(a) Interaction mean free paths (in air):

$\lambda_H = 18$ g/cm^2; $\lambda_M = 26.5$ g/cm^2; $\lambda_L = 31.5$ g/cm^2.

(b) Absorption mean free paths (in air):

$$\lambda_I' = \lambda_I/(1-P_{II});$$

$\lambda_H' = 24$ g/cm^2; $\lambda_M' = 30.5$ g/cm^2; $\lambda_L' = 34.0$ g/cm^2; $\lambda_\alpha' = 45.0$ g/cm^2.

(c) Fragmentation probabilities (in air):

Bristol values $(B)^{18}$:

$$P_{HM} = 0.46;\quad P_{HL} = 0.21;\quad P_{H\alpha} = 1.23;$$
$$P_{ML} = 0.23;\quad P_{M\alpha} = 1.27;\quad P_{L\alpha} = 0.79.$$

Rochester values $(R)^{17}$:

$$P_{HM} = 0.27;\quad P_{HL} = 0.48;\quad P_{H\alpha} = 2.07;$$
$$P_{ML} = 0.42;\quad P_{M\alpha} = 1.42.$$

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Parity Nonconservation in the Decay of Free and Bound Λ Particles

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A quantitative estimate is made of the branching ratio between two-body and more complicated mesonic decay modes for ${}_\Lambda He^4$ and ${}_\Lambda H^4$, as function of their spin J and the ratio p/s of the s- and p-channel amplitudes in free Λ decay. Comparison with the data on ${}_\Lambda H^4$ decay indicates that $J=1$ is rather improbable and that, with $J=0$, an upper limit on p/s is about unity, a lower limit of 0.45 being obtained from the observations on up-down asymmetry in polarized Λ decay. The theoretical and experimental values for the nonmesonic/mesonic ratio in hypernuclear decay are compared in the light of these limits on p/s. Assuming validity of the $\Delta T = \frac{1}{2}$ rule, the variations in the π^-/π^0 ratio for decays of light hypernuclei ($Z \leqslant 2$) due to the effect of the Pauli principle are also estimated. A brief discussion of ${}_\Lambda H^3$ decay is given in an appendix.

1. INTRODUCTION

PLANO *et al.*[1] and Crawford *et al.*[2] have recently established that the decay pions from $\Lambda \to p + \pi^-$ decay events following the $\pi^- + p \to \Lambda + K^0$ production reaction in the energy range 950 to 1100 Mev are emitted with a marked up-down asymmetry relative to the normal to the $\Lambda + K^0$ production plane. The existence of this asymmetry establishes both that this reaction produces Λ particles with a strong polarization perpendicular to their production plane, and that the $\Lambda \to p + \pi^-$ decay process does not conserve parity. In fact, as Lee and Yang[3] have pointed out, the asymmetry observed exceeds the maximum value permitted (with the angular distribution observed in the Λ rest system) for a Λ spin of $\frac{3}{2}$ or greater, being compatible only with spin $\frac{1}{2}$ for the Λ particle. Parity nonconservation in the decay of a spin-$\frac{1}{2}$ Λ particle allows the emission of both s and p waves for the outgoing pion, and the decay amplitude will have the general form

$$H(\Lambda \to p + \pi^-) = s + p\boldsymbol{\sigma}\cdot\mathbf{q}/q_\Lambda, \tag{1.1}$$

where $\mathbf{q}$ is the momentum of the decay pion in the Λ rest system (q_Λ its value for free Λ decay), $\boldsymbol{\sigma}$ denotes the baryon spin vector, and s, p denote the amplitudes for the $l_\pi = 0$ and $l_\pi = 1$ channels, respectively. With this expression (1.1), the angular distribution of the pions from decay of polarized Λ particles takes the form

$$(1 + \alpha P_\Lambda \cos\theta), \tag{1.2}$$

where θ is the polar angle of the outgoing pion relative to the initial spin direction, P_Λ is the mean polarization of the parent Λ particles, and α denotes the combination

$$\alpha = 2\,\mathrm{Re}(s^* p)/(|s|^2 + |p|^2), \tag{1.3}$$

whose value is a property of the detailed mechanism giving rise to the Λ-decay process. From the experiments mentioned above, only the combination αP_Λ can be determined. The value obtained, averaged over all production angles for the Λ particles, is given by

$$\alpha \bar{P}_\Lambda = 0.55 \pm 0.10. \tag{1.4}$$

The parameter $-\alpha$ also gives the value of the mean longitudinal polarization for the protons recoiling from Λ decay, this polarization being specified in the Λ rest system and averaged over all directions of decay. For Λ particles which decay in flight, the recoil protons observed in the laboratory system will then generally have a transverse component of polarization resulting from their longitudinal polarization in the Λ rest system and this may be measured by observations on the left-right asymmetry in their scattering from a target of known polarization properties in the standard way.

[1] Plano, Prodell, Samios, Schwartz, Steinberger, Bassi, Borelli, Puppi, Tanaka, Waloschek, Zoboli, Conversi, Fronzini, Manelli, Santangelo, Silvestrini, Glaser, Graves, and Perl, Phys. Rev. **108**, 1353 (1957).

[2] Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho, Phys. Rev. **108**, 1102 (1957).

[3] T. D. Lee and C. N. Yang, Phys. Rev. **109**, 1755 (1958).

From such observations, made in a multiplate cloud chamber, Boldt *et al.*[4] have recently established the sign of α to be positive, but a precise measurement of α in this way will require a more detailed experiment. If α could be determined in this direct way, the experiments leading to (1.4) would allow the determination of P_Λ as function of the Λ production angle, information which would be of great value in the analysis of the production reactions for the Λ particle. At present, however, this argument may only be used in reverse; the analysis of the production data allows an upper limit of 70% to be placed on the mean polarization $\bar{P}_\Lambda$ for the Λ particles considered. This leads to a corresponding lower limit on the value of α,

$$|\alpha| \geqslant 0.77 \pm 0.12. \tag{1.5}$$

In the present work, the amplitudes s and p will be assumed to be real quantities. This appears reasonable under the following circumstances. First, if it is assumed that time-reversal invariance holds for the Λ-decay interaction,[5] then it is well known[6] that the phases of s and p arise only from the scattering between the outgoing pion and nucleon, in fact

$$s = \tfrac{2}{3} s_1 e^{i\delta_1} + \tfrac{1}{3} s_3 e^{i\delta_3}, \tag{1.6a}$$

$$p = \tfrac{2}{3} p_1 e^{i\delta_{11}} + \tfrac{1}{3} p_3 e^{i\delta_{31}}, \tag{1.6b}$$

where $(s_1,\ p_1)$ and $(s_3,\ p_3)$ are the real amplitudes leading to final $T=\frac{1}{2}$ and $T=\frac{3}{2}$ pion-nucleon states, respectively, and δ_1, δ_3, δ_{11}, δ_{31} denote the pion-nucleon scattering phases for c.m. energy 37 Mev. Further the simplest interpretation of the branching ratio $(\pi^-+p)/(\pi^0+n)$ observed in Λ decay[7] is given by the $\Delta T=\frac{1}{2}$ rule of Gell-Mann, which requires that the final pion-nucleon state should consist only of $T=\frac{1}{2}$ states, that is $s_3=p_3=0$. With these assumptions, the relative phase between s and p is limited to $(\delta_1-\delta_{11})\sim 10°$, which may be neglected in expression (1.3). With s and p real, the limitation on the ratio p/s implied by (1.5) is shown in Fig. 1, giving

$$0.45 \leqslant p/s \leqslant 2.25. \tag{1.7}$$

This result still allows a wide range of variation in the relative contribution of s and p channels to the $\Lambda \rightarrow p+\pi^-$ decay rate, the contribution of the p channel lying between 18% and 82% of the total (π^-+p) decay rate.

Even a direct determination of α would still allow two possibilities for the ratio p/s, one exceeding unity, the other less than unity. In principle, measurement of the sign of the transverse polarization of the recoil protons from (π^-+p) decay of polarized Λ particles (this transverse polarization being the component in the plane of P_Λ and the proton direction, in the Λ rest system) could distinguish between these possibilities, since this component of the polarization is given by $P_\Lambda \cos\theta_\pi (s^2-p^2)/(s^2+p^2)(1+P_\Lambda\alpha\cos\theta_\pi)$. However, this quantity is obviously difficult to determine.

Our main purpose here is to discuss an argument which is based on the branching ratios observed for the decay modes of light hypernuclei and which places a limit on p/s sufficient to limit this ratio to values less than unity. This argument also establishes the spin of the ground state of the hypernuclear doublet ${}_\Lambda H^4$, ${}_\Lambda He^4$, and therefore leads to a clear conclusion concerning the spin-dependence of the Λ-nucleon interaction.

2. π^- AND π^0 DECAY MODES OF ${}_\Lambda H^4$ AND ${}_\Lambda He^4$

According as the Λ-nucleon interaction favors the singlet or triplet configuration, there are two spin values conceivable[8] for the ground state of the ${}_\Lambda H^4$, ${}_\Lambda He^4$ doublet, $J=0$ or $J=1$, since the Λ particle then moves in an s state relative to the center of mass of the system. For ${}_\Lambda H^4$, the two-body decay mode

$${}_\Lambda H^4 \rightarrow \pi^- + He^4 \tag{2.1}$$

has become well established[9] and is of special interest since the two final particles are each spinless. This implies that the relative orbital angular momentum l equals the spin J of the initial system, so that the final two-body system has definite parity $-(-1)^J$. One consequence of this is that the emission of decay pions in the mode (2.1) must have forward-backward symmetry relative to the ${}_\Lambda H^4$ spin direction if $J=1$ (being

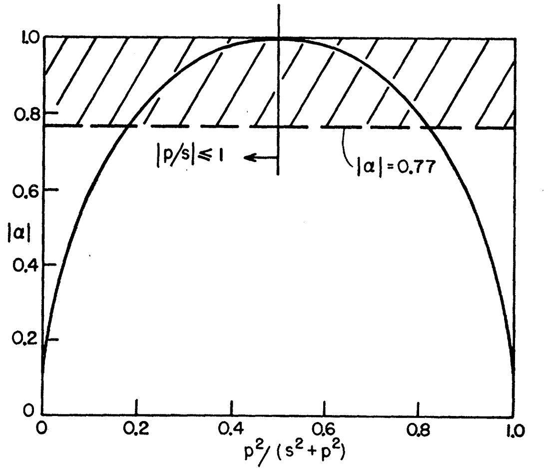

FIG. 1. A plot of the asymmetry coefficient $|\alpha|$ in Λ decay as function of the intensity of the p-channel relative to the total π^- decay rate. This plot shows the limits on $|p/s|$ implied by the present data.

[4] Boldt, Bridge, Caldwell, and Pal, Bull. Am. Phys. Soc. Ser. II, 3, 163 (1958).

[5] There is no positive evidence to date for the failure of this invariance property for any of the weak decay interactions investigated in detail.

[6] G. Takeda, Phys. Rev. 101, 1547 (1956).

[7] Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento 5, 1700 (1957).

[8] R. H. Dalitz and B. W. Downs, Phys. Rev. 111, 967 (1958).

[9] Levi-Setti, Slater, and Telegdi, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957* (Interscience Publishers, Inc., New York, 1957), Sec. 8, p. 6.

isotropic, of course, for $J=0$). More important, since the initial Λ particle moves in an s state relative to the center of mass, the outgoing pion can attain $l=1$ only through the p channel of $\Lambda \rightarrow p+\pi^-$ decay, whereas $l=0$ can be reached only through the s channel of decay.

Similar remarks may be made concerning the two-body decay of ${}_\Lambda He^4$,

$$ {}_\Lambda \mathrm{He}^4 \rightarrow \pi^0+\mathrm{He}^4, \tag{2.2} $$

for which a rather clear example has recently been reported by Levi-Setti and Slater.[10] Here the outgoing π^0 meson can be emitted with $l=1$ only through the p channel of the $\Lambda \rightarrow n+\pi^0$ decay, while $l=0$ can be reached only through the s channel of this decay mode.

The partial lifetimes for these two-body modes (2.1) and (2.2) may be computed adequately by the impulse approximation, since the secondary scattering between the outgoing pion and the alpha particle is known to be quite small at these energies. First we consider in detail the decay of ${}_\Lambda H^4$. The matrix element for the process (2.1) is then simply

$$ \int \bar{\phi}_\alpha(1,2;3,4)\bar{\chi}_\alpha(1,2;3,4) \times\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\mathbf{q}\right)e^{i\mathbf{q}\cdot\{\mathbf{r}_1-\frac{1}{4}(\mathbf{r}_1+\mathbf{r}_2+\mathbf{r}_3+\mathbf{r}_4)\}} \times\phi_T(2;3,4)u_\Lambda(1)\chi_{{}_\Lambda\mathrm{H}^4}(1;2;3,4), \tag{2.3} $$

where ϕ_α, ϕ_T denote space wave functions of He^4 and of the H^3 configuration in ${}_\Lambda H^4$, and u_Λ represents the orbital motion of the Λ particle relative to the H^3 core of ${}_\Lambda H^4$. The appropriate spin functions have been denoted by χ. The square of this matrix element, averaged over initial spin states and the outgoing directions of the pion, factors into two terms, (a) the sticking probability

$$ F^2(q)=\left|\int \bar{\phi}_\alpha(1,2;3,4)\exp\left\{\frac{i}{4}\mathbf{q}\cdot(3\mathbf{r}_1-\mathbf{r}_2-\mathbf{r}_3-\mathbf{r}_4)\right\} \times\phi_T(2;3,4)u_\Lambda(1)\right|^2, \tag{2.4} $$

and (b), a spin factor

$$ S=\frac{1}{2J+1}\sum\left|\bar{\chi}_\alpha(1,2;3,4)\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\mathbf{q}\right)\chi_{{}_\Lambda\mathrm{H}^4}(1;2;3,4)\right|^2, $$

which takes the following values:

$$ \begin{aligned} &\text{(i)}\ J=0, \quad S=s^2, \\ &\text{(ii)}\ J=1, \quad S=\tfrac{1}{3}p^2q^2/q_\Lambda^2. \end{aligned} \tag{2.5} $$

In accordance with the previous paragraph, only the s-channel parameter appears in this expression for $J=0$, only the p-channel parameter p for $J=1$.

The expression (2.4) for the sticking probability has been evaluated[8] recently as function of the Λ binding energy B_Λ, assuming Gaussian forms $\exp(-\frac{1}{2}\alpha_n \sum' r_{ij}^2)$ to hold valid for the three- and four-nucleon systems. In this case $F(q)$ may be written[11]

$$ F(q)=\left\{\frac{48\alpha_3\alpha_4}{(3\alpha_3+4\alpha_4)^2}\right\}^{\frac{3}{2}}G(q,B_\Lambda), \tag{2.6} $$

where $G(q,B_\Lambda)$ denotes an overlap integral[11] between u_Λ and the wave function representing the motion of the proton (bound in He^4) resulting from the Λ decay, which was plotted as function of q and B_Λ in the earlier work.[8] The first factor of (2.6) represents the overlap integral for the wave functions of the remaining nucleons of the initial and final states of (2.1). For this, the parameters α_4 and α_3 have been chosen to fit the charge radius observed for the alpha particle and the Coulomb energy of He^3. As discussed before,[8] the choice for α_3 involves considerable uncertainty, especially as the H^3 core of ${}_\Lambda H^4$ may be distorted appreciably by the presence of the bound Λ particle. However (2.6) happens to be extremely insensitive to the precise value estimated for α_3 within quite a wide range. With $q=130$ Mev/c (note that $q_\Lambda=100$ Mev/c) and $B_\Lambda=1.8$ Mev,[9] $G(q,B_\Lambda)$ has the value 0.68, leading to a sticking probability $F^2=0.46$. The partial transition probability for the mode (2.1) is therefore given by

$$ \begin{aligned} R_\alpha &= 2\pi\delta\left(\omega_q+\frac{q^2}{2M_\alpha}-Q\right)S[F(q)]^2q^2dq/\pi\omega_q \\ &= 2qS[F(q)]^2/(1+\omega_q/M_\alpha), \end{aligned} \tag{2.7} $$

where $Q=195.6$ Mev is the energy released in this decay.

To obtain an estimate of comparable reliability for the partial decay rate for any other of the modes observed for ${}_\Lambda H^4$ decay is very much more difficult, since it requires reliable knowledge of the wave function describing (for example) the scattering of a proton by H^3 (for the mode π^-+p+H^3) or describing the system (H^2+p+n) (for the mode $\pi^-+p+n+H^2$). Such knowledge would require a more detailed understanding of the nuclear interactions in states of four nucleons than is available at present, much beyond the knowledge of the alpha-particle structure (on which the electron scattering experiments[12] at Stanford have given direct information) used in the above discussion, and we shall not attempt such estimates here. However, the low binding energy between the Λ particle and H^3, which corresponds to a typical separation of order $\hbar/(1.5m_\Lambda B_\Lambda)^{\frac{1}{2}}=3.5$ fermi (1 fermi$\equiv 10^{-13}$ cm), suggests as a reasonable expectation that the total decay rate of the Λ particle in ${}_\Lambda H^4$, summed over all modes leading

[10] R. Levi-Setti and W. E. Slater, Phys. Rev. **111**, 1395 (1958).

[11] $G(q,B_\Lambda)$ is defined explicitly in Eq. (D4) of reference 8.

[12] R. W. Hofstadter, Revs. Modern Phys. **28**, 214 (1956).

TABLE I. Momentum distributions observed for π^- mesons from three-body and more complicated decay modes of $_\Lambda H^4$, $_\Lambda He^4$, and $_\Lambda He^5$ in the world survey.[a]

q/q_{max}	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0	q_{max}(Mev/c)
$_\Lambda H^4$	1	2	3	6	104.3
$_\Lambda He^4$	0	0	1	7	102.9
$_\Lambda He^5$	3	0	6	7	102.2

[a] See reference 9.

to a final π^- meson, should be rather close to the (π^-+p) decay rate for a free Λ particle. In these circumstances the effect of the Pauli exclusion principle on this decay rate may be fairly reliably estimated; also secondary scattering of the pion by the nucleus may be expected to be relatively unimportant, according to the known scattering cross sections for pions of 40 Mev or less.

The total decay rate for all modes involving a π^- meson, averaged over all directions of the outgoing pion, is given by

$$\frac{2\pi}{2J+1}\sum_n \delta\left(\omega_q+\frac{q^2}{8m}+E_n-\Delta\right) \times\langle|M_n(q)|^2\rangle_{Av}q^2dq/\pi\omega_q, \quad (2.8)$$

where $\Delta=174.8$ Mev, m is the nucleon mass, and

$$M_n(q)=\int\bar{\psi}_n(1,2;3,4)\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\mathbf{q}\right) \times e^{i\mathbf{q}\cdot\mathbf{r}_1}\psi_{\Lambda H^4}(1;2;3,4). \quad (2.9)$$

The summation n is over all states $\psi_n(1,2;3,4)$ of two protons (1,2) and two neutrons (3,4) which are energetically accessible, their internal energy being denoted by E_n measured relative to the energy of $(p+H^3)$. Except for the state He^4 (for which $E_n=-19.8$ Mev), E_n is a positive quantity, with $E_n=0$ corresponding to $q_{max}=103$ Mev/c. As shown in Table I, about 75% of the π^- momenta observed in three-body modes of $_\Lambda H^4$ decay lie above 85 Mev/c, so that the energies E_n which contribute in the sum (2.8) lie predominantly below 9 Mev. This distribution appears reasonable since $M_n(q)$ may be expected to diminish quite rapidly (for fixed q) as E_n increases from zero, owing to the enhancement of this matrix element for low-relative kinetic energies by the strongly attractive forces between the nucleons. On this basis, it appears a fair approximation to replace E_n in the energy conservation δ function of (2.8) by a mean value $\bar{E}_n$, q then being replaced by the corresponding mean value $\bar{q}$.

This approximation reduces expression (2.8) to

$$\left\{\frac{1}{2J+1}\sum_n\langle|M_n(\bar{q})|^2\rangle_{Av}\right\}2\bar{q}/(1+\bar{\omega}_q/4m), \quad (2.10)$$

where the summation n is now extended over all states n, disregarding the limitations of the energy conservation in (2.8).

In this approximation (2.10), the contribution of the two-body mode has been appreciably underestimated, especially for the case $J=1$ where this mode involves the p channel, since the expression (2.7) is then proportional to q^3 which varies strongly between the value $\bar{q}$ appropriate to three-body modes and the value $q=130$ Mev/c appropriate to the two-body mode. However, the addition of a term

$$(q/\bar{q})S(q)F^2(q)-S(\bar{q})F^2(\bar{q}) \quad (2.11)$$

to the curly bracket of (2.10) provides an adequate correction for this underestimate. In the use of expressions (2.10) and (2.11), the momentum $\bar{q}$ will be chosen to have the value 100 Mev/c, which lies below q_{max} but above the observed q for the events listed in Table I. For the three-body and more complicated modes, the approximation (2.10) may be an overestimate of the desired sum for several reasons:

(a) expression (2.10) includes contributions from states n which are excluded from the sum (2.8) by the requirements of energy conservation,

(b) in the replacement of q by $\bar{q}$, the phase space for the pions emitted is overestimated, and

(c) the replacement of q by $\bar{q}$ overestimates the p-channel part of $M_n(q)$, for given n, since this contains a factor q according to (1.1).

However, if the experimental distribution of the pion momenta is a sufficiently fair estimate of the distribution of q, it appears that the errors introduced by these effects are unlikely to be of importance within the accuracy needed for the discussion in this paper.

With expression (2.10), the summation over n may now be carried out explicitly by means of the completeness relation

$$\begin{aligned}\sum_n\psi_n(1,2;\cdots)\bar{\psi}_n(1,2;\cdots) &=\delta_{11'}{}^\sigma\delta_{22'}{}^\sigma\delta(\mathbf{r}_1-\mathbf{r}_1')\delta(\mathbf{r}_2-\mathbf{r}_2') -\delta_{12'}{}^\sigma\delta_{21'}{}^\sigma\delta(\mathbf{r}_1-\mathbf{r}_2')\delta(\mathbf{r}_2-\mathbf{r}_1')\\ &=(1-P_{12}{}^xP_{12}{}^\sigma)\delta_{11'}{}^\sigma\delta_{22'}{}^\sigma\delta(\mathbf{r}_1-\mathbf{r}_1')\delta(\mathbf{r}_2-\mathbf{r}_2'). \quad (2.12)\end{aligned}$$

This leads to the following expression:

$$\frac{1}{2J+1}\sum_n\langle|M_n(\bar{q})|^2\rangle_{Av}=\left[s^2+\left(\frac{\bar{q}}{q_\Lambda}\right)^2p^2\right] -\frac{1}{2J+1}\mathrm{Tr}\int\bar{\psi}_{\Lambda H^4}(1;2;3,4)\exp(-i\bar{\mathbf{q}}\cdot\mathbf{r}_1) \times\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\bar{\mathbf{q}}\right)P_{12}{}^xP_{12}{}^\sigma\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\bar{\mathbf{q}}\right) \times\exp(i\bar{\mathbf{q}}\cdot\mathbf{r}_1)\psi_{\Lambda H^4}(1;2;3,4). \quad (2.13)$$

With the $_\Lambda H^4$ wave function used in (2.3), the last term of (2.12) splits into two factors,

$$\eta=\int\bar{\phi}_T(2;3,4)u_\Lambda(1)\exp[i\bar{\mathbf{q}}\cdot(\mathbf{r}_1-\mathbf{r}_2)]\times\phi_T(1;3,4)u_\Lambda(2)d_3r_1d_3r_2d_3r_3d_3r_4, \quad (2.14a)$$

$$\frac{1}{2J+1}\mathrm{Tr}\left\{\bar{\chi}(1;2;3,4)\left[\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\bar{\mathbf{q}}\right)\left(\frac{1+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{2}\right)\times\left(s+\frac{p}{q_\Lambda}\boldsymbol{\sigma}_1\cdot\bar{\mathbf{q}}\right)\right]\chi(1;2;3,4)\right\}. \quad (2.14b)$$

After averaging over the directions of $\bar{q}$, the square bracket of the spin factor (2.14b) reduces to

$$s^2P_{12}{}^\sigma+\tfrac{1}{3}p^2\left(\frac{\bar{q}}{q_\Lambda}\right)^2(2-P_{12}{}^\sigma), \quad (2.15)$$

where suffices 1 and 2 refer to the initial Λ particle and proton, respectively. The expression (2.8) for the total π^- decay rate for the bound Λ particle finally takes the forms

$$\text{(a) for } J=0;\ \left\{s^2\left[1+\eta+\frac{q}{\bar{q}}F^2(q)-F^2(\bar{q})\right]+p^2\left(\frac{\bar{q}}{q_\Lambda}\right)^2(1-\eta)\right\}2\bar{q}/(1+\bar{\omega}_q/4m), \quad (2.16)$$

$$\text{(b) for } J=1;\ \left\{s^2(1-\eta)+p^2\left(\frac{\bar{q}}{q_\Lambda}\right)^2\left[1-\tfrac{1}{3}\eta+\tfrac{1}{3}\left(\frac{q}{\bar{q}}\right)^3F^2(q)-\tfrac{1}{3}F^2(\bar{q})\right]\right\}2\bar{q}/(1+\bar{\omega}_q/4m). \quad (2.17)$$

These expressions are to be compared with the expression

$$2q_\Lambda(s^2+p^2)/(1+\omega_\Lambda/m)$$

for the π^- decay rate of the free Λ particle.

The terms involving η in (2.16) express the effect of the Pauli principle on the π^- decay rate for the Λ particle in $_\Lambda H^4$. It is of interest to note explicitly that, for the present case where there is only one proton in the initial system, the symmetry requirements on the final state may lead to either an enhancement or suppression of the π^- decay rate. The decay rate is enhanced if the decay gives rise to a proton of spin oppositely directed to the initial proton, suppressed if the decay leads to a proton of spin parallel to the initial proton; which situation holds naturally depends on the initial spin of the system and on whether or not the decay process involves spin flip.

The value of η may be estimated by assuming the product wave function

$$\phi_T(2;3,4)u_\Lambda(1)=\exp\{-\tfrac{1}{2}\alpha_3(r_{23}{}^2+r_{31}{}^2+r_{12}{}^2)\}\times u_\Lambda(|\mathbf{r}_1-\tfrac{1}{3}(\mathbf{r}_2+\mathbf{r}_3+\mathbf{r}_4)|) \quad (2.18)$$

used for $_\Lambda H^4$ in reference 8. With this the expression (2.13a) reduces to

$$\eta=(\tfrac{3}{4})^6\left(\frac{9\alpha_3}{2\pi}\right)^{\frac{3}{2}}\int\exp\left\{-\frac{9\alpha_3}{32}(5\mathbf{R}^2+6\mathbf{R}\cdot\mathbf{S}+5\mathbf{S}^2)+\frac{3i}{4}\bar{\mathbf{q}}\cdot(\mathbf{R}-\mathbf{S})\right\}u_\Lambda(R)u_\Lambda(S)d_3Rd_3S. \quad (2.19)$$

In order to evaluate this integral, it has been convenient to approximate the wave function $u_\Lambda(r)$ by means of the form

$$u_\Lambda(r)=C[\exp(-ar^2)+y\exp(-br^2)], \quad (2.20)$$

for which the integrations may be carried out explicitly. The result is

$$\eta=(\tfrac{3}{4})^6\left(\frac{9\alpha_3}{2\pi}\right)^{\frac{3}{2}}\frac{I(a,a)+2yI(a,b)+y^2I(b,b)}{J(a,a)+2yJ(a,b)+y^2J(b,b)}, \quad (2.21)$$

where

$$I(a,b)=[A^2+(5/4)A(a+b)+ab]^{-\frac{3}{2}}\exp\{-(3\bar{q}/4)^2\times[A+(a+b)/4]/[A^2+(5/4)A(a+b)+ab]\},$$
$$J(a,b)=(a+b)^{-\frac{3}{2}},$$

and $A=9\alpha_3/8=3/16R_3{}^2$. In order to select suitable values for a, b, and y, a variational calculation for $_\Lambda H^4$ was carried through with (2.20) as trial function; this led to the values $a=0.28$ fermi^{-2}, $b=0.044$ fermi^{-2}, and $y=0.36$, which led to the optimum U_3 of 880 Mev fermi^3, less than 3% above the true value of U_3 for this case. As discussed earlier,[8] there is much uncertainty in the value appropriate for R_3, especially as the H^3 core of $_\Lambda H^4$ is likely to be considerably distorted by the presence of the bound particle. With the choice $R_3=1.4$ fermis, expression (2.21) gives $\eta=0.24$; other choices of R_3 within the possibilities which seem allowable at present give values of η lying within ±10% of this value, a variation which is unimportant within the approximations of the present treatment.

At this point, it is of interest to consider the total π^- decay rate for $_\Lambda He^4$. For this system there is of course no two-body π^--mesonic decay and the internal energy E_n of the final nucleons (measured relative to $n+H^3$) is necessarily positive. The observed π^- momenta for $_\Lambda He^4$ decay all lie above 85 Mev/c and the use of the closure approximation appears quite adequate. The main difference from the case of $_\Lambda H^4$ is that the initial system contains two protons of opposing spins, and that the final states n contain three protons. The relation (2.12) must here be replaced by

$$\sum_n\psi_n(1,2,3;\cdots)\bar{\psi}_n(1',2',3';\cdots)=(1-P_{12}{}^xP_{12}{}^\sigma-P_{13}{}^xP_{13}{}^\sigma)(1-P_{23}{}^\sigma P_{23}{}^x)\times\delta_{11'}{}^\sigma\delta_{22'}{}^\sigma\delta_{33'}{}^\sigma\delta(\mathbf{r}_1-\mathbf{r}_1')\delta(\mathbf{r}_2-\mathbf{r}_2')\delta(\mathbf{r}_3-\mathbf{r}_3'). \quad (2.22)$$

Taking into account the symmetry of the initial state, the expression corresponding to (2.15) becomes

$$s^2(P_{12}^\sigma+P_{13}^\sigma)+\tfrac{1}{3}p^2(4-P_{12}^\sigma-P_{13}^\sigma), \quad (2.23)$$

where suffix 1 refers to the initial Λ particle, suffixes 2 and 3 to the initial protons. For initial protons in a singlet spin state, $P_{12}^\sigma+P_{13}^\sigma=1$, and the expressions for the total π^- decay rate, corresponding to (2.16) for ${}_\Lambda H^4$, become

$$[s^2+p^2(\bar{q}/q_\Lambda)^2](1-\eta)2\bar{q}/(1+\bar{\omega}_q/4m), \quad (2.24)$$

irrespective of the spin J. This decay rate is always suppressed from that for a free Λ particle, owing to the effect of the Pauli exclusion principle, represented by the factor $(1-\eta)$. The term η has generally been regarded as negligible for ${}_\Lambda$He hypernuclei[13,14]; the reasons why η is not completely negligible in this present case are twofold. Although the binding energy $B_\Lambda\sim 2.0$ Mev for the Λ particle is relatively low, the spatial distribution of the Λ particle in ${}_\Lambda H^4$ or ${}_\Lambda He^4$ actually overlaps quite strongly with that for a proton in the initial system, since the mean radius of the Λ density distribution is $\hbar/2(2m_{\rm red}B_\Lambda)^{\frac{1}{2}}\sim 1.7$ fermis, comparable with the radius of the nucleon distribution in the H^3 core. Also the momentum $\bar{q}\sim 100$ Mev/c of the recoil proton must be regarded as quite low, since the wavelength $\hbar/\bar{q}\sim 2$ fermis is a length comparable with the radius of H^3 or He^3. Generally the effect of the Pauli principle will be completely negligible only when $\bar{q}$ may be regarded as large (i.e., wavelength $\hbar/\bar{q}$ short relative to the size of the initial system of nucleons) or when the wave functions of the Λ particle and the protons in the initial state have relatively little overlap; these conditions will be met only when $B_\Lambda \ll 1$ Mev, as in ${}_\Lambda H^3$.

Discussion of the decay rates for the π^0-mesonic modes of ${}_\Lambda H^4$ and ${}_\Lambda He^4$ follows closely the above discussion for the π^--mesonic modes, in terms of the expression

$$H(\Lambda\to n+\pi^0)=s_0+p_0\boldsymbol{\sigma}\cdot\mathbf{q}/q_\Lambda, \quad (2.25)$$

for the elementary interaction. For ${}_\Lambda H^4$, this discussion will lead to an expression of the form (2.24) for the total decay rate to all π^0-mesonic decay modes, the main modification being the replacement of s and p by s_0 and p_0. For ${}_\Lambda He^4$, the decay probability for the two-body mode (2.2) is given by Eq. (2.7), after replacement of (s,p) by (s_0,p_0) in the expressions (2.5) for S, and with q given the value $q_0=145$ Mev/c. With the value $B_\Lambda=2.0\pm0.2$ Mev for ${}_\Lambda He^4$, the overlap integral $G(q_0,B_\Lambda)$ then has the value 0.67, corresponding to a sticking probability $F^2(q_0)=0.45$. Replacement of (s,p) by (s_0,p_0) and q by q_0 in expressions (2.16), also leads then to the total π^0 decay rate for ${}_\Lambda He^4$.

[13] H. Primakoff, Nuovo cimento, **3**, 1394 (1956).
[14] M. Ruderman and R. Karplus, Phys. Rev. **102**, 247 (1956).

3. DISCUSSION OF THE EXPERIMENTAL EVIDENCE

The data on mesic decay modes for ${}_\Lambda H^4$ will first be considered in terms of the above discussion, since the evidence on ${}_\Lambda H^4$ decay is considerably more extensive than that available for any other hypernucleus. In the world survey of Levi-Setti *et al.*,[9] there are listed 26 certain examples and one possible example of ${}_\Lambda H^4$ decay. Of these, there are 13 examples of the two-body mode (2.1), 5 of the mode π^-+p+H^3, 6 of the mode π^-+n+He^3, and one example of the mode $\pi^-+p+n+H^2$. These authors consider that, if there is any experimental bias between the observations of various ${}_\Lambda H^4$ decay modes, this would tend to favor the three-body and more complicated modes, since the two-body mode leads only to one heavily ionizing track, the corresponding pion being rather energetic and lightly ionizing.

With $J=1$ for ${}_\Lambda H^4$, the two-body ${}_\Lambda H^4$ decays would be expected to represent a proportion R_1 of all ${}_\Lambda H^4$ decay events leading to a π^- secondary, where, from (2.16b) and (2.7), R_1 is given by

$$R_1=\tfrac{1}{3}p^2(q/q_\Lambda)^3F^2(q)/(\bar{q}/q_\Lambda)\{s^2(1-\eta)+p^2(\bar{q}/q_\Lambda)^2 \times[1-\tfrac{1}{3}\eta+\tfrac{1}{3}((q/\bar{q})^3F^2(q)-F^2(\bar{q}))]\}. \quad (3.1)$$

The following values are appropriate: $F^2(q)=0.46$, $F^2(\bar{q})=0.55$, $\eta=0.24$, and $(q/q_\Lambda)^3=2.25$. The greatest value (3.1) can take consistent with (1.7) is 0.25. On this basis the expected number of two-body decay events expected in a batch of 27 ${}_\Lambda H^4$ π^--mesonic decays is no more than 6.7. The observed number of 13 is already about 2.5 standard deviations above this expectation, from which we conclude that it is rather improbable that $J=1$ should hold for ${}_\Lambda H^4$. This conclusion may be strengthened a little further on the basis of the Karplus-Ruderman argument[14] concerning the nonmesonic/mesonic ratio in hypernuclear decay; from this argument, the present evidence on this ratio (see below) indicated that it is very unlikely that the p channel should dominate the s channel in free Λ decay. With $s=p$, the expected number of two-body decay events in the ${}_\Lambda H^4$ data is reduced to 4.8, about four standard deviations from the observed number of events.

On the other hand, with $J=0$, the proportion R_0 of two-body decays among the π^- modes will be

$$R_0=s^2(q/q_\Lambda)F^2(q)/(\bar{q}/q_\Lambda)\{s^2[1+\eta+(q/\bar{q})F^2(q) -F^2(\bar{q})]+p^2(\bar{q}/q_\Lambda)^2(1-\eta)\}. \quad (3.2)$$

The greatest value of R_0 compatible with (1.7) is 0.42, leading to 11.4 as the expected number of two-body decays in the available batch of ${}_\Lambda H^4$ events, well in accord with the observation of 13 two-body decay events. With $p/s=1$, this ratio (3.2) takes the value 0.29, which corresponds to an expectation of 8 two-body events in these data, almost two standard deviations from the observed number. For this reason, we conclude that

$$0.45 \leqslant p/s \leqslant 1. \qquad (3.3)$$

A similar discussion can be given for the π^- modes of $_\Lambda H^3$ decay, as outlined in the appendix. At present, its comparison with the experimental data can only be rather inconclusive, for two reasons. The statistics on $_\Lambda H^3$ decay are less complete and less certain[9] than for $_\Lambda H^4$ decay. The clearly identified $_\Lambda H^3$ events consist of four examples of the $(\pi^- + He^3)$ mode, four of $(\pi^+ + p + He^3)$ and one example of the $(\pi^- + p + n + p)$ mode. In addition, there are four other definite examples of $_\Lambda$H decay, although the modes they represent are not uniquely identified; however the binding energies they give for interpretation as $_\Lambda H^4$ modes are not compatible with the known binding energy for $_\Lambda H^4$, and they are probably examples of $_\Lambda H^3$ three-body modes. There are also two other $_\Lambda$H events which allow interpretation either as $_\Lambda H^3$ or $_\Lambda H^4$ decay modes. The second difficulty is that B_Λ is not at all well known for $_\Lambda H^3$, whereas the expression for the sticking probability varies with binding energy B_Λ roughly as $B_\Lambda^{\frac{1}{2}}$. For the well-identified $_\Lambda H^3$ events, the mean B_Λ is 0.2 ± 0.5 Mev, while $B_\Lambda = 0.0 \pm 0.7$ Mev is the mean value for the events which are probably or possibly $_\Lambda H^3$ events. Also there is some uncertainty as to the correct value of Q_Λ, the energy release in free Λ decay (for which the value 37.2 ± 0.2 Mev is used at present), which means a corresponding uncertainty in values of B_Λ, an uncertainty which is obviously of much greater importance for calculations on $_\Lambda H^3$ than for the heavier hypernuclei, whose B_Λ values are large relative to this uncertainty. For these reasons, we shall not discuss $_\Lambda H^3$ decay in detail here.

Earlier, it had been suggested[15] that an estimate of p/s could be obtained from a knowledge of the nonmesonic/mesonic ratio Q for the decay modes of hypernuclei. This suggestion assumed the quantitative validity of the calculations of Ruderman and Karplus,[14] which were based on the hypothesis that the nonmesonic hypernuclear decay processes were dominated by the process of internal conversion by neighboring nucleons of the pion field generated by the normal pion decay interaction of the Λ particle. With this hypothesis, the ratio Q has interpretation as an internal conversion coefficient, whose value will be characteristic of the angular momentum l of the pion wave effective in the Λ decay interaction. The internal conversion ratio Q_l for given angular momentum l is then expected to vary with l as $Q_l = (q_c/q_\Lambda)^{2l} Q_0$ where q_c is the momentum transfer in the nonmesonic capture process and $(q_c/q_\Lambda)^2 \simeq 17$. For $_\Lambda$He hypernuclei, Ruderman and Karplus have given the estimate[16] $Q_0 = 1.1$; for heavy hypernuclei, in which the Λ particle spends almost all the time immersed in nuclear matter of standard density, the corresponding estimate is $Q_0 \simeq 50$. When the emission of both s- and p-channel pions becomes possible in Λ decay, the internal conversion coefficient to be expected will lie intermediate between Q_0 and Q_1. Since p-channel emission leads to final states of parity opposite to those reached through s-channel emission, the total decay rates for either mesonic or nonmesonic modes are simply a weighted average of the decay rates for the separate channels, weighted according to their relative intensities in free Λ decay; hence

$$Q = (Q_0 s^2 + Q_1 p^2)/(s^2 + p^2). \qquad (3.4)$$

With the range of values p/s allowed by (3.1), the values estimated for Q from this expression range from 4.1 to 10 for $_\Lambda$He hypernuclei, and from 170 to 420 for heavy hypernuclei.

These estimates are significantly larger than the nonmesonic/mesonic ratios recently obtained[17] in work by the Chicago group. For $_\Lambda$He hypernuclei, a value $Q = 1.2$ ($\pm 30\%$) has been obtained, after some allowance for the difficulty of distinguishing π^0-mesonic modes from the nonmesonic modes. For $Z \geqslant 3$ (conventionally regarded as representing "heavy hypernuclei"), the determination of Q is more difficult and at present it is only possible to place the upper limit $Q \leqslant 27 \pm 10$ on this ratio. Estimates of Q given by Schneps *et al.*[16] on the basis of much poorer statistics are quite compatible with these recent results. Both for $_\Lambda$He hypernuclei, and for the heavier hypernuclei $Z \geqslant 3$, these results lie at least a factor 4 below the estimates (3.4) based on the Ruderman-Karplus values for Q_0 and Q_1.

Quite a number of factors may be relevant in the explanation of this discrepancy between the experimental ratios Q and the estimates of Ruderman and Karplus. For $_\Lambda$He hypernuclei, the estimates given for the mean proton density in the neighborhood of the Λ particle have been very crude, being based on the use of the asymptotic form of the Λ wave function over the region of the (square well) nucleus. This leads to a considerable overestimate of the nonmesonic rate; the use of the more realistic wave functions calculated in reference 8 for $_\Lambda He^4$ and $_\Lambda He^5$ lead to a nonmesonic

[15] R. H. Dalitz, *Reports on Progress in Physics* (The Physical Society, London, 1957), Vol. 20, p. 297.

[16] Schneps, Fry, and Swami, Phys. Rev. **106**, 1062 (1957). It should be noted that F. Cerulus [Nuovo cimento **5**, 1685 (1957)] has recently given values of Q_0, Q_1, etc., for $_\Lambda$He which differ very considerably from those given above. The point of importance in Cerulus' calculation is that the internal conversion processes which proceed through the π^0 and the π^- channels of Λ decay are coherent. In taking this into account, he has however omitted a spin exchange factor for the final nucleons; when this is taken into account, the final results for Q_l for a Λ particle whose spin is randomly oriented relative to the initial nucleon spins (e.g., as in $_\Lambda He^5$) are essentially those of Karplus and Ruderman. On the other hand, for nuclei such as $_\Lambda H^4$, the Λ spin is not randomly oriented relative to the proton spin, the ground state having $J = 0$ according to the conclusions above. In such cases, the coherence effect pointed out by Cerulus (but with the corrected spin exchange factors) will have an important effect on Q_l and this is at present being investigated at Chicago by S. Eckstein and the author.

[17] E. Silverstein (private communication).

capture rate lower by a factor of about 5. In the data on heavy hypernuclei, those observed to undergo π^--mesonic decay have been predominantly $_\Lambda$Li and $_\Lambda$Be; for these hypernuclei it would be reasonable to expect that a more detailed calculation of Q_0 could lead to a value intermediate between $Q_0=1.1$ for $_\Lambda$He and $Q_0\sim 50$ for the heavy systems. Allowance for this would certainly go some way in the direction of removing the discrepancy between the observations and the Ruderman-Karplus results for the hypernuclei $Z\geqslant 3$.

An assumption made in the theoretical estimates of Q was that the Λ particle is essentially a point particle, its radius R being appreciably smaller than the wavelength of the pions concerned in the mesonic and nonmesonic decay processes. In fact, since the Λ particle has a strong interaction with K particles, it will have a K meson cloud about it of extent $\hbar/m_K c$, whereas the momentum transfer q_c in the capture process is 420 Mev/c, a momentum quite comparable with $m_K c=490$ Mev/c. It is therefore quite possible that the values of s and p effective in the nonmesonic process may be significantly smaller than those effective at the lower momentum $q\sim 100$ Mev/c of free Λ decay.

It has now been realized also that there are other possible mechanisms which can contribute to the nonmesonic capture process. Treiman[18] has pointed out that the universal Fermi coupling

$$\Lambda+p\rightarrow n+p, \tag{3.5}$$

proposed by Feynman and Gell-Mann[19] as the elementary interaction giving rise to free Λ decay, through the sequence

$$\Lambda\rightarrow \bar{p}+n+p\rightarrow \pi^-+p, \tag{3.6}$$

contributes not only to the indirect process of internal conversion, but itself represents a nonmesonic capture mechanism. As the spin-dependence of (3.5) is quite different from that resulting from the internal conversion process, the capture process (3.5) interferes relatively little with the Ruderman-Karplus terms and therefore generally increases the nonmesonic rate, further increasing the experimental discrepancy. Another possibility is that the particle may transfer two pions to the neighboring nucleons in the nonmesonic capture process. A special mechanism of this kind has been discussed by Ferrari and Fonda,[20]

$$\Lambda+\mathfrak{N}\rightarrow(\Sigma+\pi)+\mathfrak{N}\rightarrow(\mathfrak{N}+\pi+\pi)+\mathfrak{N}\rightarrow\mathfrak{N}+\mathfrak{N}, \tag{3.7}$$

but there are also others which do not involve the Σ particles. These more complicated processes will generally give amplitudes which interfere with the amplitudes for the simpler mechanisms, and a quantitative estimate for the net nonmesonic capture rate is thereby made correspondingly more difficult. The mechanisms of nonmesonic decay discussed in this paragraph do not represent processes of "internal conversion," but have physically distinct origins. However the importance of the Ruderman-Karplus discussion of the internal conversion process lies in the validity of its qualitative conclusions. If p-channel emission were dominant in Λ decay, this argument is sufficient to establish that the value of Q should be large relative to Q_0 and to the experimental results, for this large value could be avoided only if these other mechanisms added terms which had the same spin dependence but which cancelled strongly with the internal conversion amplitude; and such a complete cancellation would represent a very improbable situation. For this reason, in view of the low values obtained experimentally for Q, it appears that the Ruderman-Karplus argument is still sufficient to establish that the Λ-particle spin is $\frac{1}{2}$ and that the p channel is not dominant in free Λ decay.

It is of interest to remark here, with Sakurai[21] and Marshak and Sudarshan,[22] that the $(V-A)$ universal Fermi coupling (3.3) leads, in the lowest approximation of perturbation theory, to a unique form for $H(\Lambda\rightarrow p+\pi^-)$, namely

$$(\bar{\psi}_\Lambda\gamma_\mu(1+\gamma_5)\psi_P)\frac{\partial\phi}{\partial x_\mu}\rightarrow H=H_s\left(1+\frac{m_\Lambda+m}{m_\Lambda-m}\frac{\boldsymbol{\sigma}\cdot\mathbf{q}}{2m}\right) \tag{3.8}$$

in the nonrelativistic limit. This corresponds to $p/s=+0.64$ and $\alpha=+0.91$, so that (3.8) is compatible with the experimental evidence both in magnitude [see Eq. (3.3)] and in sign. However, at present there seems no reason to believe that pionic corrections should not modify the form of (3.8) quite strongly.

Finally, the π^0-mesonic modes may be discussed briefly. For $_\Lambda He^4$, the two-body mode (2.2) should now be expected to be quite prominent relative to the π^--mesonic modes. With $J=0$, this branching ratio is estimated by

$$s_0^2(q_0/q_\Lambda)F^2(q_0)/(s^2+p^2)(1-\eta), \tag{3.9}$$

with $q_0/q_\Lambda=1.45$ and $F^2(q_0)=0.45$. With $s_0/s=1/\sqrt{2}$, the expectation from the $\Delta T=\frac{1}{2}$ rule, this ratio takes values from 0.36 to 0.21 as p/s runs from 0.45 to 1. In these light hypernuclei, the π^0/π^- ratio can be modified quite strongly from the value 0.5 for free decay by the effect of the Pauli principle. In the decay of $_\Lambda He^4$ this ratio has the form

$$\frac{\pi^0}{\pi^-}=\frac{s_0^2[1+\eta+(q_0/\bar{q})F^2(q_0)-F^2(\bar{q})]+p_0^2(1-\eta)}{(s^2+p^2)(1-\eta)}, \tag{3.10a}$$

with values from 0.82 to 0.69 as p/s runs from 0.45 to 1. For $_\Lambda H^4$ decay, the ratio is modified in the opposite

[18] S. B. Treiman (private communication).
[19] R. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
[20] F. Ferrari and L. Fonda, Nuovo cimento **7**, 320 (1958).
[21] J. J. Sakurai, Phys. Rev. **108**, 491 (1957).
[22] E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. **109**, 1861 (1958).

direction,

$$\frac{\pi^0}{\pi^-}=\frac{(s_0^2+p_0^2)(1-\eta)}{s^2[1+\eta+(q/\bar{q})F^2(q)-F^2(\bar{q})]+p^2(1-\eta)}, \quad (3.10b)$$

with values from 0.31 to 0.37 as p/s runs 0.45 through 1. For ${}_\Lambda He^5$ and ${}_\Lambda H^3$, the π^0/π^- ratio is again 0.5, apart from minor Coulomb effects. It may prove possible to examine this difference of the (π^0/π^-) ratio in ${}_\Lambda H^4$ and ${}_\Lambda He^4$ decay by observations on these hypernuclei following specific production reactions, such as the K^-+He^4 reaction.[8]

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APPENDIX. π^- DECAY MODES OF ${}_\Lambda H^3$

For the $T=0$ ground state of ${}_\Lambda H^3$, two spin values, $J=\frac{3}{2}$ or $\frac{1}{2}$, are possible according as the Λ-nucleon interaction favors the parallel or antiparallel spin configuration. The above work leads to the expectation that $J=\frac{1}{2}$ should hold for the ground state.

With $J=\frac{3}{2}$, the two-body decay mode

$${}_\Lambda H^3 \rightarrow He^3+\pi^- \quad (A1)$$

can proceed only through the p channel of Λ decay. From this it follows that the angular distribution of π^- emission from ${}_\Lambda H^3$ in this mode can have the form $(a+\cos^2\theta)$, but that there can be no up-down asymmetry relative to the ${}_\Lambda H^3$ production plane in this π^- emission. Following the methods discussed above for the two-body modes, the expected proportion of ${}_\Lambda H^3$ decays giving π^- emission which lead to the two-body mode becomes

$$\tfrac{1}{3}p^2(q/q_\Lambda)^3F^2(q)/(\bar{q}/q_\Lambda)\{s^2(1-\eta)+p^2(\bar{q}/q_\Lambda)^2 \times[1-\tfrac{1}{3}\eta+\tfrac{1}{3}((q/\bar{q})^3F^2(q)-F^2(\bar{q}))]\}, \quad (A2)$$

where $q=113$ Mev/c, $F(q)$ denotes the overlap (space) integral

$$F(q)=\int\psi_{He^3}(p,p,n)\sin(qR)/(qR)\psi_{{}_\Lambda H^3}(\Lambda,p,n), \quad (A3)$$

with $R=(2r_{\Lambda n}^2+2r_{\Lambda p}^2-r_{np}^2)^{\frac{1}{2}}/3$, and η is the (space) exchange integral

$$\eta=\int\psi_{{}_\Lambda H^3}(p,\Lambda,n)[\sin(qr_{\Lambda p})/(qr_{\Lambda p})]\psi_{{}_\Lambda H^3}(\Lambda,p,n). \quad (A4)$$

For sufficiently small B_Λ, F and η will become proportional to $(B_\Lambda)^{\frac{1}{4}}$ and $(B_\Lambda)^{\frac{1}{2}}$, respectively; however, owing to the large size of the deuteron core, this simple dependence on B_Λ will not hold until B_Λ is smaller than 0.1 Mev. No numerical estimate of η has yet been made, but it seems an adequate approximation to neglect η, since the effect of the Pauli principle should be quite unimportant in such a lightly bound structure as ${}_\Lambda H^3$, where $q\gg(2m_{red}B_\Lambda)^{\frac{1}{2}}$. $F(q)$ has been evaluated for ${}_\Lambda H^3$ only for $q=0$ and only for one choice of B_Λ; this evaluation used the ${}_\Lambda H^3$ wave function of reference 8 [see Eq. (2.12) there] with the parameters[23] found appropriate to $B_\Lambda=0.25$ Mev and a Λ-nucleon interaction of range $\hbar/2m_\pi c$ and a He^3 wave function of the form $\exp[-\lambda(r_{12}+r_{23}+r_{31})]$ with $\lambda=0.4$ fermi^{-1}, and obtained the result $F(0)=0.70$ for this case. A rough estimate of the reduction from this value which follows with the use of $q=113$ Mev/c was then made, leading to a sticking probability $F^2(q)\simeq0.35$ for $B_\Lambda=0.25$ Mev.

With $J=\frac{1}{2}$, the two-body decay mode can proceed through both s and p channel of Λ decay. The amplitude for the two-body decay takes the form

$$H({}_\Lambda H^3\rightarrow He^3+\pi^-)=-\tfrac{1}{2}\sqrt{3}F(q)\{s-p\boldsymbol{\sigma}\cdot\mathbf{q}/3q_\Lambda\}, \quad (A5)$$

where $\boldsymbol{\sigma}$ denotes the Pauli spin vector of the three-particle system. The only angular distribution which is possible for the two-body mode is now an up-down asymmetry with distribution

$$1-P({}_\Lambda H^3)\frac{2sp}{3(s^2+p^2q^2/9q_\Lambda^2)}\cos\theta_\pi, \quad (A6)$$

for ${}_\Lambda H^3$ particles of polarization $P({}_\Lambda H^3)$, θ_π being the angle of π^- emission relative to this ${}_\Lambda H^3$ polarization. The proportion of two-body decays among the π^- modes for ${}_\Lambda H^3$ decay is given by

$$\tfrac{3}{4}F^2(q)[s^2+\tfrac{1}{9}p^2(q/q_\Lambda)^2](q/q_\Lambda)/(\bar{q}/q_\Lambda) \times\{s^2[1+\tfrac{1}{2}\eta+\tfrac{3}{4}(q/\bar{q})F^2(q)-\tfrac{3}{4}F^2(\bar{q})] +p^2(\bar{q}/q_\Lambda)^2[1-\tfrac{5}{6}\eta+\tfrac{1}{12}(q/\bar{q})^3F^2(q)-\tfrac{1}{12}F^2(\bar{q})]\}. \quad (A7)$$

For $B_\Lambda=0.25$ Mev, our above estimate of F^2 leads to values for this ratio from 0.26 to 0.17 as p/s runs from 0.45 to 1; these proportions are quite compatible with the observation of 4 two-body decays in a total of 14 ${}_\Lambda H^3$ decay events.

[23] B. W. Downs and R. H. Dalitz (to be published).