$$\tau({}_{\Lambda}He^{4,5}) = (2.43_{-0.43}^{+0.60}) \times 10^{-10}\ \text{sec}.$$

C. Heavier Hyperfragments

We found only one mesonic decay in flight of a heavy hyperfragment. This was a decay of the type ${}_{\Lambda}Li^8$ hyperfragment. This was a decay of the type ${}_{\Lambda}Li^8 \to \pi^- + He^4 + He^4$. Combining it with 28 ${}_{\Lambda}Li^8$ rest events of

TABLE IX. ${}_{\Lambda}H^3$ mean-life values (10^{-10} sec) for combined two-body and three-body events for various combinations of assumptions (i)–(vi), concerning the division of ambiguous events, given in the text.

Assumption	(i)	(ii)	(iii)
(iv)	$2.95_{-0.75}^{+1.10}$	$3.20_{-0.82}^{+1.27}$	$3.56_{-0.98}^{+1.52}$
(v)	$2.63_{-0.67}^{+1.00}$	$2.85_{-0.75}^{+1.14}$	$3.16_{-0.87}^{+1.36}$
(vi)	$2.31_{-0.58}^{+0.87}$	$2.49_{-0.64}^{+1.00}$	$2.76_{-0.75}^{+1.18}$

TABLE X. ${}_{\Lambda}He^4$ mean-life values (10^{-10} sec) for various combinations of assumptions (i)–(vi) concerning the division of ambiguous events, given in the text.

Assumption	(i)	(ii)	(iii)
(iv)	$1.50_{-0.36}^{+0.45}$	$2.70_{-0.75}^{+1.30}$	$5.05_{-2.75}^{+4.20}$
(v)	$1.26_{-0.25}^{+0.44}$	$2.28_{-0.67}^{+1.13}$	$4.27_{-1.62}^{+2.23}$
(vi)	$1.04_{-0.29}^{+0.37}$	$1.86_{-0.48}^{+0.89}$	$3.48_{-1.38}^{+2.57}$

TABLE XI. ${}_{\Lambda}He^5$ mean-life values (10^{-10} sec) for various combinations of assumptions (i)–(vi) concerning the division of ambiguous events, given in the text.

Assumption	(i)	(ii)	(iii)
(iv)	$3.86_{-0.98}^{+1.56}$	$2.28_{-0.48}^{+0.72}$	$1.86_{-0.36}^{+0.59}$
(v)	$4.24_{-1.14}^{+1.84}$	$2.51_{-0.51}^{+0.74}$	$2.04_{-0.42}^{+0.56}$
(vi)	$4.26_{-1.25}^{+1.98}$	$2.73_{-0.57}^{+0.84}$	$2.23_{-0.43}^{+0.60}$

TABLE XII. Summary of data on hyperfragment lifetimes.

Hyperfragment	Predicted[a,b] mean life τ (10^{-10} sec)	Reported measurements τ (10^{-10} sec)	Reference	No. of events[c]
${}_\Lambda H^3$	2.25 ± 0.07 to 2.38 ± 0.04	$1.05_{-0.18}^{+0.20}$	9	$29F$, $7R$
		$0.9_{-0.4}^{+2.2}$	17	$3F$, $1R$
		$2.32_{-0.34}^{+0.45}$	2	$35F$, $17R$
		$2.85_{-1.05}^{+1.27}$	this work[d]	$21.5F$, $107R$[e]
${}_\Lambda H^4$	1.72 ± 0.35	$1.2_{-0.3}^{+0.6}$	15	$9F$, $43R$
		$1.8_{-0.7}^{+2.5}$	17	$3F$, $4R$
		$2.68_{-1.07}^{+1.66}$	this work[d]	$11.5F$, $85R$[e]
${}_\Lambda He^4$	2.62 ± 0.39	$2.28_{-1.29}^{+2.33}$	this work[d]	$8.9F$, $206R$[e]
${}_\Lambda He^5$	2.96 ± 0.38	$1.4_{-0.5}^{+1.9}$	17	$3F$, $25R$
		$2.51_{-0.73}^{+1.90}$	this work[d]	$16.1F$, $452R$[e]
${}_\Lambda He^{4,5}$	2.86 ± 0.38[f]	$1.2_{-0.4}^{+1.0}$	16	$5F$, $99R$
		$2.43_{-0.43}^{+0.60}$	this work[d]	$25F$, $611R$

[a] See Refs. 12–14.
[b] Using $\tau_\Lambda=(2.52\pm0.04)\times10^{-10}$ sec (see Ref. 18).
[c] F = in flight, R = at rest.
[d] Includes data reported in Refs. 1 and 3.
[e] Fractional number comes from dividing ambiguous events.
[f] This value is based on a mixture 70% ${}_\Lambda He^5$, 30% ${}_\Lambda He^4$.

this type, we obtain the estimate

$$\tau({}_\Lambda Li^8)\gtrsim 0.4\times10^{-10}\ \text{sec},$$

with a confidence limit of 95%.

V. DISCUSSION

We have attempted in the preceding to stress the difficulties involved in measuring hypernuclear lifetimes in emulsion, and have estimated as carefully as we could the effects of uncertainties in our knowledge of the biases against finding two-body decays and of the separation of ambiguous events into their various interpretations. As noted before, we have in fact probably tended to overestimate our errors.

We can now make some comparisons of our results with theoretical calculations[12–14] and other experimental results[2,9,15–17]. All of these are summarized in Table XII.[18]

As we indicated in our previous paper,[3] our value for the lifetime of ${}_\Lambda H^3$ is in good agreement with the theoretical calculations, and not in good agreement with the widely-quoted value previously obtained by Block *et al.*[9] in a helium bubble-chamber experiment. We note further that the recent value obtained by Keyes *et al.*,[2] also in a helium bubble-chamber experiment, is in agreement with our result but not with that of Block *et al.* It would appear then that the discrepancy between the theoretical calculations and the measurement of Block *et al.*, which provoked wide discussion in that there seemed to be no plausible explanation for it (see Rayet and Dalitz[14]), is turning out not to be real.

Our value for the ${}_\Lambda H^4$ lifetime is about one standard deviation greater than the predicted theoretical value. We can only point out that this is not a significant difference.

If we consider that our mixture of all ${}_\Lambda He$ events consisted of 70% ${}_\Lambda He^5$ and 30% ${}_\Lambda He^4$, then the theoretical prediction for $\tau({}_\Lambda He^{4,5})$ would be $(2.86\pm.38)\times10^{-10}$ sec. This compares very well with our experimental value $(2.43_{-0.43}^{+0.60})\times10^{-10}$ sec. With regard to our separate lifetimes values for ${}_\Lambda He^4$ and ${}_\Lambda He^5$, we can only point out that our ${}_\Lambda He^5$ value is slightly larger, which is also the case for the theoretical calculations.

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APPENDIX

The maximum-likelihood function usually used to determine the lifetimes of hyperfragments is the following:

$$\mathfrak{L}(\tau)=\prod_{i=1}^{n_a}(e^{-t_i/\tau})\prod_{j=1}^{n_b}\left(\frac{1}{\tau}e^{-t_i/\tau}\right)\prod_{k=1}^{n_c}\left[\frac{e^{-t_k/\tau}}{\tau(1-e^{-T_k/\tau})}\right].$$

The products are over events of types a, b, and c which are defined as follows:

type a—Events which came to rest, t_i is the moderation time for such an event.

type b—Events which decayed in flight but would have come to rest in the pellicle had they not decayed. t_j is the time of flight for such an event.

type c—Events which decayed in flight but would have left the pellicle had they not decayed. t_k is the time of flight of such an event and T_k is its potential time.

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τ represents the lifetime of the hyperfragment in question.

In using this formula it is implicit that every event be uniquely identified. However, we have seen that in our experiment some events have more than one interpretation. We must consider how to include such events in the likelihood function.

The information we might have for any given ambiguous event is a set of weights corresponding to each of its possible interpretations. Effectively, we wish to assign fractions of it to different hyperfragment species.

In principle we could write down an exact many-parameter likelihood function $\mathcal{L}(\tau_1,\tau_2,\tau_3,\cdots)$, where τ_1, τ_2, τ_3, $\cdots$ are the lifetimes corresponding to all the possible interpretations of events. Because we are dealing with rather low statistics and because, for the flight events, we do not have individual weights for each event but instead used an over-all separation, we found it simpler to use an approximate one-parameter likelihood function for each hyperfragment species. The error of approximation involved in doing this is about an order of magnitude smaller than the experimental error.

To see how we do this, suppose we are calculating a likelihood function for some hyperfragment and we have n events of, let us say, type b, all of which have the same flight time t_j. We would then have a term in $\mathcal{L}(\tau)$ of the form $(\tau^{-1}e^{-t_j/\tau})^n$. It is rather obvious from this that for a fraction of an event, where w is the fraction (or weight), the appropriate term is $(\tau^{-1}e^{-t_j/\tau})^w$. Generalizing, we see the appropriate form for $\mathcal{L}(\tau)$ is

$$\mathcal{L}(\tau)=\prod_{i=1}^{n_a}(e^{-t_i/\tau})^{w_i}\prod_{j=1}^{n_b}\left(\frac{1}{\tau}e^{-t_j/\tau}\right)^{w_j}\times\prod_{k=1}^{n_c}\left[\frac{e^{-t_k/\tau}}{\tau(1-e^{-T_k/\tau})}\right]^{w_k}.$$

One has to be somewhat cautious in using this since it is an approximation. Consider, for example, that we are dealing with two hyperfragments X and Y, and let us assume $\tau_Y>\tau_X$. We will have some unique events of type X, some unique events Y and some ambiguous events XY. It is clear that if all the events were ambiguous we would find τ_X and τ_Y to be equal. The effect of ambiguous events is to reduce τ_Y and increase τ_X. The size of the effect depends on the number of ambiguous events relative to unique ones and on the difference between τ_X and τ_Y. Thus the approximation is good provided the number of ambiguous events is sufficiently small.

We estimated that for our $_\Lambda H^3$, $_\Lambda H^4$ case, where we had five ambiguous flight events, the approximation error on the lifetime was less than 0.1×10^{-10} sec, and therefore, we did not consider it since it was far smaller than our experimental errors. In the $_\Lambda He^4$, $_\Lambda He^5$ case the approximation error was of similar magnitude and was not considered, especially since for other reasons the separate lifetimes were not found to be of great significance.