PART III.1

HYPERFRAGMENT STUDIES IN THE HELIUM BUBBLE CHAMBER*)

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I. INTRODUCTION

The $K^- + He^4$ reactions which are capable of producing hyperfragments are

$$
\begin{aligned}
K^- + He^4 &\rightarrow {}_{\Lambda}He^4 + \pi^- && (a)\\
&\rightarrow {}_{\Lambda}H^4 + \pi^0 && (b)\\
&\rightarrow {}_{\Lambda}H^3 + \pi^- + p && (c)\\
&\rightarrow {}_{\Lambda}H^3 + \pi^0 + n && (d)\\
&\rightarrow {}_{\Lambda}H^3 + n && (e)\ .
\end{aligned}
$$

We have not observed any cases of (e). For experimental reasons, we have confined our attention exclusively to reactions (a) - (c). Our studies were performed using the helium bubble chamber, $20 \times 10 \times 12.5$ cm^3, operated in a magnetic field of 14 kgauss. The spatial resolution is such that tracks of 0.5 mm range can be measured to an accuracy of ~ 0.1 mm.

Figure 1 shows the signature for the reactions $K^- + He^4 \rightarrow \pi^- + {}_{\Lambda}He^4$, ${}_{\Lambda}He^4 \rightarrow \pi^0 + He^4$. The hyperfragment range is 0.53 mm, the production pion momentum is 256 MeV/c and, of course, the two tracks are co-linear. The decay recoil has too low an energy to produce a visible bubble, so that we

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see "nothing" at the decay. This is by far the most typical type of $_{\Lambda}He^4$ event. Figure 2 shows the signature for the reaction $K^- + He^4 \rightarrow \pi^0 + {}_{\Lambda}H^4$, ${}_{\Lambda}H^4 \rightarrow \pi^- + He^4$. The ${}_{\Lambda}H^4$ range is 2.2 mm, and the decay pion momentum is 137 MeV/c. The recoil α particle has too low an energy to be visible. We have limited our acceptance to <u>only</u> those ${}_{\Lambda}H^4$ that undergo π^- decay (either two-body or multi-body decays). This allows us to have a sample of ${}_{\Lambda}H^4$ in which background corrections are minor. We have accepted ${}_{\Lambda}H^3$ events only in the case where the ${}_{\Lambda}H^3$ undergoes π^- decay. The signature for (c) is shown in Fig. 3.

The distinct advantages of the helium bubble chamber for studying light hyperfragments are the following:

i) All hyperfragments are completely identified by <u>production</u> kinematics. The magnetic field allows us to make momentum and charge measurements. Conservation laws of charge, baryons, etc., allow complete and certain identification.

ii) Hyperfragments are produced copiously in an exposure to stopping K^- mesons. Approximately 3% of all K^- stars produce hypernuclei.

iii) The hypernuclei are produced in a very symmetric nucleus, i.e. He^4 has spin zero and isotopic spin zero. This allows us to employ general symmetry arguments, such as conservation of angular momentum, parity, and isospin, for the analysis of the production reactions. In particular, isospin conservation leads to a 2:1 branching ratio for reactions (a) to (b), as well as for (c) to (d).

The motivation for these studies was twofold; first, the determination of the relative K-Λ parity, and second, the systematic description of the properties of the light hypernuclei.

II. K-Λ PARITY AND SPIN OF ${}_{\Lambda}H^3$, ${}_{\Lambda}H^4$, ${}_{\Lambda}He^4$

If we assume that the spin of ${}_{\Lambda}He^4$ (or ${}_{\Lambda}H^4$) is zero, then it is easily shown that the conservation of parity requires that the reactions (a) and (b) be forbidden if the K^- is scalar, and be allowed if the K^- is pseudoscalar (with respect to the Λ^0, conventionally assumed to be scalar), independent of what atomic state from which the K^- is absorbed. If we adopt the argument of Day and Snow[1] that the K^- is absorbed from an s-state Bohr orbital, then we can make an argument which immediately tells us about both the spin of the ${}_\Lambda He^4$ (or ${}_\Lambda H^4$) and the K parity. This is as follows. Consider reaction (b), where we look at only those decays where ${}_\Lambda H^4 \to \pi^- + He^4$. If our quantum axis is taken as the ${}_\Lambda H^4$ direction, and total $J = 0$, then $J_z = 0 = S_z$, where S_z is the z component of the spin of the ${}_\Lambda H^4$. Thus, the wave function for the two-body decay ${}_\Lambda H^4 \to \pi^- + He^4$ is $P_1^0(\cos\vartheta)$ or $P_0^0(\cos\vartheta)$, depending on whether the ${}_\Lambda H^4$ has a spin of 1 or 0, respectively. Table 1 summarizes the results.

Table 1

	K parity	Spin of ${}_\Lambda H^4$	Angular distribution
case (a)	pseudoscalar	0	isotropic
(b)	scalar	1	$\cos^2\vartheta$
(c)	pseudoscalar	1	forbidden
(d)	scalar	0	forbidden

To date, 347 cases of reaction (a) and 154 cases of (b) have been identified in an exposure of our bubble chamber to a stopping K^- beam from the Berkeley Bevatron. Of the 154 cases of (b), 96 cases are the two-body mode ${}_\Lambda H^4 \to \pi^- + He^4$. The angular distribution of these decay pions is shown in Fig. 4. The data obviously correspond to case (a) of Table 1, indicating that the K^- is pseudoscalar and the spin of ${}_\Lambda H^4$ is zero. Since ${}_\Lambda H^4$ and ${}_\Lambda He^4$ are isotopic doublets, this also indicates that the spin of ${}_\Lambda He^4$ is zero. The evidence strongly favours the antiparallel Λ-nucleon spin orientation as the more strongly bound state. Thus, we would expect that the spin of ${}_\Lambda H^3$ would therefore be $S = 1/2$, and not $S = 3/2$.

Dalitz and Liu[2] have outlined methods of determining the spin of ${}_\Lambda H^4$ and ${}_\Lambda H^3$ from a study of π^- decay branching ratios, using the ratios

$$R_4 = \frac{{}_\Lambda H^4 \to \pi^- + He^4}{{}_\Lambda H^4 \to \text{all } \pi^-} \quad \text{and} \quad R_3 = \frac{{}_\Lambda H^3 \to \pi^- + He^3}{{}_\Lambda H^3 \to \text{all } \pi^-},$$

respectively. The argument for ${}_\Lambda H^4$ is as follows.

i) An impulse model of the hyperfragment decay is assumed, using the parameters of the free Λ^0 decay.

ii) For the decay ${}_\Lambda H^4 \to \pi^- + {}_\Lambda He^4$, the rate of decay is proportional to s^2, if $S = 0$, because both the pion and He^4 are spin zero particles. The amplitudes of the free Λ^0 decay are s and p, corresponding to the $\ell = 0$ and $\ell = 1$ channels, respectively. Conversely, the rate of two-body decay is proportional to p^2 if $S = 1$. Since the ratio $p^2/p^2 + s^2 = 0.12 \pm 0.03$, as measured by Beall et al.[3], we expect R_4 to be large if $S = 0$ and small if $S = 1$. Similar arguments pertain to ${}_\Lambda H^3$.

We have plotted R_4 for 148 ${}_\Lambda H^4$ in Fig. 5. Also shown there is the theoretical curve of Dalitz and Liu[2]. Our value, $R_4 = 0.68 \pm 0.04$, along with the experimental values of $p^2/p^2 + s^2$, is shown in Fig. 5. It is clear that the data strongly indicate $S = 0$. We have measured $R_3 = 0.39 \pm 0.07$ for 44 cases of ${}_\Lambda H^3$. The data are shown in Fig. 6, along with the theoretical results of Dalitz and Liu using a binding energy of ${}_\Lambda H^3$, $\epsilon = 0.21$ MeV. The measured value is $\epsilon = 0.21 \pm 0.20$ MeV[4]. Since the calculated result is proportional to $\sqrt{\epsilon}$, it is clear that the theoretical uncertainty is quite large. However, the data strongly favour $S = \frac{1}{2}$. It is amusing perhaps to reverse the argument, assume $S = \frac{1}{2}$, the measured value of R_3, and the theoretical structure, and then deduce the binding energy. This leads us to a redetermination of ϵ, albeit indirect, of $\epsilon = 0.16 \pm 0.06$ MeV. The results for R_4 and R_3 are in agreement with emulsion results[5,6] of lower statistical weight.

In summary, all methods of spin determination of ${}_{\Lambda}H^3$ and ${}_{\Lambda}H^4$(${}_{\Lambda}He^4$) agree that the antiparallel Λ-nucleon spin state is more strongly bound. Thus, we must conclude that the ground state spin of ${}_{\Lambda}H^3$ is ½, and that the spins of ${}_{\Lambda}He^4$ and ${}_{\Lambda}H^4$ are zero.

If it were not for the possibility of an excited state for ${}_{\Lambda}H^4$(${}_{\Lambda}He^4$), the parity argument for the K^- would be unassailable. However, the possibility has been advanced that what really happens is that the hyperfragment is produced in an excited spin 1 state, which rapidly γ-decays to the ground state of spin zero, and that what we observe is the spin zero ground state. Dalitz and Downs[7] have estimated that if such an excited state exists, its binding energy is $\lesssim 0.1$ MeV, whereas the ground state is bound by ~ 2 MeV. This large a difference in binding energies should lead to a measurable difference in the rate of production of hypernuclei in reactions (a) and (b), i.e. the rate should be very low if the excited state is formed, because of the low binding. The ratio

$$R = \frac{({}_{\Lambda}He^4 + \pi^-)}{({}_{\Lambda}He^4 + \pi^-) + (\Lambda^0 + He^3 + \pi^-)}$$

should be proportional to $\sqrt{\epsilon}$, where ϵ is the binding energy of the type of ${}_{\Lambda}He^4$ produced. In particular, the ratios R should differ by a factor of ~ 4.5 for the ground and excited states. Originally, Dalitz and Downs calculated the ratio R using an impulse model and the reaction chain,

$$K^- + He^4 \to \pi^- + \Lambda^0 + He^3 \to \pi^- + {}_{\Lambda}He^4 \; .$$

Their result was R = 22%. More recently, the Helium Bubble Chamber Group[8] has demonstrated strong evidence for the formation of Y_1^* as an intermediate state. Thus, one must calculate the reaction chain

$$K^- + He^4 \to Y_1^{*-} + He^3 \to \pi^- + \Lambda^0 + He^3 \to \pi^- + {}_{\Lambda}He^4 \; .$$

M.M. Block[9] has calculated the ratio R assuming an intermediate Y* state. The calculation uses an impulse model, and is quite sensitive to the spin and parity assignment of the Y_1^*. The predictions, along with our experimental result R = 0.20 ± 0.02, are summarized in Table 2.

Table 2

Model	R(ϵ = 2.2 MeV)	R(ϵ = 0.10 MeV)
Simple impulse model	0.23	$\lesssim$ 0.05
Y_1^* $S_{1/2}$	0.23	$\lesssim$ 0.05
Y_1^* $P_{3/2}$	0.14	$\lesssim$ 0.05
Y_1^* $P_{1/2}$	0.07	$\lesssim$ 0.05
Experiment	0.20 ± 0.02	

Recently, two groups[10,11)] have determined the spin of the Y_1^* to be S = $3/2$, and Shafer et al.[11)] have preliminary evidence favouring $p_{3/2}$. Our experimental data strongly favour the assignment $p_{3/2}$, and at the same time indicate that the hyperfragment was produced via the ground state and not the excited state. Thus, the conclusion is reinforced that the K^- is pseudoscalar.

III. LIFETIME OF $_\Lambda H^3$

The $_\Lambda H^3$'s have a mean length before decay of ~ 0.5 cm which is a convenient and accurately measured distance in the helium chamber. Of the 69 $_\Lambda H^3$, 36 satisfied our selection criteria:

a) decay length longer than 0.5 mm;
b) decay occurring further than 1 cm from chamber boundaries;
c) χ^2 from kinematics fitting programmes were acceptably small.

These criteria were used to eliminate possible biases, and to provide accurate measurements.

A maximum likelihood function of these 36 events (seven decayed at rest), is shown in Fig. 7. The lifetime obtained was $\tau_3 = 1.05^{+0.20}_{-0.18} \times 10^{-10}$ sec, a value considerably smaller than the free Λ^0 lifetime, $\tau_\Lambda = 2.36 \pm 0.06 \times 10^{-10}$ sec [12]. Dalitz and Rajasekharan[13] have made estimates of τ_3 for various assumptions of the spin of ${}_\Lambda H^3$. They find $\tau_3(S=\frac{1}{2}) = 1.79 \pm 0.10 \times 10^{-10}$ sec, and $\tau_3(S=\frac{3}{2}) = 2.40 \pm 0.03 \times 10^{-10}$ sec. The calculations both seem in disagreement with experiment, but the experimental value is in much less disagreement with the assignment $S = \frac{1}{2}$.

IV. MEASUREMENT OF $p_0^2/p_0^2+s_0^2$ RATIO FOR $\Lambda^0 \to n+\pi^0$

The impulse model predicts that the dominant decay modes of the ${}_\Lambda He^4$ hypernucleus are

$$ {}_\Lambda He^4 \to \pi^0 + n + He^3 \qquad (1)$$

and

$$ {}_\Lambda He^4 \to \pi^- + p + H^3 . \qquad (2)$$

Further, the final state interactions between He^3 and n will often cause reaction (1) to appear as

$$ {}_\Lambda He^4 \to \pi^0 + He^4 , \qquad (3)$$

i.e. a bound state of $n - He^3$ which enhances the reaction rate. The corresponding reaction (2) between p and H^3 does not lead to a bound state and hence is not enhanced. We assume spin 0 for ${}_\Lambda He^4$; since the π^0 and He^4 are also spin zero, reaction (3) can only go via the s-wave channel of Λ^0 decay ($\Lambda^0 \to \pi^0 + n$). Thus the ratio

$$ R_0 = \frac{{}_\Lambda He^4 \to \text{all } \pi^0 \text{ modes}}{{}_\Lambda He^4 \to \text{all } \pi^- \text{ modes}} $$

will depend sensitively on the ratio $p_0^2/p_0^2+s_0^2$, where p_0 and s_0 are the amplitudes of the p and s channels, respectively, for the free decay $\Lambda^0 \to n+\pi^0$. In particular, assuming the experimental value

$p^2/p^2 + s^2 = 0.12 \pm 0.03$ for the charged decay mode ($\Lambda^0 \rightarrow \pi^- + p$), and $p^2 + s^2 = 2(p_0^2 + s_0^2)$, along with the formula derived by Dalitz and Liu[2],

$$R_0 = \frac{1.96\ s_0^2 + 0.35\ p_0^2}{0.40\ s^2 + 0.32\ p^2}\ , \qquad (4)$$

we obtain the expression

$$R_0 = 2.51 - 2.06\ p_0^2/p_0^2 + s_0^2\ . \qquad (5)$$

Table 3 is a summary of the decay modes (corrected for background and geometrical detection efficiency) of a sample of 317 observed ${}_\Lambda He^4$. From Table 3 we obtain $R_0 = 2.49 \pm 0.34$. Figure 8 shows the result of Eq. (5) and our experimental determination. We obtain $p_0^2/p_0^2 + s_0^2 = 0.01 {}^{+0.17}_{-0.01}$, a value in good agreement with the value of 0.12 ± 0.03 predicted by the $\Delta I = \frac{1}{2}$ law. This result is in agreement with the asymmetry parameter ratio $\alpha_0/\alpha_- = 1.10 \pm 0.27$ of Cork et al.[14]. However, it should be pointed out that their experiment yielded <u>two</u> solutions for $p_0^2/p_0^2 + s_0^2$, whereas this experiment also selects the proper solution.

Table 3

Decay mode distribution for 317 ${}_\Lambda He^4$ decays

Decay mode	π^0 modes	π^- modes				Non-mesic modes		π^+ modes		
Topological description	nothing	π^-	$\pi^- p$	$\pi^- pp$	$\pi^- ppp$	p	pp	π^+	$\pi^+ p$	$\pi^+ p$ or pp
Observed	199	4	58	11	0	10	32	0	2	1
	199	73				42		2(+1)		
Background corrections	182	75				33		2(+1)		
Geometrical corrections	251	101				52		3(+1)		

V. DECAY MODES OF $_{\Lambda}He^4$

Table 3 summarizes the decay modes for 317 $_{\Lambda}He^4$. We observe that R_N = (non-mesonic modes / π^- modes) is given by $R_N = 0.52 \pm 0.10$. Further, $R_0 = 2.49 \pm 0.34$. We also note a quite high ratio of π^+/π^- decays, i.e. $\approx 3\%$. The two π^+ decays definitely identified both had the π^+ stopping in the chamber, undergoing the characteristic $\pi^+ \to \mu^+ \to e^+$ decay chain. The uncertain event had too short a decay track to rule out the "proton" hypothesis. The mean π^+ momentum is very low ($\approx$ 65 MeV/c), which is to be contrasted with a typical π^- decay, which has a momentum ~ 90 MeV/c.

Ferrari and Fonda[15] have noted that the basic force between Λ^0 and nucleons could be due to an intermediate Σ state as shown in Fig. 9a. Deloff et al.[16] have calculated the formation of π^+, using as a model the decay of the intermediate Σ, as shown in Fig. 9b. They find that the ratio of π^+/π^- can be as high as several percent, and further, that the π^+ decay momentum would be quite low for the decay $_{\Lambda}He^4 \to \pi^+ + n + H^3$.

The non-mesonic events broke up into two categories, i.e. 10 "p" and 32 "pp" events. It was estimated that of the 10 "p" events, 4 were really $_{\Lambda}He^4 \to \pi^0 + He^3 + n$, where the He^3 recoil produced a visible track. Either the direct four-fermion interaction

$$\Lambda^0 + p \to p + n \tag{6}$$

or the reabsorption of a virtual pion by a nucleon,

$$\Lambda + N \to (N + \pi) + N \to N + N \tag{7}$$

can be responsible for the non-mesic decay of the $_{\Lambda}He^4$ hypernucleus.

The direct four-fermion interaction, however, forbids in principle

$$\Lambda + n \to n + n ,$$

because of the absence of neutral currents in the Fermi interaction (it can still be permitted in practice by absorption and emission of virtual pions).

On the other hand, the $(\Lambda^0 p)$ interactions

$$\Lambda^0 + p \rightarrow (p + \pi^-) + p \rightarrow p + n \qquad (8a)$$

$$\Lambda^0 + p \rightarrow (n + \pi^0) + p \rightarrow n + p \qquad (8b)$$

or the $(\Lambda^0 n)$ interactions,

$$\Lambda^0 + n \rightarrow (p + \pi^-) + n \rightarrow n + n \qquad (9a)$$

$$\Lambda^0 + n \rightarrow (n + \pi^0) + n \rightarrow n + n \qquad (9b)$$

can occur.

It is clear that if the non-mesonic decay occurs via either (6) or (8), it involves the emission of a fast proton ($\approx$ 400 MeV/c) due to the rather large energy release in the interaction, while if the decay goes via reactions (9a) or (9b), there are two fast neutrons, and visible protons can come only from the evaporation process in the residual nucleus. If the proton had a momentum of $\gtrsim$ 250 MeV/c, we arbitrarily decided to call the event de-excitation off a proton. All of the "p" events had a momentum less than 250 MeV/c. Of the 32 "pp" events, only 6 had both protons < 250 MeV/c. Thus, an estimate of the ratio of non-mesonic de-excitation off the proton to that off the neutron is

$$\frac{\Lambda - p}{\Lambda - n} = 2.2 \pm 0.8 \ .$$

Since ${}_\Lambda He^4$ has twice as many protons as neutrons, the ratio <u>per pair</u> is 1.1 ± 0.4. The number is too crude, however, to be more than an indication that the basic de-excitation mechanism for non-mesonic decay is about the same with either the proton or neutron.

VI. NON-MESONIC DECAYS OF ${}_\Lambda H^4$

If we accept charge independence in the production of ${}_\Lambda H^4$ and ${}_\Lambda He^4$, we observe that the number of ${}_\Lambda H^4$ produced is one-half the number of ${}_\Lambda He^4$ produced. Although we observe only ${}_\Lambda H^4 \rightarrow \pi^-$, we can, using the production argument, find out how many ${}_\Lambda H^4$ decayed via either π^0

modes or non-mesonic decays. Further, if we assume the $\Delta I = \frac{1}{2}$ law for the decay of ${}_{\Lambda}H^4$ and ${}_{\Lambda}He^4$, then the ratio we obtained for ${}_{\Lambda}He^4$, i.e.

$$R_0 = \frac{{}_{\Lambda}He^4 \rightarrow \pi^0}{{}_{\Lambda}He^4 \rightarrow \pi^-} = 2.49 ,$$

is related to the same ratio for ${}_{\Lambda}H^4$, i.e.

$$R_0({}_{\Lambda}He^4) \times R_0({}_{\Lambda}H^4) = \frac{1}{4} ,$$

as shown by Dalitz and Liu[2]. Thus

$$R_0({}_{\Lambda}H^4) \equiv \frac{{}_{\Lambda}H^4 \rightarrow \pi^0}{{}_{\Lambda}H^4 \rightarrow \pi^-} = 0.10 .$$

Putting these numbers together, after using a restricted sample where all events have been measured, and allowing for corrections for detection efficiency, background, etc., we find that we predict (from the ${}_{\Lambda}He^4$ rate) that 163 ± 10 ${}_{\Lambda}H^4$ were produced, compared to 120 ± 11 ${}_{\Lambda}H^4 \rightarrow \pi^-$. Thus, 132 ± 12 ${}_{\Lambda}H^4$ decayed either via π^- or π^0 modes. The remainder, attributed to non-mesonic decays, is therefore 31 ± 15. Thus, the ratio of (non-mesonic)/(π^- mesic) for ${}_{\Lambda}H^4$ is found to be $26 \pm 13\%$.

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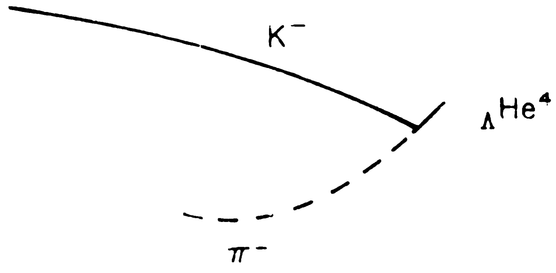

Fig. 1. Schematic Drawing of Reaction $K^- + He^4 \rightarrow \pi^- + {}_{\Lambda}He^4$, ${}_{\Lambda}He^4 \rightarrow \pi^o + He^4$.

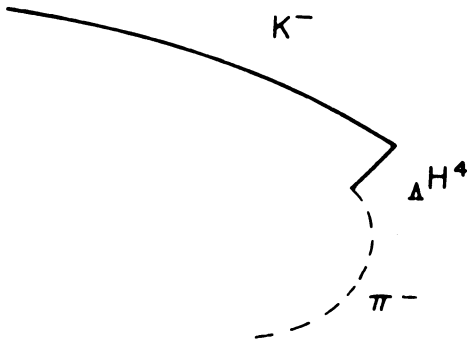

Fig. 2. Schematic Drawing of Reaction $K^- + He^4 \rightarrow \pi^o + {}_{\Lambda}H^4$, ${}_{\Lambda}H^4 \rightarrow \pi^- + He^4$.

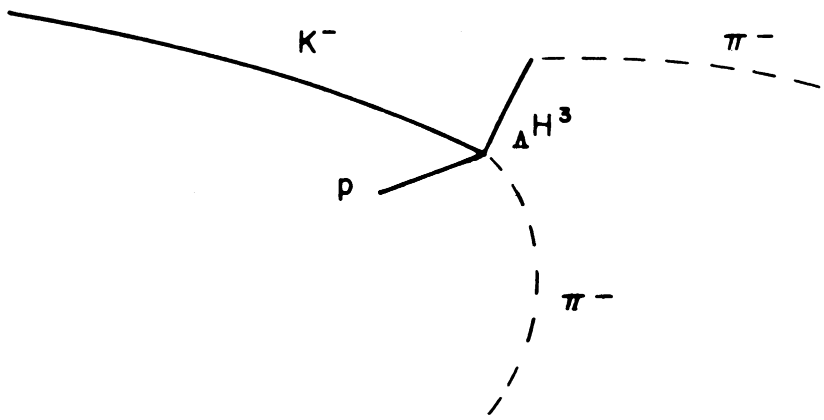

Fig. 3. - Schematic Drawing of Reaction $K^- + He^4 \rightarrow p + \pi^- + {}_{\Lambda}H^3$, ${}_{\Lambda}H^3 \rightarrow \pi^- + He^3$.

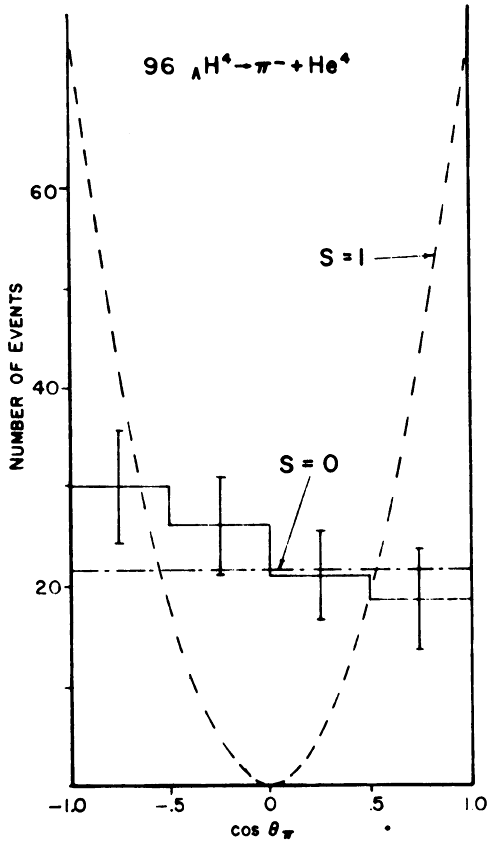

Fig. 4. - The Angular Distribution of the π^- from 96 Decays $_{\Lambda}H^4 \to \pi^- + He^4$, for Hyperfragments Produced in the Capture Reaction $K^- + He^4 \to \pi^0 + {}_{\Lambda}H^4$.

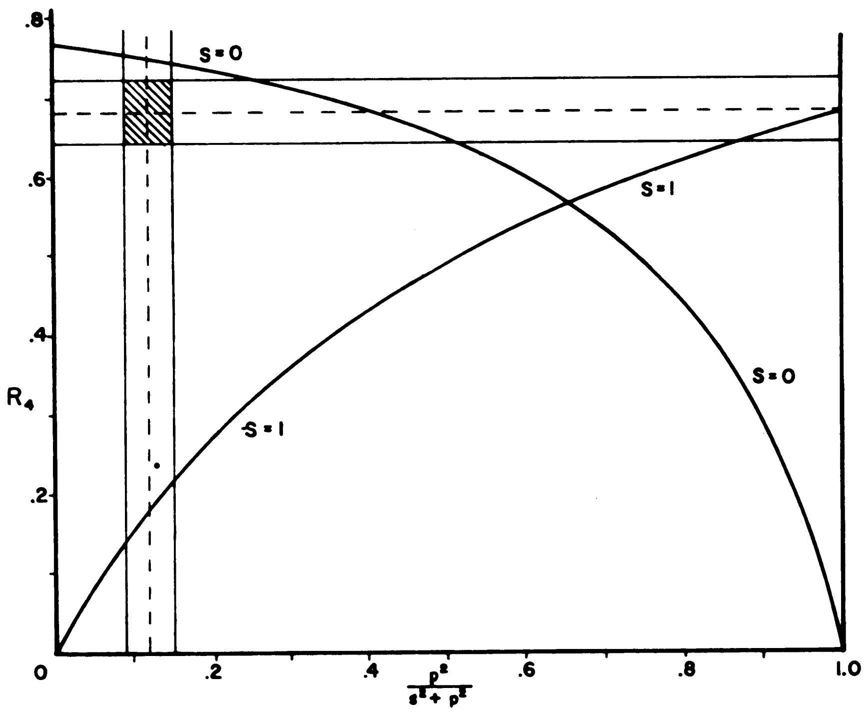

Fig. 5. - R_4, the Ratio of $_{\Lambda}H^4 \to \pi^- + He^4$ to $_{\Lambda}H^4 \to$ all π^- modes, as a function of $p^2/p^2 + s^2$. The Theoretical Curves are the Calculated R_4 of Dalitz and Liu for S = O and S = 1.

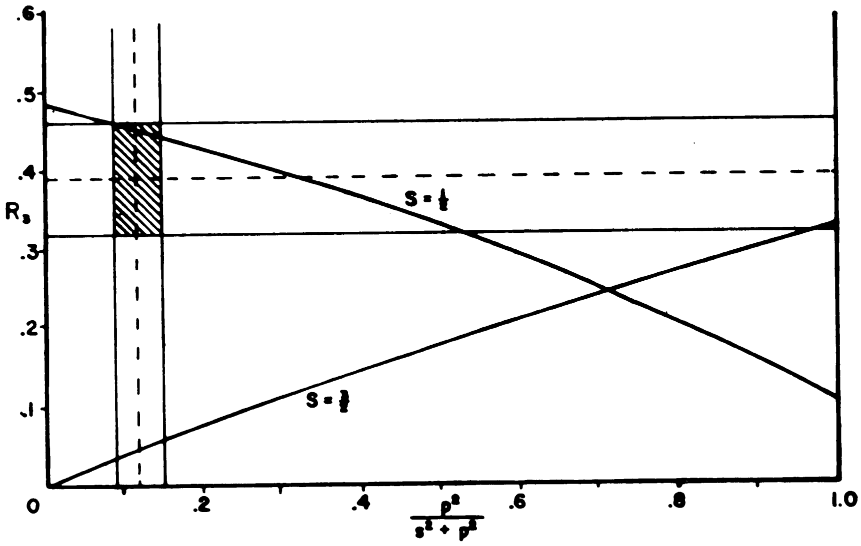

Fig. 6. - R_3, the Ratio of ${}_\Lambda H^3 \rightarrow \pi^- + He^3$ to ${}_\Lambda H^3 \rightarrow$ all π^- modes as a Function of $p^2/p^2 + s^2$. The Theoretical Curves are the Calculated R_3 of Dalitz and Liu for S = 1/2 and S = 3/2.

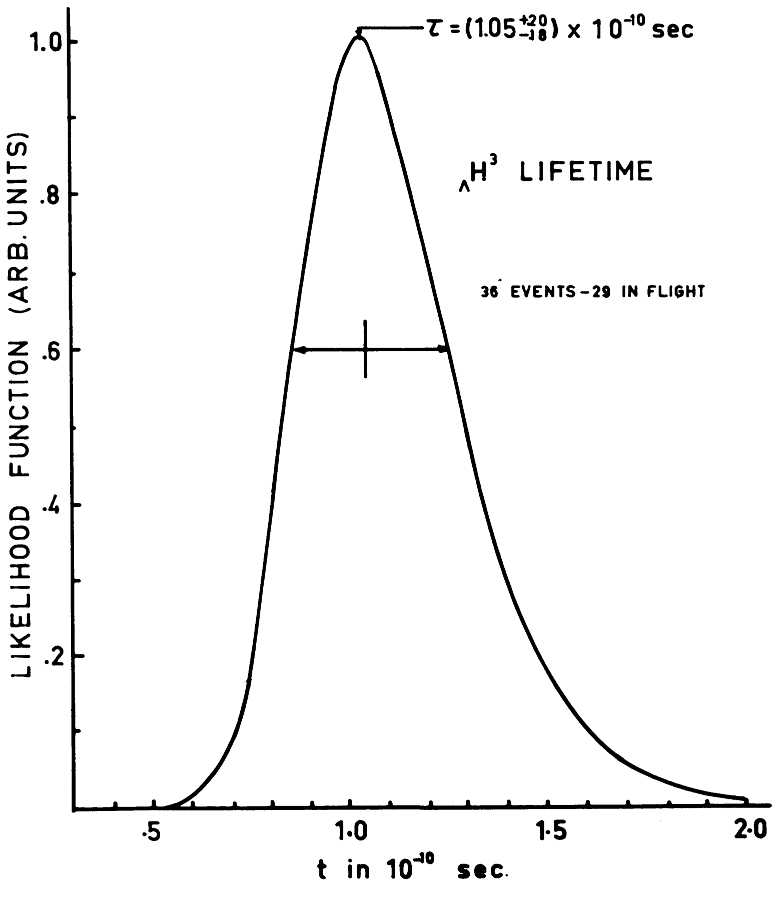

Fig. 7. - The Likelihood Function in Arbitrary Units, for 36 ${}_\Lambda H^3$ Decays, as a Function of the ${}_\Lambda H^3$ Lifetime.

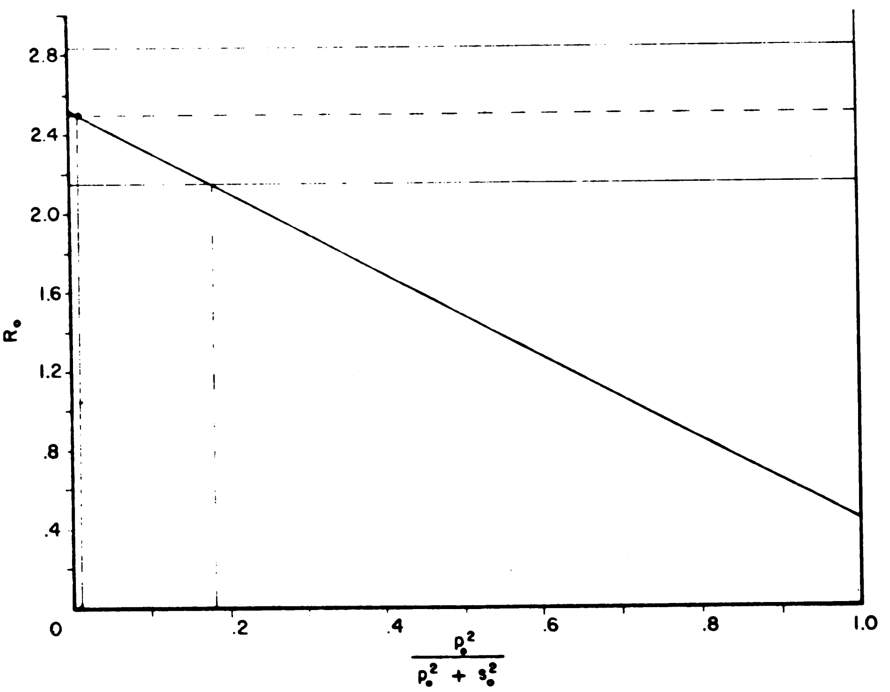

Fig. 8. - R_o, the Ratio of ${}_\Lambda He^4 \rightarrow$ all π^o modes to ${}_\Lambda He^4 \rightarrow$ all π^- modes, as a Function of $p_o^2/p_o^2 + s_o^2$.

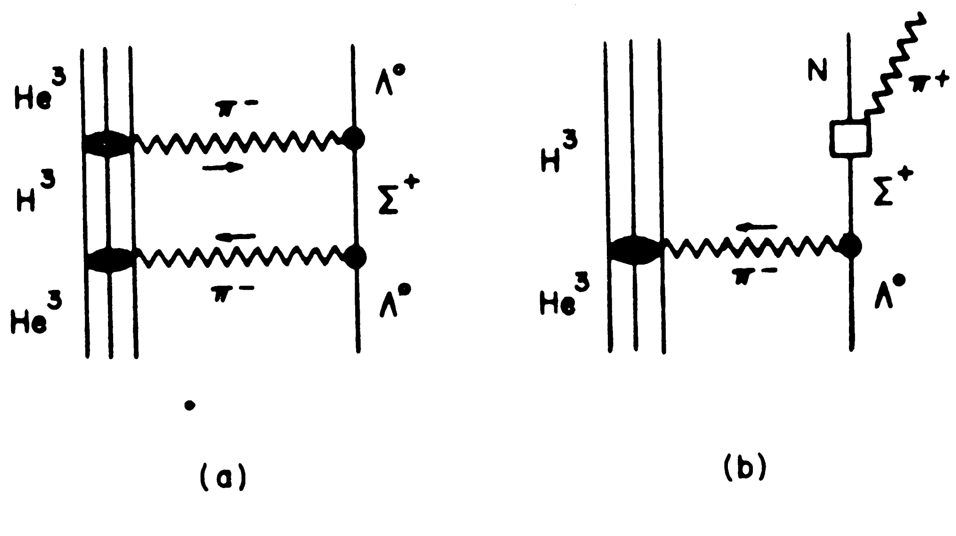

Fig. 9. - Feymman Diagrams of Intermediate States.