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An Historical Overview of the Importance of the Weak Decay of Hypernuclei

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Weak decay of hypernuclei, first cousin to the β-decay of conventional, nonstrange nuclei, was initially observed in the 1950s. Pionic decay rates have proven a challenge – to reconcile nuclear decay rates with that of free Λ decay. Pauli blocking of the decay nucleon plays an important role. Nonmesonic decay provides our only practical means of exploring the four-fermion, strangeness-changing $N\Lambda \to NN$ weak interaction. The $N\Lambda\rho$ vertex can be investigated in no other way. The large momentum transfer in the nonmesonic decay process suggests a means to probe short distance aspects of the interaction, possibly revealing baryon substructure effects. Whether the ΔI=1/2 rule, which governs free Λ decay, also applies to the nonmesonic decay process remains an open question. The free Λ does not decay by emission of a π^+; the π^+ decay of ${}^4_\Lambda$He is a puzzle. Finally, the weak decay of strangeness -2 hypernuclei is an important topic, because the pionic decay process is central to current efforts to seek and identify $\Lambda\Lambda$ hypernuclei.

1. Introduction

Let me begin by paying tribute to Dick Dalitz and Don Davis. Prof. Dalitz led the thinking of theorists in this area for many years. Prof. Davis and his collaborators gave us much of our early data. Without these two gentlemen – as well as others such as our conference chair – one would not have a field of hypernuclear physics.

In free space the Λ decays via

$$\Lambda \to p + \pi^- \ + \ 38\,\text{MeV}\ (64\%), \qquad \Lambda \to \text{n} + \pi^0 \ + \ 41\,\text{MeV}\ (36\%),$$

with a lifetime $\tau_\Lambda = 1/\Gamma_\Lambda = (1/\Gamma_{\pi^-} + 1/\Gamma_{\pi^0})^{-1} = 2.63 \times 10^{-10}s$. This ΔS=1 transition can occur theoretically with a change in isospin of $\Delta\text{I} = 1/2$ or $\Delta\text{I} = 3/2$. An s quark converts into a u (or d) quark via exchange of a charged W boson. The V-A Hamiltonian description of the decay can be written as

$$H_{V-A} = \frac{G_F}{\sqrt{2}} \sin\theta_C \cos\theta_C O_{V-A} + \text{ c.c.}, \quad O_{V-A} = \bar{u}\gamma_\mu(1-\gamma_5)s\bar{d}\gamma^\mu(1-\gamma_5)u \ , \tag{1}$$

where θ_C is the Cabibbo angle. Such a model implies equal strength for $\Delta\text{I} = 1/2$ and $\Delta\text{I} = 3/2$ transitions. However, experimentally one finds the $\Delta\text{I} = 1/2$ amplitude to be

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enhanced by an order of magnitude over the $\Delta I = 3/2$ amplitude. The practical result is

$$\Gamma(\Lambda \to p\pi^-)/\Gamma(\Lambda \to n\pi^0) \simeq 1.9 \,, \quad (2)$$

or approximately 2, which is the square of the ratio of C-G coefficients in the $I = \frac{1}{2}$ amplitude

$$|1/2, -1/2> = \sqrt{2/3}|p\pi^- > - \sqrt{1/3}|n\pi^0 > . \quad (3)$$

There is no universal explanation for this $\Delta I = 1/2$ rule that governs free hyperon decay as well as CP violation in kaon decay.

Hypernuclei along with their weak decay were discovered in 1952 [1]. Key questions regarding hypernuclear weak decay include: (1) How should the weak interactions of baryons be described when embedded in a strongly interacting many-baryon system? (2) Does the empirical $\Delta I = 1/2$ rule, which governs the $Y \to N\pi$ mesonic decay, characterize the $N\Lambda \to NN$ transition of nonmesonic decay? (3) Does the internal structure of baryons play a significant role in the decay of hypernuclei? Quarks and gluons are assumed to be the fundamental degrees of freedom in describing hadrons, but are they the relevant degrees of freedom in the realm of nonperturbative QCD? Electrons and photons are fundamental degrees of freedom in condensed matter, but BCS pairs are the relevant degrees of freedom in a Type I superconductor.

2. Mesonic Weak Decay of Hypernuclei

Hypernuclei provide a laboratory for studying the medium modifications of hyperon weak decay. The free Λ decays into a nucleon and a pion, the nucleon having a momentum of approximately 100 MeV/c or about 5 MeV of kinetic energy [2]. Even neglecting the binding, a Λ at rest in nuclear matter cannot decay into a nucleon of this momentum, because the nucleon Fermi momentum is $k_F \simeq 270$ MeV/c. That is, the process is Pauli blocked. (The effect of Pauli blocking in medium and heavy hypernuclei has received significant attention – see the discussion by Oset.) Mesonic weak decay should be significant only in the light hypernuclei [3]:

$$\Gamma_{\pi^-}/\Gamma_\Lambda \simeq 1/2 \quad \text{for } {}^5_\Lambda\text{He}\,,$$

while

$$\Gamma_{\pi^-}/\Gamma_\Lambda \simeq 1/10 \quad \text{for } A = 11,\ 12\,.$$

Therefore, let us look more closely at the lightest hypernucleus, the hypertriton.

From ^{3}H investigations [4] it is well known that obtaining the correct binding energy [$B({}^3\text{H}) = 8.48$ MeV] in a model calculation leads to a correct description of the low energy physical observables such as the *r.m.s.* radius and the Coulomb energy in ^{3}He. Because ${}^3_\Lambda$H is weakly bound [$B_\Lambda({}^3_\Lambda\text{H}) = 130$ keV], one has a Λ-deuteron molecular-like halo structure in which the distance of the Λ from the *c.m.* of the deuteron core is $7\times$ that of the NN separation in the deuteron. The large size is not typical of hypernuclei, but ${}^3_\Lambda$H is one hypernucleus whose lifetime we can calculate. One expects $\tau({}^3_\Lambda\text{H}) \simeq \tau_\Lambda$. Experimentally one observes $\tau({}^3_\Lambda\text{H}) = 2.2^{+1.02}_{-0.53} \times 10^{-10}$s and $\tau({}^3_\Lambda\text{H}) = 2.64^{+0.92}_{-0.54} \times 10^{-10}$s [5]. Because the overlap of the ^{3}H and $^3_\Lambda$H wave functions is not one (their sizes are very different) one is not surprised by the small ratio of $\Gamma(\pi^- + ^3\text{He})/\Gamma(\text{all } \pi^- \text{ modes}) = 0.30 \pm 0.07$ [5] and 0.39 ± 0.07 [6]. The small Λ separation energy in the hypertriton implies a large breakup probability in the weak decay. From the photodisintegration of ^{3}H, one knows that the nd channel absorbs most of the strength from the I $= \frac{1}{2}$ nnp channel, so that the nd channel should be the dominant continuum channel in $^3_\Lambda$H mesonic decay. Detailed calculations [7] confirm this. Thus, the mesonic decay of light hypernuclei is reasonably well understood and should provide an excellent testing ground for model wave functions. Note, because $B_\Lambda(^3_\Lambda\text{H})$ is so small (and the corresponding Λd separation so large), one anticipates that the nonmesonic decay mode should be negligible.

3. Nonmesonic Weak Decay

Within the nuclear medium new weak decay channels open: $n\Lambda \to nn + 176$ MeV and $p\Lambda \to pn + 176$ MeV. The large energy release ($k \simeq 400$ MeV/c) in these nonmesonic modes serves as the signature for the $N\Lambda \to NN$ strangeness-changing weak decay. The nonmesonic decay channel opens as rapidly as the increase in nuclear density with A will permit. Nonmesonic decay provides a practical means of investigating the four-fermion, strangeness-changing $N\Lambda \to NN$ weak interaction. The $N\Lambda\rho$ vertex can be explored by no other means.

The total nonmesonic decay rate $\Gamma_{nm} = \Gamma_{nn} + \Gamma_{pn}$ is reasonably well accounted for in model calculations [8]. It is the the ratio Γ_{nn}/Γ_{nm} which has been a puzzle. As Don Davis will confirm, the emulsion measurements show $0.6 \leq \Gamma_{nn}/\Gamma_{nm} \leq 0.9$ [9]. However, most theoretical calculations have been based upon a simple impulse approximation philosophy in which the $^3S_1$ transitions dominate over the $^1S_0$ transition (as is found for π and ρ components of a model Hamiltonian [10]) but do not contribute to the $n\Lambda \to nn$ process. Thus, the $n\Lambda \to nn$ branch of nonmesonic decay is estimated to be relatively small: $\Gamma_{nn} \ll \Gamma_{pn}$. McKellar [11] showed in a schematic model that including I $= \frac{1}{2}$ exchanges, such as K exchange, can enhance the $n\Lambda \to nn$ rate due to A_0 interference effects:

$$\frac{\Gamma_{nn}}{\Gamma_{np}} = \left|\frac{A_0 + A_1}{A_0 - 3A_1}\right|^2 . \tag{4}$$

However, resolution of the Γ_{nn}/Γ_{pn} puzzle more likely lies in the strong NN final-state interactions following the weak decay transition.

In the $N\Lambda \to NN$ weak decay process, one deposits significant momentum within the interior of the nucleus. The two energetic nucleons will certainly interact with the other nucleons in the nucleus as they emerge. In particular, final-state charge exchange is a process that could unitize the Γ_{nn}/Γ_{np} ratio. Recall that in πN scattering near the (3,3) resonance

$$R = \sigma_n^+/\sigma_n^- = 1/3 . \tag{5}$$

Therefore, one predicts a similar 1/3 ratio for $^{12}C(\pi^+, \pi^+ n)^{11}C/^{12}C(\pi^-, \pi^- n)^{11}C$ in impulse approximation. However, the measured ratio is $\geq 2/3$, the result of NN charge-exchange final-state interactions. Assuming for simplicity that the impulse approximation rate for $n\Lambda \to nn$ is much less than that for $p\Lambda \to pn$ and that the charge-exchange probability is P_x, then the measured nonmesonic decay rate ratio would be

$$\Gamma_{nn}/\Gamma_{pn} \to \frac{(p\Lambda \to pn) \times \mathrm{P_x}}{(p\Lambda \to pn) \times (1 - \mathrm{P_x})} .$$

A small value of P_x would alter Γ_{nn}/Γ_{pn} significantly while leaving the total rate, Γ_{nm}, unmodified.

One can experimentally test whether the $\Delta \mathrm{I} = 1/2$ rule is satisfied in the nonmesonic decay of s-shell hypernuclei. Following the exposition of Dalitz and collaborators [12], one can schematically define rates for $N\Lambda \to NN$ conversion in the spin state $S = 0, 1$ as R_{NS}, where N is a proton or a neutron and R corresponds to the spin and charge for a specific hypernucleus:

$$\Gamma_{nm}({}^3_\Lambda\mathrm{H}) = \frac{\rho_3}{8}(R_{p1} + 3R_{p0} + R_{n1} + 3R_{n0}) \quad (6)$$

$$\Gamma_{nm}({}^4_\Lambda\mathrm{H}) = \frac{\rho_{4-}}{6}(2R_{p0} + 3R_{n1} + R_{n0}) \quad (7)$$

$$\Gamma_{nm}({}^4_\Lambda\mathrm{He}) = \frac{\rho_{4+}}{6}(3R_{p1} + R_{p0} + 2R_{n0}) \quad (8)$$

$$\Gamma_{nm}({}^5_\Lambda\mathrm{He}) = \frac{\rho_5}{8}(3R_{p1} + R_{p0} + 3R_{n1} + R_{n0}) . \quad (9)$$

The ρ factors represent the mean nucleon density of the Λ in each hypernucleus. One can demonstrate that the ratio R_{n0}/R_{p0}, which should be 2 if the $\Delta \mathrm{I} = 1/2$ rule holds, can be determined by measuring Γ_{nn}/Γ_{pn} for ${}^4_\Lambda\mathrm{H}$, because the ratio has already been measured for ${}^4_\Lambda\mathrm{He}$ and ${}^5_\Lambda\mathrm{He}$. [See the discussion by Gill of experiment E931 at the BNL AGS.]

4. π^+ Decay

We know that $\Gamma({}^4_\Lambda\mathrm{He}\to \pi^- X)/\Gamma({}^4_\Lambda\mathrm{He}\to \pi^0 X) < 1$, because in the π^- decay of ${}^4_\Lambda\mathrm{He}$ the proton pair fill the $1s$ shell. That is, no ${}^4_\Lambda\mathrm{He}$ analog decay into $\pi^- + {}^4\mathrm{He}$ is possible. Even more interesting is the observation that the ratio

$$R = \frac{({}^4_\Lambda\mathrm{He} \to \pi^+\mathrm{X})}{({}^4_\Lambda\mathrm{He} \to \pi^-\mathrm{X})} , \ \mathrm{X} = \text{all modes} , \quad (10)$$

is non zero even though the free Λ has no π^+ decay mode. In fact, one observes $R = 4.3 \pm 1.7\%$ [13]. Dalitz and von Hipple [14] investigated explanations in terms of free Σ^+ ($\to n\pi^+$) decay as well as pion charge exchange following $\Lambda(\to p\pi^0)$ decay. Cieply and Gal [15] recently provided a detailed study of the pion change-exchange contribution, demonstrating that it alone might contribute as much as $\sim 1\%$ to the branching ratio.

The π^+ kinetic energy spectra for

(a) ${}^4_\Lambda\mathrm{He} \to \pi^- + p + {}^3\mathrm{He}$,

(b) ${}^4_\Lambda\mathrm{He} \to \pi^+ + n + {}^3\mathrm{H}$,

(c) ${}^4_\Lambda\mathrm{H} \to \pi^- + n + {}^3\mathrm{He}$,

(d) ${}^{4}_{\Lambda}\mathrm{H} \rightarrow \pi^- + p + {}^{3}\mathrm{H}$,

were summarized by Sacton [16]. As discussed in Ref. [17], the π^- decays are similar in shape to a fermi-averaged two-body π^- decay of a free Λ. In contrast, the flat character of the π^+ decay (*b*) spectrum resembles that of a three-body decay. The isotropic nature of the π^+ angular distribution is also characteristic of a three-body decay. This led to a suggestion [17] that the mechanism may be that of the decay of a virtual Σ^+ from the mixing of $N\Lambda \leftrightarrow N\Sigma$ within the hypernucleus. That is, the decay is of the $N\Sigma^+ \rightarrow N\pi^+ n$ type involving a virtual Σ^+ in the hypernucleus. This mechanism depends crucially upon the nuclear core of the Λ hypernucleus having more protons than neutrons, to permit an excess of $p\Lambda \rightarrow n\Sigma^+$ transition strength. It would be automatically ruled out by the observation of a π^+ branching ratio of more than 1% in ${}^{4}_{\Lambda}\mathrm{H}$ or ${}^{5}_{\Lambda}\mathrm{He}$.

5. Strangesess −2

The primary interest in the decay of strangeness −2 systems has been in the identification ${}_{\Lambda\Lambda}\mathrm{A}$ hypernuclei. Motoba's talk summarized the progress which has been made in this area. One seeks

$$ {}_{\Lambda\Lambda}\mathrm{A} \rightarrow \pi^- + {}_{\Lambda}\mathrm{A} $$

followed by

$$ {}_{\Lambda}\mathrm{A} \rightarrow \pi^- + \mathrm{A}^{(*)} $$

to yield well defined π^- energies. (See the discussion of AGS E907 by Fukuda.)

One reason for such a keen interest in double-Λ hypernuclei lies in Jaffe's [18] prediction of a bound di-Λ or **H** particle. If ${}_{\Lambda\Lambda}\mathrm{A}$ hypernuclei exist, then the existence of a deeply bound **H** is called into question. A double-Λ system should decay into a deeply bound **H** before the ${}_{\Lambda\Lambda}\mathrm{A}$ hypernucleus can decay weakly into two pions.

Assuming the existence of ${}_{\Lambda\Lambda}\mathrm{A}$ hypernuclei with two Λs in the $1s$ shell, one would expect to also be able to observe the nonmesonic decay mode

$$ {}_{\Lambda\Lambda}\mathrm{A} \rightarrow (\mathrm{A}-2) + \Sigma^- + \mathrm{p}\,. $$

Such a decay mode suffers no neutrals in the final state, which makes it attractive experimentally.

Finally, the decay of a Ξ hypernucleus would require detection of a mode of either the mesonic type

$$ \Xi^0 \rightarrow \Sigma^{+(-)} + \pi^{-(+)} $$

or of the nonmesonic type

$$ \Xi^0 + n \rightarrow \Sigma^- + p $$

or

$$ \Xi^- + p \rightarrow \Sigma^- + p $$

to be easily observed.

6. Summary

The hypernuclear weak decay process is an important aspect of the investigation of hypernuclear or strangeness physics. The significant roles which weak decays play can be summarized as follows:

- Mesonic decays have been the means by which Λ hypernuclei were identified. Mesonic decay properties provide a test of our ${}_{\Lambda}A$ wave functions at $q \neq 0$, just as ${}^{3}H$ decay tests our (nonstrange) A=3 nuclear wave functions.

- A key question is whether the $\Delta I = 1/2$ rule that governs mesonic decay also governs nonmesonic decay. A crucial test awaits measurement of the π^0 decay of ${}^{4}_{\Lambda}H$ at the BNL AGS.

- Another open issue is whether the internal structure of baryons plays a significant role. Although current calculations fail to account for the Γ_{nn}/Γ_{pn} ratio in nonmesonic decay, charge-exchange reactions in the final state must be explored in detail before more exotic mechanisms such as quark effects can be deemed to be required.

- Observation of the π^+ decay of Λ hypernuclei without a nuclear core having more protons than neutrons could signal that quark effects do play a role.

- The sizable π^+ decay branching ratio for ${}^{4}_{\Lambda}He$ provides physical evidence for significant $N\Lambda \leftrightarrow N\Sigma$ mixing in Λ hypernuclei.

- Weak decay of $\Lambda\Lambda$ hypernuclei is the preferred signal in the current BNL search for such systems, definitive results of which are eagerly awaited.

REFERENCES

1. M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953).
2. See, for example, R.H. Dalitz in *Nuclear Physics*, ed. by C. de Witt and V. Gillet (Gordon and Breach, NY, 1969), p. 701.
3. J. Szymanski *et al.*, Phys. Rev. C **43**, 849 (1991).
4. B.F. Gibson, Nucl. Phys. **A 543**, 1c (1992).
5. G. Keys *et al.*, Phys. Rev. Lett. **20**, 819 (1968); Phys. Rev. D **1**, 66 (1970); Nucl. Phys. **B 67**, 269 (1973).
6. M.M. Block *et al.*, in Proc. Sienna Int'l. Conf. on Elementary Particles, Ed. by G. Bernandini and G.P. Puppi (Soc. d. Fiisica, Bologna, 1963), p. 62.
7. H. Kamada *et al.*, Phys. Rev. C **57**, 1595 (1998).
8. A. Parrenõ *et al.*, Phys. Rev. C **56**, 339 (1997).
9. J.P. Lagnaux *et al.*, Nucl. Phys. **60** 97 (1964).
10. B.H.J. McKellar and B. F. Gibson, Phys. Rev. C **30**, 322 (1984).
11. B.F. Gibson, Nuovo Cimento **102A**, 367 (1989).
12. R.H. Dalitz and L. Liu, Phys. Rev. **116**, 1312 (1959); R.H. Dalitz and G. Rajasekaran, Phys. Lett. **1**, 58 (1962); M.M. Block and R.H. Dalitz, Phys. Rev. Lett (1963).

13. G. Keys *et al.*, Nuovo Cimento **31A**, 401 (1976).
14. R.H. Dalitz and F. von Hipple, Nuovo Cimento **34**, 799 (1964); Phys. Rev. **36**, B455 (1964); R.H. Dalitz, in Proc. Int. School of Physics "Enrico Fermi" XXXVIII, Interaction of High Energy Particles and Nuclei, Ed. by T. E. O. Ericson (Acad. Press, NY-London, 1967) p. 89.
15. A. Cieply and A. Gal, Phys. Rev. C **55**, 2715 (1997).
16. J. Sacton, in Proc. Int. School of Physics "Enrico Fermi" XXXVIII, Interaction of High Energy Particles and Nuclei, Ed. by T. E. O. Ericson (Acad. Press, NY-London, 1967) p. 77.
17. B.F. Gibson and R.G.E. Timmermans, Nucl. Phys. **A 628**, 417 (1998).
18. R.L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977).