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THE PRODUCTION AND DECAY OF HYPERNUCLEI

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ABSTRACT

Hypernuclei have been studied for the last 35 years using several techniques. Since 1970, the $^A_Z (K^-, \pi^-) ^A_\Lambda Z$ strangeness-exchange reaction has been used at CERN, BNL and KEK to produce hypernuclei and study their spectroscopic properties. These studies also include experiments where decay gamma rays and hypernuclear weak decay products are detected in coincidence with hypernuclear production. Recent experiments at BNL and KEK have proven the utility of the $^A_Z (\pi^+, K^+) ^A_\Lambda Z$ reaction to study hypernuclear spectroscopy. Although I have no hope of covering this field in much detail, I write this paper as an introduction to the subject and highlight some of the recent experimental developments.

INTRODUCTION

The properties of hypernuclei reflect the characteristics of the hyperon-nucleon weak and strong interactions. The hyperon-nucleon strong interaction gives the level structure of hypernuclei. The hyperon is distinguishable from the nucleons because of the presence of a strange quark, so the hyperon is not Pauli-blocked from occupying low-lying states in the nucleus. The distinguishability of hyperons seems to hold true even for heavy hypernuclear systems.

A hyperon bound within a nucleus has a large probability of overlap with one of the constituent nucleons. Thus, a new weak-decay mode, $\Lambda + N \rightarrow N + N$ opens up in hypernuclei and is the dominant decay mode for all but the lightest hypernuclear species. These weak decays are interesting because of the modification of the weak force in the presence of strongly-interacting particles.

The Λ -N strong interaction differs from the N-N strong interaction in several ways¹:

- a) There is no $1-\pi$ exchange because of isospin conservation.
- b) There is $1-K$ exchange, unlike the N-N interaction.
- c) Because of a), the Λ -N interaction is generally weaker than the N-N interaction. In fact, the model of a Λ weakly coupled to the nuclear core is quite successfully applied to understand the structure of Λ -hypernuclei.

The Λ -N interaction may be written as

$$V_{\Lambda N}(r) = V_0(r) + V_\sigma(r) \bar{S}_N \cdot \bar{S}_\Lambda + V_\Lambda(r) \bar{I}_{N\Lambda} \cdot \bar{S}_\Lambda + V_N(r) \bar{I}_{N\Lambda} \cdot \bar{S}_N + V_T(r) S_{\Lambda N},$$

where $S_{\Lambda N}$ is the usual tensor spin operator. The interaction can be expressed as a potential by integrating over harmonic oscillator wave functions. The radial integrals derived from the five terms of the above expression are designated as V , Δ , S_Λ , S_N

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and T, respectively. These are referred to as the spin-averaged central, the spin-spin, the spin-orbit, the induced spin-orbit and the tensor terms. Dalitz and Gal² have found the best fit to the existing p-shell data gives these parameters as 0.15, 0.57, -0.21 and 0.0 MeV for the Δ , S_Λ , S_N and T terms, respectively. More recently, Millener et al.³ found 0.50, -0.04, -0.08 and 0.04 for these parameters. It is the goal of many hypernuclear production and decay experiments to better understand this two-body interaction.

HYPERNUCLEAR PRODUCTION REACTIONS

Several complimentary reaction mechanisms have been used to study hypernuclei. They fall under these broad categories:

a) Strangeness exchange, the general form of which is:

The elementary reaction is $K^- + n \rightarrow \pi^- + \Lambda$. Some of the targets that have been studied with the (K^-, π^-) reaction are: ${}^4\text{He}$, ${}^6,7\text{Li}$, ${}^9\text{Be}$, ${}^{12,13}\text{C}$, ${}^{16}\text{O}$, ${}^{32}\text{Si}$, ${}^{40}\text{Ca}$ and ${}^{209}\text{Bi}$.

b) Associated production, where an outgoing (Strangeness=+1) K^+ tags the residual ($S=-1$) Λ . Examples are:

c) Strangeness and charge exchange:

where the elementary process is $K^- + p \rightarrow \pi^+ + \Sigma^-$. The subject of Σ hypernuclei is under active study, but will not be pursued further here. See the paper by Tang et al.⁴ and references therein.

d) Annihilation, where the two-step process

is producing hypernuclei. This reaction has been used at LEAR to study the weak decay of heavy hypernuclei using the recoil-shadow technique.⁵

All of the above processes have been used to produce hypernuclei except (γ, K^+) and (p, K^+) , although efforts to use these reactions are proceeding and will be covered in the section on new initiatives. Most of the existing data are for the (K^-, π^-) and (π^+, K^+) reactions leading to the formation of Λ hypernuclei. Thus, for the remainder of this paper, I switch to a discussion of the production and decay of Λ hypernuclei.

THE (K^-, π^-) AND (π^+, K^+) REACTIONS

The (K^-, π^-) reaction was first used at CERN in 1970.^{6,7} The CERN-Heidelberg-Warsaw collaboration pioneered many techniques used in (K^-, π^-) studies.

An example of the typical level structure seen in hypernuclei is the high-resolution $^{12}\text{C}(K^-, \pi^-)^{12}_{\Lambda}\text{C}$ missing-mass spectrum shown in Fig. 1.⁸ The observed states are identified with the removal of a neutron from the $p_{3/2}$ shell and replaced by a Λ in the s shell (lower mass state) or by a Λ in the p shell (higher mass state). The (p^{-1}, s) (p neutron-hole, s Λ -particle) state is lighter than the (p^{-1}, p) state because the neutron is more strongly bound to the nuclear core than the Λ . Similar results are seen with the (π^+, K^+) reaction.

Fig. 1 High-resolution $^{12}\text{C}(K^-, \pi^-)^{12}_{\Lambda}\text{C}$ mass spectrum, showing the neutron-hole Λ -particle states (p^{-1}, s) and (p^{-1}, p) .

The (K^-, π^-) and (π^+, K^+) reactions are complementary in several ways. Fig. 2 contains a comparison of the momentum transfer, q , versus incoming beam momentum for the two reactions. The (π^+, K^+) reaction clearly yields a larger q than the (K^-, π^-)

Fig. 2 Momentum transfer, q , for the (K^-, π^-) and (π^+, K^+) reactions versus beam momentum.

Table I

Comparison of the (K^-, π^-) and (π^+, K^+) reactions.¹⁰ The listed cross section is the typical differential cross section to a particular hypernuclear state.

	(K^-, π^-)	(π^+, K^+)
q	$<100 \text{ MeV/c}$	$\sim 300 \text{ MeV/c}$
Selectivity	low spin states	high spin states
Cross Section	$0.3\text{-}1 \text{ mb/sr}$	$10\text{-}20 \text{ } \mu\text{b/sr}$
Intensity	10^5	10^7
Beam Purity	$K/\text{all} \sim 8\text{-}10\%$	$\pi/\text{all} \sim 80\%$

reaction, which can actually produce a Λ with zero momentum (the 'magic momentum' of 530 MeV/c for the (K^-, π^-) reaction). The (π^+, K^+) reaction, on the other hand, has a typical q of 300 MeV/c and therefore populates higher spin states than (K^-, π^-) . Table I compares the (K^-, π^-) and (π^+, K^+) reactions. The count rates for production of a particular hypernuclear state are comparable for the two techniques, because the larger available π^+ flux compensates for the smaller (π^+, K^+) cross section.

Fig. 3 shows the ^{89}Y mass spectrum obtained in BNL exp. 798, a recent (π^+, K^+) experiment.^{9,10} The peaks are identified with Λ -particle-neutron-hole states (g^{-1}, s) , (g^{-1}, p) , (g^{-1}, d) and (g^{-1}, f) . The high spin (g^{-1}, s) and (g^{-1}, s) states are seen.

Fig. 3 A (π^+, K^+) mass spectrum obtained at BNL with a ^{89}Y target. The data points are compared to a DWBA calculation¹¹ using the experimental neutron-hole strength for ^{90}Zr .

The observation of these deeply bound states supports the view that the Λ hyperon is indeed distinguishable even within a heavy nucleus. The (π^+, K^+) program at KEK has also obtained good quality results on $^{12}_{\Lambda}\text{C}$ and $^{56}_{\Lambda}\text{Fe}$.¹²

Coincidence experiments to detect hypernuclear γ transitions have been carried out at BNL and CERN. The first hypernuclear γ rays were observed by stopping a K^- beam in Be and Li.^{13,14} The observed γ rays at 1.04 MeV and 1.15 MeV for $^4_{\Lambda}\text{H}$ and $^4_{\Lambda}\text{He}$, respectively, fix the first excited 1^+ state at about 1 MeV above the ground state. The first in-flight experiment occurred at BNL and utilized the (K^-, π^-) reaction to produce and tag hypernuclear states. The γ rays were detected in NaI detectors placed around the hypernuclear production target. This experiment resulted in the observation of hypernuclear transitions from the 2.034 MeV second excited state of $^7_{\Lambda}\text{Li}$ and from the 3.079 MeV $^9_{\Lambda}\text{Be}$ doublet. The doublet consists of $5/2^+$ and $3/2^+$ components and the fact that this splitting was not resolved puts an upper bound on the strength of the ΛN spin-orbit splitting of $|S_{\Lambda}| < 0.04 \text{ MeV}$.¹⁵

A later experiment at BNL was designed to observe spin-flip transitions within the ground-state doublet of ${}_{\Lambda}^{10}\text{B}$. This experiment was sensitive to γ rays in the energy range of 100 keV to 500 keV, but saw no evidence for the spin-flip transition. The smallness of the ΛN spin-orbit term, S_{Λ} , and the absence of γ lines in the ${}_{\Lambda}^{10}\text{B}$ ground state implies the spin-spin splitting, Δ , is < 0.22 MeV.¹⁶ This is in contrast to the value used by Millener et al.³ of $\Delta=0.5$. There is clearly a problem in fitting a consistent set of p-shell potential parameters.

HYPERNUCLEAR WEAK DECAY

In most cases, a particle-stable hypernucleus will decay electromagnetically to its ground state before undergoing a strangeness-changing weak decay to a normal nucleus. The predominant decay modes are of two types: mesonic and nonmesonic. The mesonic modes are $\Lambda \rightarrow p \pi^-$ (partial rate Γ_{π^-}) and $\Lambda \rightarrow n \pi^0$ (partial rate Γ_{π^0}) while the nonmesonic modes are $\Lambda p \rightarrow n p$ (proton stimulated partial rate Γ_p) and $\Lambda n \rightarrow n n$ (neutron stimulated partial rate Γ_n). The leptonic decay modes are orders of magnitude smaller and will be neglected in this discussion. The mesonic modes are analogous to free Λ decay, but are modified in hypernuclei because of phase-space changes and Pauli blocking of the final state nucleons¹⁷. Conversely, the nonmesonic modes become available in hypernuclei and are the dominant decay modes for all but the smallest hypernuclear systems. An experimental attraction of the nonmesonic modes is the ease of their identification because of the energetic nucleons produced in the final state. The total mesonic decay rate is denoted Γ_m where $\Gamma_m = \Gamma_{\pi^-} + \Gamma_{\pi^0}$ and the total nonmesonic decay rate is denoted Γ_{nm} where $\Gamma_{nm} = \Gamma_p + \Gamma_n$. The sum of all four partial rates gives the total decay rate $\Gamma_{\text{total}} = 1/\tau$ for a particular hypernucleus.

At the quark level, the lowest-order Hamiltonian describing $\Delta S=1$ weak decay is the result of the combination of V-A theory with the Cabibbo hypothesis:¹⁸

$$H_{V-A} = \frac{G_F}{\sqrt{2}} \sin \theta_c \cos \theta_c Q_{V-A} + \text{c. c.}$$

where G_F is the Fermi coupling constant, θ_c is the Cabibbo angle and the operator, Q_{V-A} , is:

$$Q_{V-A} = \bar{u} \gamma_{\mu} (1 - \gamma_5) s \bar{d} \gamma^{\mu} (1 - \gamma_5) u.$$

This Hamiltonian leads to transitions of both $\Delta I = 1/2$ and $\Delta I = 3/2$ with comparable strength. It is well known,¹⁹ however, that both kaon decay and free hyperon decay data suggest that the $\Delta I = 1/2$ amplitude is about a factor of twenty stronger than the $\Delta I = 3/2$ amplitude. The origin of this empirical " $\Delta I = 1/2$ Rule" is not understood. Some progress has been made using quark models which include strong interaction corrections to the weak Hamiltonian, but the full effect has yet to be explained.

The nonmesonic decay modes are described with the quark model and with meson exchange, as shown in Fig. 4.^{20,21,22,23,24,25} The $\Delta I = 1/2$ rule is put into the meson exchange picture explicitly.

The experiment 759 and 788 collaborations at BNL have been studying the weak decay of $^{12}_{\Lambda}\text{C}$, $^5_{\Lambda}\text{He}$ and $^4_{\Lambda}\text{He}$.^{26,27} The experiments utilize the (K^-, π^-) reaction to produce and tag hypernuclear states. Charged and neutral decay products are detected in plastic scintillator spectrometers located around the hypernuclear production target. Protons, pions and neutrons are identified and counted in coincidence with the formation of a particular hypernuclear state. A summary of some of the experimental results is contained in Table II.²⁷

Fig. 4 Quark model and meson-exchange model of the nonmesonic weak decay $\Lambda N \rightarrow NN$.

Table II
 $^{12}_{\Lambda}\text{C}$ and $^5_{\Lambda}\text{He}$ weak decay experimental results. Γ_{nm} is quoted in units of the free Λ decay rate.

	Γ_{nm}	Γ_n/Γ_p	$\Gamma_{nm}/\Gamma_{\pi^-}$
$^{12}_{\Lambda}\text{C}$	1.14 ± 0.20	$1.33^{+1.12}_{-0.81}$	22^{+43}_{-12}
$^5_{\Lambda}\text{He}$	0.41 ± 0.14	0.93 ± 0.55	0.92 ± 0.31

The most striking feature of the results is the large drop in Γ_{π^-} in going from $^5_{\Lambda}\text{He}$ to $^{12}_{\Lambda}\text{C}$. The Γ_{π^-} rate is difficult to measure in $^{12}_{\Lambda}\text{C}$, because so few pions are observed in coincidence with the $^{12}_{\Lambda}\text{C}$ ground state. Γ_{nm} is increasing slowly and, in fact, roughly scales with the number of nucleons available for nonmesonic decay in these light hypernuclei. These experiments continued in the spring of 1990 with a run

during which the ${}^5_{\Lambda}\text{He}$ weak-decay measurements were repeated and ${}^4_{\Lambda}\text{He}$ weak-decay data were taken.

The detection of decay products in coincidence with hypernuclear formation can give information on the structure of levels. For example, the ${}^6\text{Li} (K^-, \pi^-) {}^6_{\Lambda}\text{Li}$ mass spectrum taken during the experiment 788 weak decay data run is shown in figure 5. This spectrum requires that a proton from nonmesonic decay (energy > 30 MeV) is observed in coincidence with the (K^-, π^-) reaction. This is to be compared to the spectrum shown in figure 6, which was taken earlier by Bertini et al.²⁸ and which has

Fig. 5 ${}^6\text{Li} (K^-, \pi^-) {}^6_{\Lambda}\text{Li}$ mass spectrum with an energetic ($T > 30$ MeV) proton coincidence requirement.

Fig. 6 ${}^6\text{Li} (K^-, \pi^-) {}^6_{\Lambda}\text{Li}$ mass spectrum with no coincidence requirement.

no decay coincidence requirement. The (p^{-1}, p) state is not seen when an energetic proton is required, indicating that this state must break up by Λ emission. That is, an energetic proton can only be produced by a bound Λ undergoing a nonmesonic decay, and cannot be produced by a free Λ (the proton in $\Lambda \rightarrow p \pi^-$ has less than 5 MeV). This observation confirms calculations by Majling et. al.²⁹, and Auerbach and Giai³⁰ in which the large width ($\Gamma = 7 - 10$ MeV) of the (p^{-1}, p) state is related to its particle-unstable character.

NEW INITIATIVES IN HYPERNUCLEAR PHYSICS

There are four new programs that I wish to discuss. First, the ongoing, strong program at KEK needs to be mentioned in more detail. In the recent past, there have been experiments at KEK looking at Σ -hypernuclear states³¹, mesonic weak decay³² and $(\pi^+, K^+)^{12}$. There are plans to construct a superconducting spectrometer for (π^+, K^+) studies³³ and to build a new, large-acceptance spectrometer³⁴.

There are plans for the study of hypernuclei using associated production with the (p, K^+) reaction. Specifically, the COSY ring is to be used to produce heavy hypernuclei and study their decay.³⁵ A new era in hypernuclear physics will open up if cooler rings can be successfully used for hypernuclear production.

The photoproduction of hypernuclei has been proposed for CEBAF.³⁶ These experiments are designed to reach an ultimate resolution of ~ 200 keV. The hope is to resolve the spin doublet splittings of p-shell hypernuclear ground states. The initial, lower resolution, stage of this experiment is expected to run soon after the CEBAF turn-on.

Another interesting new initiative is the PILAC project at LAMPF.³⁷ The PILAC is a superconducting RF linear accelerator, which accelerates pions from the P^3 channel at LAMPF to just over 1 GeV/c. There pions are above the (π^+, K^+) threshold. The preliminary design calls for 10^9 π^+ /sec and 200 keV resolution. The construction of PILAC would represent a one- to two-order-of-magnitude increase in rate over existing facilities, with approximately a one-order-of-magnitude improvement in resolution.

SUMMARY

The study of hypernuclei has matured to the point where sophisticated coincidence experiments have been undertaken to better understand the Λ -N strong and weak interactions. This work will continue at the present facilities in the near future. Many experiments await new facilities with higher resolution and/or counting rates. I strongly encourage these efforts.

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