LIFETIME OF $_\Lambda H^3$†

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In a nuclear-emulsion experiment to determine the lifetime of $_\Lambda H^3$ we find a value consistent with that of the free Λ hyperon as predicted by theory, and not in good agreement with a previous measurement.

In a recent Letter Rayer and Dalitz[1] have discussed the lifetime of $_\Lambda H^3$ in view of the fact that the only previous accurate experimental determination was much shorter than the lifetime for free Λ decay. The experimental value they referred to was that obtained by Block et al.,[2] in a helium bubble chamber, $\tau(_\Lambda H^3) = (0.95_{-0.15}^{+0.19})\times 10^{-10}$ sec. This they compared with the free-Λ lifetime measured in the same bubble chamber,[3] $\tau_\Lambda = (2.36 \pm 0.06)\times 10^{-10}$ sec.

Since the Λ particle is very lightly bound in $_\Lambda H^3$ it is not expected that the $_\Lambda H^3$ decay rate should be very much different from that of the free Λ. In their Letter Rayet and Dalitz discussed various mechanisms which might conceivably contribute to a large $_\Lambda H^3$ decay rate. However, these contributions all turned out to be small and they gave their best estimate that $\Gamma(_\Lambda H^3)$ ranged between $1.03\Gamma_\Lambda$ and $1.10\Gamma_\Lambda$ where Γ_Λ is the free-Λ decay rate. We quote the last paragraph of their Letter:

"We conclude that no plausible explanation is yet available for the rapid decay rate observed by Block et al. for $_\Lambda H^3$, and that further $_\Lambda H^3$ lifetime measurements are now very desirable to confirm this discrepancy. Until this discrepancy is resolved, or understood, there will remain a lingering doubt concerning the ultimate validity of all the calculations (otherwise internally consistent) which have been made on the properties of the light Λ hypernuclei."

We have now obtained results for the $_\Lambda H^3$ lifetime in a nuclear-emulsion experiment by studying both three- and two-body decays. From the three-body decays we find the best value to be $\tau(_\Lambda H^3) = (3.84_{-1.32}^{+2.40})\times 10^{-10}$ sec. From the two-body decays we find the value to be $\tau(_\Lambda H^3) = (2.00_{-0.64}^{+1.10})\times 10^{-10}$ sec. Combining these two results yields $\tau(_\Lambda H^3) = (2.74_{-0.72}^{+1.10})\times 10^{-10}$ sec. The errors shown on these numbers are only the statistical errors. There is also error due to uncertainty in our knowledge of the biases against finding two-body decays, and due to the error in statistically separating the number of $_\Lambda H^3$ rest events from $_\Lambda H^{3,4}$ ambiguous events. These points will be discussed further on.

The hyperfragments used in this study were mainly produced by 1.1-GeV/c K^- mesons from the Bevatron. In addition we have used some events reported in a previous paper by our group.[4] In that paper we also described our method of scanning, which consisted in area scanning for double stars under low power, and in addition examining all apparent scatterings under high power in order to find any light π-meson tracks which might have been missed under low power. The decay modes used in this study were the following:

$$_\Lambda H^3 \to \pi^- + p + H^2, \tag{1}$$

$$_\Lambda H^3 \to \pi^- + He^3. \tag{2}$$

There are two main problems to be faced in determining hypernuclear lifetimes in emulsion: (1) We must consider whether there is a bias against finding decays in flight as compared with decays at rest. (2) In cases where events have more than one interpretation we must be able to make a meaningful statistical separation.

Let us first consider the decay mode $_\Lambda H^3 \to \pi^- + p + H^2$. In this case we are dealing with a three-body decay which is quite easy for our scanners to find. We expect no bias against detecting decays in flight. In fact, in portions of our stack which were double scanned no difference was found in the efficiency of our scanners with regard to finding in-flight or at-rest decays.

On the other hand, we do have to deal with the second type of problem mentioned above. Not only do we find events which can be uniquely identified as $_\Lambda H^3 \to \pi^- + p + H^2$, but we also find an appreciable number which are ambiguous between $_\Lambda H^3$ and $_\Lambda H^4$, as well as those which can be uniquely classified $_\Lambda H^4 \to \pi^- + p + H^3$. This situation occurs for both the at-rest and in-flight events. In addition, for the rest events we have some which are ambiguous between $_\Lambda H$ and $_\Lambda He$.

We deal with the at-rest events in the following way. Following Mayeur et al.,[5] we first determine which are the unique events by applying stringent momentum-balance and recoil-range conditions. That is, we do not use the observed binding energy to identify these events. As Mayeur et al. point out it is then reasonable to assume that the ambiguous events have the same binding-energy distributions as the unique events. We use the unique events to determine the mean binding energies of ${}_\Lambda H^3$ and ${}_\Lambda H^4$ in our stack. We then determine the mean value of the binding energy of all the ambiguous ${}_\Lambda H^{3,4}$ events. This value depends directly on how these events divide up between ${}_\Lambda H^3$ and ${}_\Lambda H^4$. Of course, when we determine the mean value we must calculate the ambiguous events as if they were all ${}_\Lambda H^3$ or all ${}_\Lambda H^4$. This means that sometimes we are calculating a real ${}_\Lambda H^4$ as if it were ${}_\Lambda H^3$ and vice versa. The correction for this is not large and not difficult to make.

We found in our new three-body data five unique ${}_\Lambda H^3$ events, seven unique ${}_\Lambda H^4$ events, and 81 ambiguous ${}_\Lambda H^{3,4}$ events. The relatively large number of ambiguous events is due to the stringent conditions we used in choosing unique events. Following the procedure outlined above we determined that $(53 \pm 22)\%$, or 43 ± 18, of these were ${}_\Lambda H^3$, and the rest ${}_\Lambda H^4$. In addition we had 45 ambiguous events of the type $({}_\Lambda H, {}_\Lambda He) \rightarrow \pi^- + p + (H, He)$. We determined the fraction of these which were ${}_\Lambda H$ by comparing the range distribution of these events with those of ${}_\Lambda H$ and ${}_\Lambda He$. We then were able to determine that 14 of these were ${}_\Lambda H^4$ and five were ${}_\Lambda H^3$. The net result was that 53 ± 18 events were found to be ${}_\Lambda H^3$. Adding to this the 14 events from our previous work,[4] we obtain a total of 67 ± 18 ${}_\Lambda H^3$ at rest.

We have checked this value for consistency in two ways. First we use the branching ratio determined from Block et al.[2]: ${}_\Lambda He^3$(two body)/${}_\Lambda H^3$(all π^-) $= 0.39 \pm 0.07$. We combine this with our estimated number of two-body decays, 43, to obtain an estimate of other than two-body decays, which is then 71 ± 13. About 10% of these are expected to be ${}_\Lambda H^3 \rightarrow \pi^- + p + p + n$ thus leaving about 64 ± 13 as ${}_\Lambda H^3 \rightarrow \pi^- + p + d$, in good agreement with the number found above. Secondly, we compared the range distribution of our ${}_\Lambda H^{3,4}$ ambiguous events with those of our unique ${}_\Lambda H^3$ and ${}_\Lambda H^4$ events. Form this we obtained an estimate of 56 ± 19 ${}_\Lambda H^3$ three-body events, also in good agreement with our original estimate.

We did not apply the same method to the three-body decays in flight because, first, there were only 21 events to deal with, not a large statistical sample; second, the binding energies for decays in flight are not as well determined as for rest events; and third, we wanted to identify each flight event in the best possible way since these events contain the most lifetime information. Therefore, we used every possible method to extract information about these events, including the use of the measured binding energy and measurements on individual tracks. In this way we obtained from our new data eight ${}_\Lambda H^3$ events, eight ${}_\Lambda H^4$ events, and five ambiguous ${}_\Lambda H^{3,4}$ events. Adding two ${}_\Lambda H^3$ and one ${}_\Lambda H^4$ events from our previous work yields a total of ten ${}_\Lambda H^3$, nine ${}_\Lambda H^4$, and five ambiguous events.

To obtain what we consider the best ${}_\Lambda H^3$ lifetime we assume that the ambiguous flight decays divide in the same ratio as the unique ones, that is, each ambiguous event is weighted 10/19 ${}_\Lambda H^3$ and 9/19 ${}_\Lambda H^4$. However, we also calculate some extreme values of the lifetime based on various combinations of the following assumptions:

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

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

(C) None of the ambiguous flight events is ${}_\Lambda H^3$.

(D) The number of rest ${}_\Lambda H^3$ events is one standard deviation more than the determined number.

(E) The number of rest events is the determined number.

(F) The number of rest events is one standard deviation less than the determined number.

All the lifetimes were calculated by the Bartlett maximum-likelihood method as discussed by Franzinetti and Morpurgo.[6] The values obtained are shown in Table I. The central value, $\tau({}_\Lambda H^3) = (3.84^{+2.40}_{-1.32}) \times 10^{-10}$ sec, corresponds to our best value.

The two-body ${}_\Lambda H^3$ events have no problem of ambiguous interpretations. However, there is the question of whether there is bias against finding these decays. In the case of the rest decays we have been able to determine the bias by studying the angular distribution of the recoil in our

Table I. Lifetime values (in units of 10^{-10} sec) for three-body events for various combinations of assumptions *A* through *F* given in the text.

Assumption	*A*	*B*	*C*
D	$3.84^{+2.40}_{-1.32}$	$4.68^{+3.36}_{-1.74}$	$6.26^{+5.60}_{-2.58}$
E	$3.16^{+1.98}_{-1.08}$	$3.84^{+2.76}_{-1.42}$	$5.12^{+4.58}_{-2.10}$
F	$2.48^{+1.54}_{-0.86}$	$3.00^{+2.16}_{-1.12}$	$3.99^{+3.56}_{-1.64}$

32 ${}_{\Lambda}H^3$ events and also in 103 ${}_{\Lambda}H^4 \to \pi^- + He^4$ events. We find that some $(26 \pm 4)\%$ of these events are missed. These correspond mainly to steep recoils where the projected range of the recoil is very short (0-3 μ) and also to very flat recoils. The missing of events with flat recoils can be attributed to the fact that a very flat π is usually more difficult to see in emulsion than one which is dipping. We observed 32 ${}_{\Lambda}H^3$ rest events and, taking into account the bias, estimate that there were a total of 43, a number we have used before.

We found nine two-body decays in flight. The determination of the bias against finding such decays is more difficult because of the small number of events. However, we can make an estimate on the following basis. The two-body decays in flight were mainly picked up by observing a scattering under low power, and then carefully examining the scattering to see if a π meson was also emitted. This examination was carried out twice for each scattering, by a different person each time. In a few cases the π was found under low power. We find that our scanners have a high efficiency for observation of scatterings greater than about 10 deg. We calculated, for our momentum distribution of ${}_{\Lambda}H^3$, the fraction of events which would have a recoil making a projected angle of less than 10 deg with the hyperfragment, assuming an isotropic distribution in the center of mass. This fraction turned out to be 0.34. Of our nine events eight had projected angles greater than 10 deg. Thus we would have expected four events under this angle. We observed one, suggesting that three were missed. Therefore, the fraction of all events missed would be $3/(9+3) = 0.25$. We note that this is about the same as the bias against finding rest decays. Using this estimate of the bias and that previously found for rest decays we obtain for the two-body decays $\tau({}_{\Lambda}H^3) = (2.00_{-0.64}^{+1.10}) \times 10^{-10}$ sec. If we combine our two- and three-body data and calculate extreme values as we did for the three-body decays alone we obtain the results shown in Table II, the central value being $\tau({}_{\Lambda}H^3) = (2.74_{-0.72}^{+1.10}) \times 10^{-10}$ sec.

Clearly the value 0.25 for the bias against finding two-body in-flight decays is only a rough value. We estimate that the true value lies between 0.10 and 0.40. To see the effect of this we calculate some extreme limits on the two-body lifetime and on the central value of the combined lifetime (Table II). We also use the limits on the bias against two-body rest events, 0.22 to 0.30.

Table II. Lifetime values (in units of 10^{-10} sec) for two- and three-body events for various combinations of assumptions *A* through *F* given in the text.

Assumption	*A*	*B*	*C*
D	$2.84_{-0.72}^{+1.06}$	$3.08_{-0.80}^{+1.22}$	$3.42_{-0.94}^{+1.46}$
E	$2.53_{-0.64}^{+0.96}$	$2.74_{-0.72}^{+1.10}$	$3.04_{-0.84}^{+1.30}$
F	$2.22_{-0.56}^{+0.84}$	$2.40_{-0.62}^{+0.96}$	$2.66_{-0.72}^{+1.14}$

This yields, in units of 10^{-10} sec,

$$\text{two body,} \quad 1.61_{-0.44}^{+0.64} < \tau({}_{\Lambda}H^3) < 2.46_{-0.76}^{+1.28};$$

$$\text{combined,} \quad 2.25_{-0.52}^{+0.74} < \tau({}_{\Lambda}H^3) < 3.00_{-0.78}^{+1.14}.$$

Our conclusions may be stated as follows: From our data the ${}_{\Lambda}H^3$ lifetime turns out to have a value comparable with that of the free Λ, $\tau_{\Lambda} = (2.54 \pm 0.03) \times 10^{-10}$ sec.,[7] and in agreement with theoretical estimates.[1,8,9] Even by stretching all our uncertainties in the same direction it would be difficult for us to achieve a value as low as that obtained by Block et al.[2]

We not that in a recent experiment Keyes et al.[10] have also found a value for the ${}_{\Lambda}H^3$ lifetime which is consistent with that of the free Λ particle.

The details of the events used in this work will appear in a future paper concerning the lifetime of light hyperfragments.

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[1]M. Rayet and R. H. Dalitz, Nuovo Cimento 46A, 786 (1966).

[2]M. M. Block, R. Gessaroli, S. Ratti, M. Schneeberger, L. Grimellini, T. Kikuchi, L. Lendimara, L. Monari, W. Becker, and E. Harth, in Proceedings of the Sienna International Conference on Elementary Particles, edited by G. Bernardini and G. P. Puppi (Societã Italiana di Fisica, Bologna, Italy, 1963), Vol. I, p. 62.

[3]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).

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

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

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

[7]A. H. Rosenfeld, N. Barash-Schmidt, A. Barbaro-Galtieri, W. J. Podolsky, L. R. Price, P. Söding, C. G. Wohl, M. Roos, and W. J. Willis, University of California Radiation Laboratory Report No. UCRL-8030 (revised), 1967 (unpublished).

[8]R. H. Dalitz and L. Liu, Phys. Rev. 116, 1312 (1959).

[9]R. H. Dalitz and G. Rajasekharan, Phys. Letters 1, 58 (1962).

[10]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).

LEVEL STRUCTURE OF H^4

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A particle-unstable hydrogen isotope of mass 4 is formed in the reaction $\pi^- + Li^7 \rightarrow H^3 + H^4$. Two discrete levels of H^4 have been found and their binding energies and widths have been determined. Some evidence for the existence of a third level is presented.

The question of the existence of a hydrogen isotope of mass 4 has stimulated a number of theoretical and experimental investigations. The literature on the subject has been comprehensively reviewed by Meyerhof and Tombrello[1] and we refer to their compilation for general information on the four-nucleon system and especially H^4.

A number of experimental searches for particle-stable H^4 have been either negative or inconclusive. Included in this category are efforts to observe the reactions[1] $H^3(d,p)H^4$, $Li^6(\gamma, 2p)H^4$, $He^4(\gamma,\pi^+)H^4$, and $H^3(n,\gamma)H^4$. Positive indications for the existence of particle-unstable H^4 have so far been presented only by Tombrello[2] and by Cohen et al.[3] Tombrello carried out a phase-shift analysis of $H^3(n,n)H^3$ angular distributions, measured by Seagrave, Cranberg, and Simmons,[4] and concluded the existence of particle-unstable 1^- and 2^- levels of H^4. In a more direct way Cohen et al.,[3] have searched in Li for the following pion-capture reactions:

$$\pi^- + Li^6 \rightarrow 2H^3, \tag{1}$$

$$\pi^- + Li^6 \rightarrow H^2 + H^4, \tag{2}$$

$$\pi^- + Li^7 \rightarrow H^3 + H^4. \tag{3}$$

Their results indicate that particle-unstable H^4 is formed in Reaction (2) (55% confidence level) and Reaction (3) (90% confidence level).

We have investigated Reaction (3) and have found unambiguous evidence that H^4 exists and that it is formed in at least two different states.

The experiment. – The experimental arrangement is shown in Fig. 1. A low-energy (100-MeV) π^- beam from the 600-MeV synchrocyclotron at the National Aeronautics and Space Administration Space Radiation Effects Laboratory in Newport News, Virginia, was stopped in a lithium target. The stopping rate was approximately 60 pions/g sec. The target area was 100 cm^2. Scintillation counters were used to select events consisting of a pion stopping in the target followed by the emission of two charged parti-

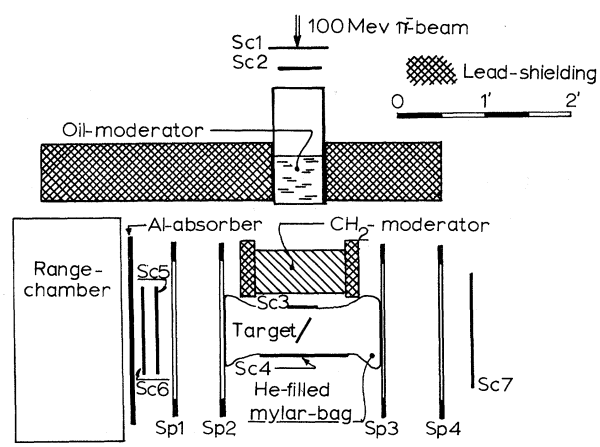

FIG. 1. Schematic view of the apparatus.