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Electromagnetic Transitions in Hypernuclei

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The interaction of electromagnetic radiation with the nucleus has provided classical nuclear physics with an indispensable tool for illuminating the structure of nuclei. Similarly, for the study of hypernuclei, the observation of γ -ray transitions is essential in the interpretation of hypernuclear level schemes.

Hypernuclei are those nuclear systems which contain one or more hyperons in addition to the usual nucleons. They are usually produced in strangeness exchanging reactions from kaon beams. The detailed comparison of hypernuclear level schemes with those of nuclei provides a valuable insight into the nature of the strong force.

The importance of this information can be placed in perspective by noticing that the spin-dependent hyperon-nucleus potentials--and here, and in what follows one concentrates exclusively on the Λ -hyperon--are weaker than the corresponding nuclear ones. The spin-spin and spin-orbit splittings of hypernuclear level multiplets will be smaller and harder to resolve than in the nuclear case.

High resolution spectroscopy is therefore essential in unravelling hypernuclear decay schemes, and it must be carried out under extremely adverse conditions. The difficulties include 1) relatively poor magnetic resolution for in-flight kaon measurements--at best 0.2%; 2) relatively low beam intensities compared to conventional nuclear physics, about 8 orders of magnitude lower; 3) relatively poor beam quality--typically 90% pion contamination in a kaon beam; 4) extremely unfavorable background conditions from meson decays and background reactions; and, finally, 5) a world-wide scarcity of suitable facilities.

In spite of these obstacles, electromagnetic transitions from hypernuclei have been observed, and have contributed, in some cases, decisively to our knowledge of the effective two-body hyperon-nucleon forces in the nucleus. The object of the review is to survey these contributions and make some evaluation of possible future research.

1. Predictions for Electromagnetic Transitions in Light Hypernuclei

All of the available γ -ray data presented are limited to the p-shell hypernuclei and the $A=4$ systems. An extensive analysis of p-shell hypernuclear transitions have been presented by MILLENER et al. [1] and DALITZ and GAL [2]. These are generally restricted to particle-bound states of the form $p_n s_{\Lambda}$. We will consider transitions between the core states in which the Λ is a spectator and the core configuration changes, and between members of the same multiplet, where a Λ spin flip occurs. Schematically this is shown in Fig. 1.

The ΛN effective interaction is characterized by three spin-dependent matrix elements: Δ (spin-spin), S_{Λ} (Λ spin-orbit), and T (tensor). In energy separation of states built on different core states involving induced nucleon spin-orbit interaction.

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Fig. 1 Doublet states of Λ -hypernuclei in which an S-shell Λ is coupled to core states of the $A-1Z$ target

The spin-doublet splittings are determined by Δ , S_Λ and T , which can be expressed in terms of radial integrals over the ΛN potentials. These are taken as constants across the p-shell. An approximate representation of the doublet splittings in terms of the parameters δ , δ' , for the $p_{3/2}$ and $p_{1/2}$ shells respectively, is as follows:

$$\delta = 2/3 \Delta + 4/3 S_\Lambda - 8/5 T \quad ; \quad \delta' = -1/3 \Delta + 4/3 S_\Lambda + 8 T \quad (1)$$

As is apparent from the above, the effect of the tensor interaction is relatively large at the end of the p-shell. A systematic measurement across the shell together with the assumption of constant coefficients would determine the matrix elements uniquely. This is a major goal of Λ hypernuclear spectroscopy.

2. Experiments

The data base for γ rays in hypernuclei is extremely limited. All of the published observations to date are listed in Table I. These do not include results described in conferences, proceedings, or work in progress.

The experiments of Table I fall into three classes. Those of references 3-5 referring to stopping kaons in a thick target; reference 8 refers to an in-flight experiment with no energy selection on the incoming kaon or outgoing pion. In ref. 7, the energy differences between incoming and outgoing particles are measured in a spectrometer with a precision of about 1%. Thus only in ref. 7 is it possible to associate the observed γ ray with the excitation of the hypernucleus, and to associate γ -ray prediction with the region of hypernuclear particle bound states, or the production of specific hypernuclear fragments. Thus the assignment of γ rays to specific transitions is unambiguous only in that experiment.

The first observations were reported by BAMBERGER et al. [3] and subsequently refined by the CERN-LYON-WARSAW collaboration [4-6]. Gamma rays were observed by stopping kaons in thick targets of lithium. The observed radiation were ascribed to the hyperfragments ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$. It is important to note that for these light systems the weak decay mode is primarily mesonic, and because of the large binding of the α particle, phase space favors the following modes:

$${}^4_\Lambda\text{H}^* \rightarrow {}^4_\Lambda\text{H} + \gamma \quad ; \quad {}^4_\Lambda\text{H} \rightarrow {}^4\text{He} + \pi^- \quad [E_{\pi^-} = 53 \text{ MeV}] \quad ; \quad E_\gamma = 1.04 \text{ MeV} \quad (2)$$

$${}^4_\Lambda\text{He}^* \rightarrow {}^4_\Lambda\text{He} + \gamma \quad ; \quad {}^4_\Lambda\text{He} \rightarrow {}^4\text{He} + \pi^0 \quad [E_{\pi^0} = 57 \text{ MeV}] \quad ; \quad E_\gamma = 1.15 \text{ MeV}$$

Table 1: Table of Reported Hypernuclear γ Rays

Target	E_γ	Identification	Ref.
${}^6\text{Li}, {}^7\text{Li}$	1.09	$1^+ \rightarrow 0^+$; ${}^4_\Lambda\text{H}$; ${}^4_\Lambda\text{He}$	3
${}^7\text{Li}$	1.09 ± 0.03	$1^+ \rightarrow 0^+$; ${}^4_\Lambda\text{H}$	4
${}^6\text{Li}, {}^7\text{Li}$	1.04 ± 0.04	$1^+ \rightarrow 0^+$; ${}^4_\Lambda\text{H}$	5
	1.15 ± 0.04	$1^+ \rightarrow 0^+$; ${}^4_\Lambda\text{He}$	5
${}^7\text{Li}$	1.108 ± 0.01	$1^+ \rightarrow 0^+$; ${}^4_\Lambda\text{H}$ ${}^4_\Lambda\text{He}$	7
${}^7\text{Li}$	2.034 ± 0.023	$5/2^+ \rightarrow 1/2^+$; ${}^7_\Lambda\text{Li}$	7
${}^9\text{Be}$	3.079 ± 0.04	$5/2^+, 3/2^+ \rightarrow 1/2^+$; ${}^9_\Lambda\text{Be}$	7
${}^7\text{Li}$	0.789 ± 0.04	? (${}^7_\Lambda\text{Li}$)	8
${}^6\text{Li}, {}^7\text{Li}$	1.42	?	3
${}^9\text{Be}$	0.31 ± 0.02	?	3
${}^9\text{Be}$	1.22 ± 0.02	? (${}^8_\Lambda\text{Li}$)	6

In these experiments the γ rays were not resolvable with the sodium iodide detectors used. The energy assignments of 1.04 MeV for ${}^4_\Lambda\text{H}$ and 1.15 MeV for ${}^4_\Lambda\text{He}$ were made on the basis of examining the spectra in coincidence with the π^- and π^0 , respectively. These 1 MeV γ rays are attributed to the $1^+ \rightarrow 0^+$ spin-flip transitions in these systems. These transitions can be used to evaluate the spin-spin interaction matrix Δ appropriate to the p shell if three-body forces are neglected and a nuclear size correction is made. The result is $\Delta \approx 0.5$ MeV.

These stopped kaon experiments are useful only for the lightest systems because of their inability to specify the initial state of the hypernucleus unambiguously. The next step in the development of hypernuclear γ spectroscopy was to place γ -ray detectors at the target position of the hypernuclear spectrometer, Moby Dick, at the AGS, and record radiation in coincidence with the kaon and pion in the strangeness exchange reaction (K^-, π^-). The simultaneous measurement of the K, π momentum difference permits a specification of the energy spectrum of the hypernuclear states. In practice the energy resolution for a thick target, while poor, is in the order of 6-7 MeV. This is adequate to separate the region of particle bound states (where γ transitions are expected to occur) from the quasi-free (unbound or continuum) region. Further, the continuum can be divided into different regions corresponding to the thresholds for production of various hyperfragments.

The technique is illustrated in the observation of a transition in ${}^9_\Lambda\text{Be}$ of 3.079 MeV, as shown in Fig. 2. Two γ rays of approximately equal intensities are expected to depopulate the first excited $5/2^+, 3/2^+$ doublet built on the 2.94 2^+ core excited state of ${}^8\text{Be}$. The spacing of this doublet is almost exclusively determined by the matrix element of the spin-orbit term, S_Λ . The failure to resolve this doublet places a tight constraint on S_Λ ; namely $|S_\Lambda| < 0.04$ MeV. This constraint is the most stringent one on the Λ spin-orbit interaction, which is known to be small from previous (K^-, π^-) studies in, for example, ${}^{13}\text{C}$.

Fig. 2 A hypernuclear γ -ray transitions in $\Lambda^9\text{Be}$.

Fig. 3 The γ -ray transitions observed for $\Lambda^7\text{Li}$

The same experiment also reported results for $\Lambda^7\text{Li}$ as shown in Fig. 3. The observation of the γ ray at 2.034 MeV is attributed to the transition for the $5/2^+$ member of the doublet built on the 2.18 MeV 2^+ ^6Li core to the $1/2^+$ gs of $\Lambda^7\text{Li}$. The reduction of the energy from the core value of 2.18 MeV is attributed by Millener et al. to the induced spin-orbit matrix element S_N . This matrix element can be affected by 3-body ANN contributions. Finally, one very important result of the experiment is the confirmation of the 1 MeV γ rays reported by the stopped kaon experiments. These appear at an excitation above break up of $\Lambda^7\text{Li}$ into the hyperfragments $\Lambda^4\text{He}$ and $\Lambda^3\text{H}$.

As a final remark on previous experiments, I list in Table I, below the horizontal line, those experiments reporting γ rays which have not been verified, and which do not fit into the expected level schemes of refs. 1 and 2.

3. Present and Future Plans

It is natural to consider the extension of hypernuclear spectroscopy to high resolution Ge diode detectors. There is actually a limited energy range of usefulness for such detectors as illustrated in Fig. 4. The lower limit of energy (≈ 50 keV) is determined by the competition with weak decay, and for γ 's of higher than 300 keV, Doppler broadening becomes significant and detector efficiency falls. Fortunately this range is well-suited to the region estimated for the spin-flip M-1 γ rays for p shell hypernuclei.

Valuable experience with high resolution γ spectroscopy was gained in AGS experiment 781, where an array of 6 Ge coaxial detectors, in mini (0.41)-cryostats was assembled to view targets of ^{10}B and ^{16}O (as water) [9]. With present facilities, an estimated sensitivity is obtained, for 100 keV of γ -ray energy, of about 10 $\mu\text{b/sr}$. This is comparable to predicted transition rates. Thus the experiments are marginal at best. Peaks which are plausible candidates for spin-flip M-1's were observed at 160 keV for ^{10}B and near 80 keV for ^{16}O in the above experiment.

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Fig. 4 The window of utility
for high resolution spectroscopy

Detailed analyses, which are still underway, have however failed to establish statistically significant confidence levels for those peaks.

For future facilities such as the proposed new "kaon factories" it will be possible to continue a productive γ -ray spectroscopy program for hypernuclei. The most helpful advances would be the provision of highly separated beams, preferably with K to π ratios near one to one, sufficient intensities ($> 10^6$) to allow well shielded detectors to be placed outside the beam halo, and 100% duty factor. These will provide the order-of-magnitude increase in rate that is desired.

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