FEW BODY HYPERNUCLEAR SYSTEMS: WEAK DECAYS

SEP 20 1987

Carl B. Dover

Brookhaven National Laboratory
Upton NY, USA 11973

BNL--40210

DE87 014920

Abstract

The experimental and theoretical situation regarding mesonic and non-mesonic decays of light hypernuclei is reviewed. Although some models give reasonable results for pionic decays as well as the total weak decay rate, no existing approach explains, even qualitatively, the observed spin-isospin dependence of $\Lambda N \rightarrow NN$ non-mesonic weak decays.

Invited Talk

XIth European Conference on Few-Body Physics
Fontevraud, France
August 31 - September 5, 1987

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

MASTER

FEW BODY HYPERNUCLEAR SYSTEMS: WEAK DECAYS

Carl B. Dover

Brookhaven National Laboratory
Upton NY, USA 11973

Abstract

The experimental and theoretical situation regarding mesonic and non-mesonic decays of light hypernuclei is reviewed. Although some models give reasonable results for pionic decays as well as the total weak decay rate, no existing approach explains, even qualitatively, the observed spin-isospin dependence of $\Lambda N \rightarrow NN$ non-mesonic weak decays.

Introduction

It has long been realized that light hypernuclei offer a unique laboratory for the study of the non-mesonic weak decay process $\Lambda N \rightarrow NN$. The light systems ${}^3_\Lambda\text{H}$, ${}^4_\Lambda\text{H}$, ${}^4_\Lambda\text{He}$ and ${}^5_\Lambda\text{He}$ provide nuclear cores of different spin and isospin, so that one can derive information on the characteristic spin-isospin dependence of $\Lambda N \rightarrow NN$ conversion. For light systems, the pionic decay modes ($\Lambda \rightarrow p\pi^-, n\pi^0$) are comparable in rate to the non-mesonic modes, whereas for heavier systems ($A > 12$) the latter are dominant (due to strong Pauli blocking effects for the low momentum recoiling nucleon in mesonic decay). Existing calculations for the decay widths use simplified wave functions for the 3, 4, and 5-body hypernuclear systems. In view of the large experimental uncertainties, the use of more sophisticated wave functions has not been necessary. However, this situation could change in the future if more precise data become available.

We first review briefly the experimental situation; new data on ${}^5_\Lambda\text{He}$ are available from an experiment at Brookhaven. We consider the implications of the new results for the spin-isospin dependence of the $\Lambda N \rightarrow NN$ process. Various theoretical approaches to the problem are discussed. Although some of these are consistent with the total weak decay rates of hypernuclei, none are able to account for more interesting features such as the spin-isospin dependence.

The Experimental Situation

The total weak decay width Γ_{TOT} of a hypernucleus is given as a sum

$$\Gamma_{\text{TOT}} = 1/\tau = \Gamma_{\pi^-} + \Gamma_{\pi^0} + \Gamma_{\text{NM}}^p + \Gamma_{\text{NM}}^n \quad (1)$$

of partial widths $\{\Gamma_{\pi^-}, \Gamma_{\pi^0}, \Gamma_{\text{NM}}^p, \Gamma_{\text{NM}}^n\}$ corresponding to $\Lambda \rightarrow p\pi^-, \Lambda \rightarrow n\pi^0, \Lambda p \rightarrow np$ and $\Lambda n \rightarrow nn$, respectively. The widths Γ_{π} involve processes in which the π is

This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

detected in the final state, as in free space Λ decay, whereas $\Gamma_{NM}^{p,n}$ results from strangeness changing ($\Delta S = 1$) reactions related to $\Delta S = 0$ four fermion weak interactions in the $NN \rightarrow NN$ sector. Further, we define

$$\begin{aligned}\Gamma_{NM} &= \Gamma_{NM}^p + \Gamma_{NM}^n \\ Q^- &= \Gamma_{NM} / \Gamma_{\pi^-} \\ R_0 &= \Gamma_{\pi^0} / \Gamma_{\pi^-} \\ n &= \Gamma_{NM}^n / \Gamma_{NM} .\end{aligned}\tag{2}$$

Now if the rate for $\Lambda N \rightarrow NN$ conversion in spin state $S = 0, 1$ is defined as R_{NS} , then the spin dependence of the process is revealed by considering the ratios

$$\begin{aligned}\gamma_{nm} &= \Gamma_{NM}({}^4_\Lambda\text{He}) / \Gamma_{NM}({}^4_\Lambda\text{H}) \\ \gamma_{np}^4 &= \Gamma_{NM}^n({}^4_\Lambda\text{He}) / \Gamma_{NM}^p({}^4_\Lambda\text{He}) \\ \gamma_{np}^5 &= \Gamma_{NM}^n({}^5_\Lambda\text{He}) / \Gamma_{NM}^p({}^5_\Lambda\text{He}) .\end{aligned}\tag{3}$$

In terms of the R_{NS} values, we find

$$\begin{aligned}\gamma_{nm} &= (3R_{p1} + R_{p0} + 2R_{n0}) / (3R_{n1} + R_{n0} + 2R_{p0}) \\ \gamma_{np}^4 &= 2R_{n0} / (3R_{p1} + R_{p0}) \\ \gamma_{np}^5 &= (3R_{n1} + R_{n0}) / (3R_{p1} + R_{p0})\end{aligned}\tag{4}$$

or the inverse

$$\begin{aligned}R_{p0}/R_{p1} &= 3(1 + \gamma_{np}^4 - \gamma_{nm}\gamma_{np}^5) / D \\ R_{n0}/R_{p1} &= 3\gamma_{nm}\gamma_{np}^4 / D \\ R_{n1}/R_{p1} &= \gamma_{nm}(2\gamma_{np}^5 - \gamma_{np}^4) / D ,\end{aligned}\tag{5}$$

with $D = \gamma_{nm}(2 + \gamma_{np}^5) - \gamma_{np}^4 - 1$. Furthermore, the ratio

$$\alpha = \Gamma_{NM}^n({}^4_\Lambda\text{H}) / \Gamma_{NM}^p({}^4_\Lambda\text{H}) = (3R_{n1} + R_{n0}) / 2R_{p0}\tag{6}$$

is not independent, and is given by

$$\alpha = \gamma_{nm}\gamma_{np}^5 / (1 + \gamma_{np}^4 - \gamma_{nm}\gamma_{np}^5) .\tag{7}$$

For these light systems ($A \leq 5$), one can safely assume that the two-body ΛN system is in a state of relative orbital angular momentum $L = 0$. Further, we assume that final state interactions (for instance, nucleon charge exchange) are negligible, so that the measured ratios γ reflect the spin-isospin dependence of the primary process.

The $\Delta I = 1/2$ rule is satisfied for the free $\Lambda \rightarrow N\pi$ decay to a very good approximation (here I is isotopic spin, and the $N\pi$ final state is dominantly $I = 1/2$). For $\Lambda N \rightarrow NN$, the situation is less clear. Here, $\Delta I = 1/2$ implies $R_{n0} = 2R_{p0}$ and $R_{n1} \leq 2R_{p1}$, hence

$$\gamma_{np}^5 = (2(1 + \gamma_{np}^4) - \gamma_{nm}\gamma_{np}^4) / 2\gamma_{nm}\tag{8a}$$

$$\gamma_{nm} \geq 2(1 + \gamma_{np}^4) / (4 + \gamma_{np}^4) .\tag{8b}$$

Now consider the experimental data. Block *et al.* [Ref. 1] give

$$\gamma_{np}^4 \approx 0.45 \pm 0.17 . \quad (9)$$

To calculate γ_{nm} , we use the relation

$$\gamma_{nm} = \frac{\tau \left(\frac{4}{\Lambda} \text{H} \right)}{\tau \left(\frac{4}{\Lambda} \text{He} \right)} \cdot \frac{Q^- \left(\frac{4}{\Lambda} \text{He} \right)}{Q^- \left(\frac{4}{\Lambda} \text{H} \right)} \cdot \frac{(1 + R_0 + Q^-)_{\frac{4}{\Lambda} \text{H}}}{(1 + R_0 + Q^-)_{\frac{4}{\Lambda} \text{He}}} , \quad (10)$$

and the measured values (units 10^{-10} sec)

$$\begin{aligned} \tau \left(\frac{4}{\Lambda} \text{H} \right) &\approx \begin{cases} 1.8^{+2.5}_{-0.7} & [2] \\ 2.0 \pm 0.8 & [3] \end{cases} \\ \tau \left(\frac{4}{\Lambda} \text{He} \right) &\approx 2.3^{+2.3}_{-1.3} \quad [4] \\ Q^- \left(\frac{4}{\Lambda} \text{He} \right) &\approx \begin{cases} 0.52 \pm 0.10 & [1] \\ 0.70 \pm 0.19 & [5] \end{cases} \\ Q^- \left(\frac{4}{\Lambda} \text{H} \right) &\approx 0.26 \pm 0.13 \quad [1] \\ (R_0)_{\frac{4}{\Lambda} \text{He}} &\approx 2.49 \pm 0.34 \quad [1] \end{aligned} \quad (11)$$

The ratio R_0 has not been directly measured for $\frac{4}{\Lambda} \text{H}$. However, the $\Delta I = 1/2$ rule gives the constraint [Ref. 6]

$$(R_0)_{\frac{4}{\Lambda} \text{H}} (R_0)_{\frac{4}{\Lambda} \text{He}} = 1/4 , \quad (12)$$

and hence $(R_0)_{\frac{4}{\Lambda} \text{H}} \approx 1/10$. Since $(R_0)_{\frac{4}{\Lambda} \text{H}}$ is small, our estimate of γ_{nm} will change little if moderate deviations from the $\Delta I = 1/2$ rule are permitted. We finally obtain

$$\gamma_{nm} \approx 0.7 \pm 0.15 . \quad (13)$$

Since Eq. (8b) implies $\gamma_{nm} \geq 0.65$, we see that Eq. (13) is consistent with the $\Delta I = 1/2$ rule. The value (13) also implies that one is close to the limit where $R_{n1} = 2R_{p1}$ i.e. isospin $I = 1$ NN final states dominate the $\Lambda N \rightarrow NN$ process. This was the situation before the measurement of γ_{np}^5 : the definitive early work is due to Dalitz and his collaborators [6-9], and a review can be found in Ref. 10.

If we use the $\Delta I = 1/2$ rule (Eq. (8a)) and the values for γ_{np}^4 and γ_{nm} from Eqs. (9) and (13), we would predict

$$\gamma_{np}^5 \approx 1.85 , \quad (14)$$

where the recent $\frac{5}{\Lambda} \text{He}$ measurement at the Brookhaven AGS by a Carnegie Mellon - Brookhaven - Houston - New Mexico - Vassar collaboration yielded [Ref. 11]

$$\gamma_{np}^5 \approx 1.30^{+0.65}_{-1.6} , \quad (15)$$

in rough agreement with the range of values 0.77-2.0 found by Miller *et al* [Ref. 12] and the limit $\gamma_{np}^5 \geq 1.4$ given by Kenyon *et al.* [Ref. 13]. Since Eqs. (14) and (15) are consistent within one standard deviation, one might leave it at that. Note, however,

that if the central values given by Eqs. (9), (13), and (15) are taken at face value and inserted in Eq. (5), we would obtain

$$R_{p0}/R_{p1} \approx 1.9, \quad R_{n0}/R_{p1} \approx 1.1, \quad R_{n1}/R_{p1} \approx 1.75, \quad (16)$$

i.e. the $\Lambda N \rightarrow NN$ process would have a large spin singlet ($S = 0$) component, unlike previous analyses [7-10], which yield dominance of the spin triplet ($S = 1$). As we see later, a large $S = 0$ contribution to the $\Lambda N \rightarrow NN$ reaction does not arise in any current model. Equation (16) also implies a substantial violation of the $\Delta I = 1/2$ rule, since

$$|\gamma_{np}^5(\text{exp}) - \gamma_{np}^5(\Delta I = 1/2)|/\gamma_{np}^5(\text{exp}) \approx 0.4. \quad (17)$$

The scenario implied by Eqs. (16) and (17) seems rather unlikely. However, better data are required before one can decisively test the $\Delta I = 1/2$ rule. Note that by using values $\gamma_{nm} = 0.8$, $\gamma_{np}^4 = 0.45$, $\gamma_{np}^5 = 1.6$, each well within the error bars, we retain the $\Delta I = 1/2$ rule, and get

$$R_{p0}/R_{p1} \approx 0.36, \quad R_{n0}/R_{p1} \approx 0.76, \quad R_{n1}/R_{p1} \approx 1.54, \quad (18)$$

i.e. the $S = 1$, $I = 1$ channel is the most important, but the others are not negligible. Equation (18) may be compared to the analysis of Dover and Walker [Ref. 10], who give

$$R_{p0}/R_{p1} \approx 0.39, \quad R_{n0}/R_{p1} \approx 0.67, \quad R_{n1}/R_{p1} \approx 2. \quad (19)$$

Here, the $S = 1$, $I = 1$ rate is relatively even stronger than in Eq. (18). Equation (19) implies $\gamma_{nm} \approx 0.64$, $\gamma_{np}^4 \approx 0.4$, and $\gamma_{np}^5 \approx 1.94$, the latter value at the top end of the error bar in Eq. (15). The analysis of Ref. 10 did not include γ_{np}^5 , but used instead the ratio $\gamma_{np}^H = (\Gamma_{NM}^n/\Gamma_{NM}^p)_H$ for heavy emulsion hypernuclei ($A \approx 40 - 100$). Various values have been reported for this quantity:

$$\gamma_{np}^H \approx \begin{cases} 1.5 - 9 & [14] \\ 5.7 & [15] \\ 9 & [16] \end{cases} \quad (20)$$

If we now assume that the heavy emulsion hypernuclei have $N \approx Z$, then we can take nuclear matter spin-isospin weights to obtain

$$\gamma_{np}^H \approx (3R_{n1} + R_{n0}) / (3R_{p1} + R_{p0}) \quad (21)$$

and hence, without assuming the $\Delta I = 1/2$ rule, we have

$$\frac{R_{n0}}{R_{n1}} = \frac{(3\gamma_{np}^4/\gamma_{np}^H)}{(2 - \gamma_{np}^4/\gamma_{np}^H)}. \quad (22)$$

If we assume $\gamma_{np}^H \approx 2.3$, as in Ref. 10, we obtain $R_{n0}/R_{n1} \approx 1/3$, as in Eq. (19). On the other hand, we note that ${}^5_\Lambda\text{He}$ has the same spin-isospin weights as nuclear matter, so we expect

$$\gamma_{np}^5 \approx \gamma_{np}^H. \quad (23)$$

The problem of consistency of the various measurements is now clear, since Eq. (15) disagrees with Eq. (20), except possibly for Ref. 14.

From the preceding discussion, we see the key role of the ${}^4_\Lambda\text{He}$ measurement in determining the spin dependence, since γ_{np}^4 would vanish in the absence of $S = 0$, $I = 1$ $\Lambda N \rightarrow NN$ conversion. The fact that γ_{np} is much larger in ${}^5_\Lambda\text{He}$ and heavy hypernuclei than in ${}^4_\Lambda\text{He}$ is due to the strong spin dependence of $\Lambda N \rightarrow NN$, with $S = 1$ favored. The ratio α in ${}^4_\Lambda\text{H}$ (see Eq. (7)) would be useful to measure as a consistency check on the presumed smallness of the $S = 0$ $\Lambda N \rightarrow NN$ process.

The ratio of neutron to proton induced non-mesonic decay for ${}^{12}_\Lambda\text{C}$ was also recently measured [Ref. 11]. The result is

$$\gamma_{np}^{12} = \left(\Gamma_{NM}^n / \Gamma_{NM}^p \right)_{^{12}_\Lambda\text{C}} \approx 1.36^{+1.09}_{-0.84}. \quad (24)$$

Thus to a good approximation, we have

$$\gamma_{np}^{12} \approx \gamma_{np}^5. \quad (25)$$

Note that Eq. (24) is only marginally consistent with the value $\gamma_{np} \approx 0.6$ cited in Ref. 14 for a combined ${}_\Lambda\text{B}$, ${}_\Lambda\text{C}$, ${}_\Lambda\text{N}$ sample of events. In Ref. 11, it is also noted that

$$\frac{\Gamma_{NM}({}^{12}_\Lambda\text{C})}{\Gamma_{NM}({}^5_\Lambda\text{He})} \approx \frac{11}{4}, \quad (26)$$

i.e. for light systems, the total non-mesonic decay width is proportional to the number of nucleons. For heavier systems, one expects a saturation effect due to the diminished overlap of higher nucleon orbitals with the $1s$ Λ . One sees this effect in the data, i.e.

$$\frac{\Gamma_{NM}({}^{238}_\Lambda\text{U})}{237} \approx \frac{1}{10} \frac{\Gamma_{NM}({}^5_\Lambda\text{He})}{4} \quad (27)$$

using the data for ${}^{238}_\Lambda\text{U}$ of Bocquet *et al.* [Ref. 17].

Non-Mesonic Weak Decays: Theoretical Aspects

Several reviews of the theory of $\Lambda N \rightarrow NN$ decays in hypernuclei have already appeared [18-20], so we can be brief. We focus on the rather striking discrepancies between the model calculations to date [21-26] and the data, particularly as regards the Γ^n/Γ^p ratios.

The $\Lambda N \rightarrow NN$ process in free space is characterized by a momentum transfer (or c.m. momentum of the final state nucleons for an initial ΛN system at rest) of $q \approx 420\text{MeV}/c$, corresponding to a distance scale of order 0.5 fm. Thus we expect the $\Lambda N \rightarrow NN$ rate to be sensitive to short range phenomena, inviting a description in terms of quark degrees of freedom (or, in exchange models, the inclusion of heavy mesons).

The total non-mesonic decay rate Γ_{NM} may be written as

$$\Gamma_{NM} = 4\pi \sum \int \frac{d^3\vec{q}}{(2\pi)^3} \int \frac{d^3\vec{Q}}{(2\pi)^3} \delta(q^2/2m_N + Q^2/4m_N - m_\Lambda + m_N + B_\Lambda + B_N) \\ | \langle \psi(A-2) \chi_{NN} | V_{tr} | \psi({}^A_\Lambda Z) \rangle |^2 \quad (28)$$

where $\vec{q}$ and $\vec{Q}$ are the relative and total momentum of the final NN pair, $\psi(\Lambda Z)$ is the ground state wave function of the hypernucleus, $\psi(A-2)$ is the wave function for the recoiling $A-2$ nucleon system (usually only the ground state is included here), χ_{NN} is the wave function of the NN pair in the final state ($e^{i\vec{q}\cdot\vec{r}} e^{i\vec{Q}\cdot\vec{R}}$ in plane wave approximation), and $\sum$ indicates a sum/average over final/initial spins. The longest range part of the transition potential V_{tr} for the $\Lambda N \rightarrow NN$ process is due to one pion exchange, for which

$$V_{\pi} = V_{\pi,c}^{\text{PC}} + V_{\pi,t}^{\text{PC}} + V_{\pi}^{\text{PV}} \quad (29)$$

where $V_{\pi,c}^{\text{PC}}$ and $V_{\pi,t}^{\text{PC}}$ are central and tensor terms which give rise to parity conserving (PC) $\Lambda N \rightarrow NN$ transitions ($^1S_0 \rightarrow ^1S_0$, $^3S_1 \rightarrow ^3S_1$ for $V_{\pi,c}^{\text{PC}}$ and $^3S_1 \rightarrow ^3D_1$ for $V_{\pi,t}^{\text{PC}}$), and V_{π}^{PV} leads to parity violating (PV) transitions ($^1S_0 \rightarrow ^3P_0$, $^3S_1 \rightarrow ^3P_1$, $^3S_1 \rightarrow ^1P_1$). We have

$$\begin{aligned} V_{\pi,c}^{\text{PC}} &= V_{0\pi} \phi_c(x) \vec{\sigma}_1 \cdot \vec{\sigma}_2 \vec{\tau}_1 \cdot \vec{\tau}_2 \\ V_{\pi,t}^{\text{PC}} &= V_{0\pi} \phi_t(x) S_{12} \vec{\tau}_1 \cdot \vec{\tau}_2 \\ V_{\pi}^{\text{PV}} &= i\xi V_{0\pi} \phi_{\text{PV}}(x) \vec{\sigma}_1 \cdot \hat{r} \vec{\tau}_1 \cdot \vec{\tau}_2 \end{aligned} \quad (30)$$

where

$$\begin{aligned} V_{0\pi} &= -g_{\omega} g_{\pi} \lambda \mu_{\pi}^3 / 48 \pi m_N M, \\ \xi &= -6M / \lambda \mu_{\pi}, \\ \phi_c(x) &= e^{-x}/x, \\ \phi_t(x) &= (1 + 3/x + 3/x^2) \phi_c(x), \\ \phi_{\text{PV}}(x) &= (1 + 1/x) \phi_c(x), \\ x &= \mu_{\pi} r, \\ M &= (m_N + m_{\Lambda})/2, \end{aligned}$$

$g_{\pi}^2/4\pi = 14$ is the πNN strong coupling constant, and $\{g_{\omega}, \lambda\} = \{2.4 \times 10^{-7}, -6.9\}$ are the weak coupling constants fitted to the free space $\Lambda \rightarrow N\pi$ decay, using an effective weak Hamiltonian $H_w = g_w \bar{\psi}_N (1 + \lambda \gamma_5) \bar{\pi} \psi_{\Lambda} \bar{\phi}_{\pi}$. Numerically, we have $V_{0\pi} = 0.39$ eV and $\xi = 6.43$. Note that since ξ is large, the potential V_{π}^{PV} is in fact stronger than $V_{\pi,t}^{\text{PC}}$ for $r \geq 0.7$ fm, so one might expect comparable rates for PV and PC transitions. This is not the case for two reasons: (i) the spin matrix element for PC transitions (ex. $\langle ^3S_1 | S_{12} | ^3D_1 \rangle = 2\sqrt{2}$) is larger than that for PV transitions (ex. $\langle ^3S_1 (m_s = 0) | \vec{\sigma}_1 \cdot \hat{r} | ^1P_1 \rangle = 1$), and (ii) the PC and PV transitions involve different orbital angular momentum transfer ΔL through the radial matrix element

$$I_{\Delta L} = \int_0^{\infty} r^2 dr j_{\Delta L}(qr) V_{\pi}^{\text{PC,PV}}(r) u_{N\Lambda}(r) \quad (31)$$

where $u_{N\Lambda}(r)$ is the initial state ΛN relative wave function. Roughly speaking, $I_{\Delta L}$ is maximum when $\Delta L \approx qR$, where R is a range characteristic of the product $V_{\pi}(r) u_{N\Lambda}(r)$. For $R \approx 1$ fm, we have $\Delta L \approx 2$, i.e. the $^3S_1 \rightarrow ^3D_1$ transition induced by S_{12} is well

TABLE

Widths Γ for transitions $\Lambda N \rightarrow NN$ from $L = 0$ initial states, in units of Γ_Λ (free), from Ref. 19. For final states, the notation is $^{2I+1,2S+1}L_J$.

Transition	π only	all mesons
$^1S_0 \rightarrow ^{31}S_0$	0.01	0.001
$^1S_0 \rightarrow ^{33}P_0$	0.156	0.018
$^3S_1 \rightarrow ^{11}P_1$	0.468	0.110
$^3S_1 \rightarrow ^{13}S_1$	0.01	0.202
$^3S_1 \rightarrow ^{33}P_1$	0.312	0.456
$^3S_1 \rightarrow ^{13}D_1$	2.93	0.444

matched kinematically. Thus we can understand the large width $\Gamma(^3S_1 \rightarrow ^{13}D_1)$ in the table. Note, however, that the rates are very sensitive to short range correlations in $u_{NA}(r)$ and the cutoff used for $V_\pi(r)$.

The results in the table are due to de la Torre, Donoghue, Dubach and Holstein [22], as reported by Dubach [19,20]. This is the most complete meson exchange calculation, and includes $\{\eta, \rho, \omega, K, K^*\}$ exchange in addition to the pion. The processes included are shown in Fig. 1. All the meson exchange calculations [19-22, 25, 26] impose the $\Delta I = 1/2$ rule by treating the Λ as an isospin 1/2 spurion. In Ref. 22, $SU(6)_w$ symmetry and PCAC are used to obtain the weak coupling vertices for the heavy mesons (the uniqueness of this procedure has been questioned by McKellar [18]).

Fig. 1. Meson exchange processes included by Dubach and collaborators [19, 20, 22] in a calculation of the non-mesonic $\Lambda N \rightarrow NN$ decay. The crosses correspond to weak transition vertices, and the dots refer to strong vertices. $SU(3)$ and $SU(6)_w$ symmetries and PCAC are used to constrain the couplings.

In the case of π exchange (without correlations in the ΛN or NN wave functions), one has the relations $\Gamma(^1S_0 \rightarrow ^{31}S_0) = \Gamma(^3S_1 \rightarrow ^{13}S_1)$, $\Gamma(^3S_1 \rightarrow ^{33}P_1) = 2\Gamma(^1S_0 \rightarrow ^{33}P_0)$ and $2\Gamma(^3S_1 \rightarrow ^{11}P_1) = 3\Gamma(^3S_1 \rightarrow ^{33}P_1)$, as seen explicitly in the " π only" column of the table. The first of these relations is qualitatively modified by correlations: $\Gamma(^1S_0 \rightarrow ^{31}S_0)$ is sharply reduced by omitting the short range part of the integral I_0 of Eq. (31), while $\Gamma(^3S_1 \rightarrow ^{13}S_1)$ is enhanced by the operation of a strong NN tensor final

state interaction, which gives rise to a second order process [$^3S_1 \rightarrow ^3D_1(\text{weak}) + ^3D_1 \rightarrow ^3S_1(\text{strong})$].

We now use the formulae

$$R_{n0} = 2R_{p0} = \Gamma(^1S_0 \rightarrow ^3S_1) + \Gamma(^1S_0 \rightarrow ^3P_0) \quad (32)$$

$$R_{n1} = \Gamma(^3S_1 \rightarrow ^3P_1)$$

$$R_{p1} = [\Gamma(^3S_1 \rightarrow ^3S_1) + \Gamma(^3S_1 \rightarrow ^3D_1) + \Gamma(^3S_1 \rightarrow ^1P_1) + \Gamma(^3S_1 \rightarrow ^3P_1)] / 2$$

and Eq. (4) to obtain $\gamma_{nm} = 4.78$, $\gamma_{np}^4 = 0.055$ and $\gamma_{np}^5 = 0.193$ for the “ π only” case (without correlations). These results are completely at odds with the experimental data of Eqs. (9), (13), and (15); i.e. γ_{nm} is much too large, while $\gamma_{np}^{4,5}$ are too small. The problem lies with the dominance of the $^3S_1 \rightarrow ^3D_1$ transition in the “ π only” model. Since the final state isospin for this transition is zero due to the restrictions of the Pauli principle, it does not contribute to the $\Lambda n \rightarrow nn$ rate, which is observed to be large experimentally. Including initial and final state correlations (as per Refs. [19, 20]) in a “ π only” model does not significantly help the situation: one predicts $\gamma_{nm} = 6.52$, $\gamma_{np}^4 = 0.027$, $\gamma_{np}^5 = 0.144$, still qualitatively disagreeing with the data.

Some improvement is obtained when the heavy meson exchanges are included. According to Dubach [19, 20], the K exchange contribution is particularly important. The effect is to enhance the PV $^3S_1 \rightarrow ^3P_1$ transition and suppress the PC $^3S_1 \rightarrow ^3D_1$ transition. This serves to increase the $(\Lambda n \rightarrow nn) / (\Lambda p \rightarrow np)$ ratio, as required by experiment. Using the entries in the “all meson” column of the table, one obtains $R_{n1}/R_{p1} = 0.75$, $R_{p0}/R_{p1} = 0.016$, $R_{n0}/R_{p1} = 0.032$ or

$$\gamma_{nm} \approx 1.33, \quad \gamma_{np}^4 \approx 0.02, \quad \gamma_{np}^5 \approx 0.76. \quad (33)$$

Note that

$$\frac{\Gamma_{\Lambda p \rightarrow np}}{\Gamma_{\Lambda n \rightarrow nn}} = \frac{1}{\gamma_{np}^5} \approx 1.31 \quad (34)$$

when all mesons are included, which differs from the value 2.9 cited by Dubach [19, 20]. This is due to a factor of 3 omitted [19, 20] in the definition of the $I = 1$ decay width $\Gamma_{I=1}$, i.e., the correct formulae are [27]:

$$\frac{\Gamma_{\Lambda p \rightarrow np}}{\Gamma_{\Lambda n \rightarrow nn}} = \frac{3\Gamma_{I=0} + \Gamma_{I=1}}{2\Gamma_{I=1}} \quad (35)$$

$$\Gamma_{I=0} = \Gamma(^3S_1 \rightarrow ^1P_1) + \Gamma(^3S_1 \rightarrow ^3S_1) + \Gamma(^3S_1 \rightarrow ^3D_1)$$

$$\Gamma_{I=1} = \Gamma(^1S_0 \rightarrow ^3S_1) + \Gamma(^1S_0 \rightarrow ^3P_0) + 3\Gamma(^3S_1 \rightarrow ^3P_1).$$

Even though the inclusion of heavy meson exchange augments the $^3S_1 \rightarrow ^3P_1$ rate and decreases that for $^3S_1 \rightarrow ^3D_1$, in the direction to improve agreement with experiment, it does not go nearly far enough. For instance the 1S_0 transitions are predicted [19, 20] to be negligible ($\gamma_{np}^4 \approx 0$), whereas the experimental value $\gamma_{np}^4 \approx 1/2$ clearly indicates the presence of spin singlet $\Lambda N \rightarrow NN$ conversion. Similarly, the ratio γ_{np}^5 of Eq. (33) is still too small, indicating an incorrect ratio of PV to PC widths. From

$$\Gamma_{I=0}/\Gamma_{I=1} = (2 - \gamma_{np}^5) / 3\gamma_{np}^5, \quad (36)$$

we see that $\Gamma_{I=1}$ dominates as γ_{np}^5 approaches 2, as suggested by the data, whereas the meson exchange model gives $\Gamma_{I=0}/\Gamma_{I=1} \approx 0.56$. Equivalently, since the ${}^3S_1 \rightarrow {}^{13}D_1$ (PC) and ${}^3S_1 \rightarrow {}^{33}P_1$ (PV) transitions are largest ("all mesons" included), we have

$$\Gamma_{PC}/\Gamma_{PV} \approx \Gamma({}^3S_1 \rightarrow {}^{13}D_1) / \Gamma({}^3S_1 \rightarrow {}^{33}P_1) \approx (2 - \gamma_{np}^5) / \gamma_{np}^5. \quad (37)$$

The data suggest that this ratio is less than 1/2, while the meson theory gives a result of order unity.

The non-mesonic rates in ${}^4_\Lambda\text{H}$, ${}^4_\Lambda\text{He}$ and ${}^5_\Lambda\text{He}$ have been evaluated by Takeuchi, Takaki and Bando [26], using Eq. (28), with $\Psi(A-2)$ restricted to the ground state, and $\Psi({}^A_\Lambda Z)$ written as a product $\Psi(A-1)\phi_\Lambda$ of a core wave function $\Psi(A-1)$, taken to be a Gaussian, and a Λ wave function ϕ_Λ obtained from a folded Λ -core potential. Here, only $\pi + \rho$ exchange were included in V_{tr} , as in Ref. 21, so the ${}^3S_1 \rightarrow {}^{13}D_1$ transition is again dominant. The resulting value of $\Gamma_{NM}({}^4_\Lambda\text{H})$ is then much too small, since this transition does not enter. No proper 4-body calculations of the ${}^4_\Lambda\text{H}$ or ${}^4_\Lambda\text{He}$ decays have been done. Once one has an adequate theory of the decay transition operator V_{tr} , it may be important to perform these calculations.

McKellar [18] has discussed in detail other technical problems associated with meson exchange models, and also suggests several additional mechanisms which should be included, such as $\Lambda N \rightarrow \Sigma N \rightarrow NN$ second order processes, and $\Lambda NN \rightarrow \Sigma NN \rightarrow NNN$ three body contributions. These are perhaps significant, but are not likely to remedy the rather qualitative failings of meson exchange models. Another suggestion is that relative ΛN p-states might play a role in p-shell hypernuclei. For $L = 1$, one expects that $\Lambda N \rightarrow NN$ conversion should be less dependent on short range effects, and hence π exchange should assert itself relatively more strongly. In this case, we expect an important ${}^3P_2 \rightarrow {}^{33}F_2$ $\Delta L = 2$ transition mediated by S_{12} . On the basis of this, Dubach [20] predicts a decrease of almost a factor of 2 in the ratio $\Gamma_{\Lambda p \rightarrow np} / \Gamma_{\Lambda n \rightarrow nn}$ as one passes from ${}^5_\Lambda\text{He}$ ($L = 0$ ΛN pairs only) to ${}^{12}_\Lambda\text{C}$, (mixture of $L = 0, 1$ ΛN pairs). There is no evidence for this effect in the data, i.e.

$$\left(\Gamma_{\Lambda p \rightarrow np} / \Gamma_{\Lambda n \rightarrow nn} \right)_{{}^5_\Lambda\text{He}} \approx \left(\Gamma_{\Lambda p \rightarrow np} / \Gamma_{\Lambda n \rightarrow nn} \right)_{{}^{12}_\Lambda\text{C}} \quad (38)$$

according to Szymanski [11].

Since the $\Lambda N \rightarrow NN$ process is very sensitive to heavy meson exchange, it may be more desirable and economical to describe the short range aspects in the quark model. This has been attempted by Kisslinger and collaborators [23, 24] in the context of a hybrid model in which V_{tr} is taken to be π exchange for $r \geq r_0 \approx 1$ fm, and is calculated for $r < r_0$ using explicit six quark wave functions and perturbative W^- exchange as illustrated in Fig. 2. For the interior six quark region, they assume the validity of quark counting rules and obtain $\Gamma_{\Lambda p \rightarrow np}^{6q} / \Gamma_{\Lambda n \rightarrow nn}^{6q} = 3/2$, whereas for the π exchange ($r \geq r_0$) region, the result is $\Gamma_{\Lambda p \rightarrow np}^\pi / \Gamma_{\Lambda n \rightarrow nn}^\pi \approx 5.3$. Since the overall rate is dominated by the exterior region, they obtain a result

$$\Gamma_{\Lambda p \rightarrow np} / \Gamma_{\Lambda n \rightarrow nn} \approx 2.7, \quad (39)$$

Fig. 2. Typical quark diagrams leading to the non-mesonic $\Lambda N \rightarrow NN$ process.

or $\gamma_{np}^5 \approx 0.37$, far below the experimental value of Eq. (15). Thus, the simplest quark approach does not solve the qualitative problem of how to obtain a sufficiently large rate for the $PV \ ^3S_1 \rightarrow \ ^3P_1$ transition. Part of the problem may be that the quark counting rule is not valid in general in the presence of a spin-dependent transition operator, if one takes the spin-flavor correlations of the Λ and N wave functions into account. One also suspects that non-perturbative effects, not taken into account in Fig. 2, could be important. One would like to formulate a model in which the transition from short to long range dynamics is continuous. The model of refs. [23, 24], in which one passes abruptly from a "compound nucleus" state for $r \leq 1$ fm to a picture for $r \geq 1$ fm in which the Λ and N retain their identity and quark antisymmetrization effects are totally ignored, does not meet this criterion.

Pionic Weak Decays of Hypernuclei

The classic calculations of pionic decays of $A \leq 5$ hypernuclei are due to Dalitz [9, 28], and there exists a recent attempt for $^5_\Lambda\text{He}$ [29]. There has been no effort to redo these calculations for $A = 3, 4$ using realistic wave functions. As better data become available, such an effort may become warranted.

In the p-shell, there are now extensive calculations of Γ_{π^0} and Γ_{π^-} due to Bando and collaborators [30, 31]. They use realistic density-dependent Hartree-Fock wave functions and take into account distortion and absorption effects due to pion final state interactions. The pion decay rate probes nucleon occupation probabilities in the hypernuclear ground state wave function. Neglecting short range correlations, one finds a suppression

factor of the decay width in the nucleus (relative to Γ_Λ (free)) of

$$S_\pi = 1 - 1/2 \sum_{nlj} N_{nlj} \eta_{nlj}$$

$$\eta_{nlj} = |\langle \phi_\Lambda(r) | j_l(qr) | \phi_{nlj}(r) \rangle|^2 \quad (40)$$

where N_{nlj} denotes the occupation number for nucleons in orbit $\{nlj\}$ and q is the momentum release in the decay. For $A \sim 100$, Eq. (40) gives $\Gamma_{\pi^-}/\Gamma_\Lambda \sim 10^{-3}$ whereas the data of Lagnaux *et al.* [14] suggest $\Gamma_{\pi^-}/\Gamma_\Lambda \sim (1-3) \cdot 10^{-2}$, an order of magnitude larger. Bando and Takaki [30] propose to cure this problem by including short range correlations (via the usual “wound integral” κ) and pion final state interactions via an absorption parameter a . Thus, Eq. (40) is replaced by

$$S_\pi = a - \left(\frac{1-\kappa}{2} \right) \sum_{nlj} N_{nlj} \tilde{\eta}_{nlj} \quad (41)$$

where $\tilde{\eta}_{nlj}$ is calculated with pion distorted waves rather than $j_l(qr)$. For heavy hypernuclei ($A \geq 100$), Bando and Takaki [30] find a saturation effect of $\Gamma_{\pi^-}/\Gamma_\Lambda$; they obtain $S_\pi \simeq a\kappa$ and $\Gamma_{\pi^-}/\Gamma_\Lambda \sim 10^{-2}$ in agreement with the old data (Lagnaux *et al.* [14]). For $^{12}_\Lambda\text{C}$, using this approach, Motoba *et al.* [31] obtain $\Gamma_{\pi^-}/\Gamma_\Lambda = 0.066$, in good agreement with the experimental value of $0.06^{+0.08}_{-0.05}$ cited in ref. [11]. The pion rate is enhanced somewhat due to final state interactions [31], but not as dramatically as predicted by Oset and Salcedo [25].

As one passes from $^7_\Lambda\text{Li}$ to $^{15}_\Lambda\text{N}$, the summed pion rate $(\Gamma_{\pi^-} + \Gamma_{\pi^0})/\Gamma_\Lambda$ drops from about 0.42 to 0.11 [31], reflecting the increased efficiency of Pauli blocking. There are dramatic variations in the ratio $\Gamma_{\pi^-}/\Gamma_{\pi^0}$ which reflect the particular J values of the hypernucleus and the $(A-1)$ daughter nucleus, as well as the dominant spin-isospin character ($\Delta I = 1/2$, non-spin-flip) of the free space $\Lambda \rightarrow N\pi$ amplitude. For instance, in $^{12}_\Lambda\text{C}$, Motoba *et al.* [31] find $\Gamma_{\pi^-}/\Gamma_{\pi^0} \approx 0.69$, far from the free space value $\Gamma_{\pi^-}/\Gamma_{\pi^0} = 2$. Long ago, it was recognized that pionic decay rates were useful in determining ground state spins of hypernuclei, for instance $^4_\Lambda\text{H}$ [9].

The theory of pionic decays of light hypernuclei, unlike the situation for non-mesonic decays, is in relatively good shape. For Γ_π , one is anchored to a decay amplitude of well known spin-isospin structure in free space, and the π final state interactions are also more or less reliably calculable from phenomenological optical potentials for low momentum π -nucleus scattering and absorption. The nucleon occupation numbers N_{nlj} which enter can be estimated reasonably well from Hartree-Fock calculations.

Summary

The study of the weak decays of the light s-shell hypernuclei $^3_\Lambda\text{H}$, $^4_\Lambda\text{H}$, $^4_\Lambda\text{He}$ and $^5_\Lambda\text{He}$ offers the unique possibility of unraveling the spin-isospin structure of the non-mesonic $\Lambda N \rightarrow NN$ conversion-process. For such decays, which involve substantial momentum release ($q \approx 420\text{MeV}/c$), short range dynamics is crucial: one pion exchange, by itself, is in qualitative disagreement with experiment. The addition of heavy meson exchanges,

although improving the situation somewhat, fails to build up sufficient parity-violating and spin singlet transition strength. The simplest form of the quark model, which applies counting rules at short distances, also fails to improve the situation. Although spin-isospin averaged decay rates are reasonably well reproduced with existing models, the understanding of the ratio of $\Lambda n \rightarrow nn$ and $\Lambda p \rightarrow np$ widths remains an open problem. Eventually, if one could study the decay of polarized hypernuclei (formed, for instance, via the (π^+, K^+) or $(e, e'K^+)$ reactions), terms involving the interference of parity conserving (ex. ${}^3S_1 \rightarrow {}^1D_1$) and parity violating (ex. $({}^3S_1 \rightarrow {}^3P_1) \Lambda N \rightarrow NN$ transitions might be measurable. Such data, as well as more precise partial rate measurements for ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$, would provide strong constraints on the theory.

References

1. Block, M. M. *et al.* : *Proc. Intern. Conf. on Hyperfragments*, St. Cergue (1963), CERN Report 64-1, January 1964, p. 63.
2. Prem, R. J., Steinberg, P. H. : *Phys. Rev.* **136**, 1803 (1964).
3. Murphy, C. T. : *Proc. Intern. Conf. on Hypernuclear Physics*, Argonne (1969), p. 438.
4. Phillips, R. E., Schneps, J. : *Phys. Rev.* **180**, 1309 (1969).
5. McKenzie, J. : in ref. [3].
6. Dalitz, R. H., Liu L. : *Phys. Rev.* **116**, 1312 (1959).
7. Dalitz, R. H., von Hippel, F. : *Nuovo Cim.* **34**, 799 (1964).
8. Block, M. M., Dalitz, R. H. : *Phys. Rev. Lett.* **11**, 96 (1963).
9. Dalitz, R. H. : *Hypernuclear Physics, Proc. Intern. School of Physics "Enrico Fermi" Varenna* (1966), Course 38 (Academic Press, NY, 1967), pp. 89-131.
10. Dover, C. B., Walker, G. E. : *Phys. Reports* **89**, 1-177 (1982); see especially pp 148-156 for a review of hypernuclear weak decays.
11. Szymanski, J. J. : "The weak decay of lambda hypernuclei" PhD thesis, Carnegie Mellon University, April 1987;
Grace, R., *et al.* : *Phys. Rev. Lett.* **55**, 1055 (1985).
12. Miller, H. G., Holland, M. W., Roalsvig, J. P., Sorenson, R. G. : *Phys. Rev.* **167**, 922 (1968).
13. Kenyon, I. R., *et al.* : *Nuovo Cim.* **30**, 1365 (1963).
14. Lagnaux, J. P. *et al.* : *Nucl. Phys.* **60**, 97 (1964).
15. Ganguli, S. N., Swami, M. S. : *Proc. Indian Acad. Sci.* **66A**, 77 (1967).
16. Cuevas, J., *et al.* : *Nucl. Phys.* **B1**, 411 (1967).
17. Bocquet, J. P. *et al.* : *Phys. Lett.* **B182**, 146 (1986).
18. McKellar, B. H. J. : *Proc. of 1986 INS Intern. Symposium on Hypernuclear Physics* Tokyo, Japan, August 1986, Eds. H. Bando, O. Hashimoto and K. Ogawa: Institute for Nuclear Study, University of Tokyo (1986), pp. 146-159.

19. Dubach, J. : *Proc. of Intern. Conf. on Intersections Between Particle and Nuclear Physics*, Lake Louise, Canada, May 1986, Ed. D. F. Geesaman, AIP Conf. Proc. No. 150, American Institute of Physics, NY (1986), pp. 946-951.
20. Dubach, J. : *Weak and Electromagnetic Interactions in Nuclei, Proc. Intern. Symposium*, Heidelberg, FRG, July 1986, Ed. H. V. Klapdor: Springer Verlag, Berlin (1986), pp. 576-582.
21. McKellar, B. H. J., Gibson, B. F. : *Phys. Rev.* C30, 322 (1984).
22. de la Torre, L., Donoghue, J. F., Dubach, J., Holstein, B. R. : to be published.
23. Cheung, C.-Y., Heddle, D. P., Kisslinger, L. S. : *Phys. Rev.* C27, 335 (1983).
24. Heddle, D. P., Kisslinger, L. S. : *Phys. Rev.* C33, 608 (1986) and preprint (1987).
25. Oset, E., Salcedo, L. L. : *Nucl. Phys.* A443, 704 (1985).
26. Takeuchi, K., Takaki, H., Bando, H. : *Prog. Theor. Phys.* 73, 841 (1985).
27. I would like to acknowledge discussions with Avraham Gal on this point. The factor of 3 in the definition of $\Gamma_{J=1}$ is clearly necessary in order to recover the correct result $\Gamma_{\Lambda p \rightarrow np} / \Gamma_{\Lambda n \rightarrow nn} = 2$ in the limit where 1S_0 widths vanish and 3S_1 widths are all equal.
28. Dalitz, R. H. : *Phys. Rev.* 112, 605 (1958).
29. Kurihara, Y., Akaishi, Y., Tanaka, H. : *Phys. Rev.* C31, 971 (1985).
30. Bando, H., Takaki, H. : *Prog. Theor. Phys.* 72, 106 (1984) and *Phys. Lett.* 150B, 409 (1985).
31. Motoba, T., Itonaga, K., Bando, H. : Osaka University preprint OUAM 87-6-3 (1987).