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DETECTING GAMMA RAYS FROM HYPERNUCLEI

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Robert E. Chrien
Brookhaven National Laboratory, Upton, New York, 11973, USA

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ABSTRACT

Electromagnetic radiation from p-shell hypernuclei has been detailed in the $(K^-, \pi^- \gamma)$ reaction at the Brookhaven AGS. The technique makes it possible to characterize the spin-dependent terms in the Λ -N effective interaction.

INTRODUCTION

Experiments on the structure of hypernuclei have been under-way for the past ten years.^{1,2} Secondary beams of K-mesons for such studies have been available at the CERN proton synchrotron, the KEK accelerator, and the Brookhaven AGS. The (K, π) strangeness exchanging reactions have been exploited with magnetic spectrometers to arrive at the excitation spectrum of the recoiling hypernucleus. A considerable body of information is now available from such studies. It is already clear that there are striking differences between ordinary nuclei and strange nuclei. For example, the Λ -nucleon spin-orbit force is virtually zero and it has the opposite sign to the nuclear spin-orbit force.³ The one-body Λ -nucleus potential is weaker than in the nucleon-nucleus case.¹ On the other hand there is some evidence for a sizable Σ -nucleon spin-orbit interaction.⁴

It has become evident, however, that the details of the Λ and Σ -nucleon forces are difficult to deduce from magnetic spectrometers which are limited to a resolution of about 0.1%. The hypernuclear multiplets formed by alternate spin-couplings of the Λ to the nuclear core are closely spaced and unresolvable. Furthermore, many of these levels are not populated strongly by a strangeness exchanging K, π reaction. At Brookhaven we have resorted to a technique to circumvent these difficulties--the technique of γ -ray spectroscopy. Just as in conventional nuclear physics, the technique not only allows us to populate a variety of levels, but to do so with a resolution which is orders of magnitude better than is available with magnetic techniques.

The γ -ray spectroscopy of hypernuclei was started by Henryk Piekarczyk and his colleagues some ten years ago.⁵ The Piekarczyk experiment, however, used stopped kaons, and the energy transferred to the hypernucleus is very large. Typically, several recoil fragments are thereby produced and the excitation spectra can be very complicated. There is one case, an especially simple one, which can be done in this way. That case involves the pair of $A=4$ hypernuclei, ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$.

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MASTER

The first excited state and ground state of these mass 4 hypernuclei form a spin doublet which can deexcite by the emission of an M-1 γ ray, as shown in Fig. 1.

Piekarczyk and his collaborators were able to identify uniquely the origin of the γ rays from their target as arising from the mass 4 hypernuclear systems by recording γ rays in coincidence with the pionic decay modes of these hypernuclei.

Fig. 1 The spin-flip transitions in the ${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$ systems.

Although very high singles rates were present in the 10×7.5 cm NaI detectors surrounding the target (about $400,000 \text{ sec}^{-1}$), the pion coincidence enabled them to detect γ rays with energies of 1.04 and 1.15 MeV for the ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ systems respectively.

This experiment led us to expect that detection electromagnetic radiation from hypernuclei was indeed practical. However, to study the p-shell systems, for example, would require a more precise specification of the initial state of the hypernucleus. That would of course be provided by a measurement of the production kaon and pion momenta, as well as that of the γ -ray energy, in a $(K, \pi\gamma)$ reaction. This requirement, as we shall see, is an absolutely necessary requirement for a unique γ -ray signature.

As was shown several years ago in the extensive review article on p-shell hypernuclei by Dalitz and Gal,⁶ the configuration applicable to the bound states has the form: $\{(1S)_N^L(1P)^{A-5}_N(1S_{\Lambda})\}$, and the reaction proceeds via a $\Delta L=1$ orbital angular momentum transfer.

The γ -ray transitions can be divided into two classes, depending on the role of the Λ :

1) spin-flip doublet transitions - These are M-1 transitions connecting the members of the hypernuclear doublet built on a core state. In this type the Λ spin is flipped with respect to the core spin.

2) core transitions - In this type the γ -ray transition connects core states, and the Λ plays the role of a spectator (whose presence, however, perturbs the core states).

These types are illustrated in the level scheme of ${}^7_{\Lambda}\text{Li}$ of Fig. 2, taken from the recent work of D. J. Millener et al. They

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Fig. 2. The ${}^7\text{Li}$ level scheme (ref. 7).

have updated the earlier work of Dalitz and Gal, using a phenomenological analysis with a Λ -N potential model to determine a set of four $P_N S_\Lambda$ two-body matrix elements to describe the spin-dependent ΛN interaction in the p-shell.

The spin-dependent potential parameters are referred to as the spin-spin term Δ , the Λ spin orbit S_Λ , the induced nuclear spin-orbit S_N , and the tensor T .

Figure 2 provides an example of the type 1) transition referred to above: the $3/2^+$ to $1/2^+$ gs M-1 transition. The $5/2^+$ to $1/2^+$ transition is of the type 2) above and is closely related to the 3^+ to 1^+ ${}^6\text{Li}$ E2 core transition.

The most direct information on the spin dependence of the interaction depends on the separation of the S_Λ doublets built on non-zero core states. For pure states, neglecting the perturbing effect of the Λ on the core, the doublet separation is at the start of the p shell,

$$\delta = 2/3 \Delta + 4/3 S_\Lambda - 8/5 T; (p_{3/2N}^{-1} s_{1/2\Lambda}) \text{ configuration} \quad (1)$$

and, at the end,

$$\delta' = -1/3 \Delta + 4/3 S_{\Lambda} + 8 T; (p_{1/2}^{-1} n s_{1/2} \Lambda) \text{ configuration.} \quad (2)$$

Armed with these theoretical estimates, a series of experiments was designed to be executed at the BNL AGS hypernuclear facility. The most critical parameter affecting these experiments is simply beam intensity. As contrasted to the situation in "non-strange" or normal nuclear physics, where beam particle intensities of $\sim 10^{14}$ particles/sec are often available, the Moby Dick spectrometer, as described is capable of putting only about 10^5 kaons/sec on target. Typical cross sections, near 0° , for producing $\Delta L=1$ bound states are small, $50 \mu\text{b sr}^{-1}$ being a typical value. Furthermore, one must contend with the very large pion flux which unavoidably accompanies separated kaons. In spite of the rate limitations and background problems, a successful $(K, \pi\gamma)$ experiment was completed in June 1982, on targets of ^7Li and ^9Be .⁸

An array of NaI detectors consisting of 6 12.7×7.62 cm crystals 11.4 cm from the target and 2 20.32×15.24 cm crystals 20 cm from the target, with a total solid angle of 30% of 4π was employed in this experiment. Sources of ^{203}Hg , ^{56}Co and ^{229}Th were mounted near the crystals to provide in-beam energy calibrations. With about 10^6 particles (both pions and kaons) incident on the thick (8 gm/cm^2) targets used, the energy resolution was 10% at 511 keV and the time resolution was better than 5 ns at 511 keV. Singles rates in each of these detectors were 2 to $4 \times 10^5 \text{ sec}^{-1}$.

With the level scheme predicted by Millener et al. in mind, the data shown in Fig. 3 may be referred to:

Fig. 3. The excitation spectrum of $^7_{\Lambda}\text{Li}$ (inset) and 4 γ -ray spectra derived from 4 cuts on the excitation spectrum.

a) In the excitation spectrum, below the hypernuclear gs, no peaks, except for the ever-present 511 keV annihilation, are observed.

b) In the region $-2 < E_x < 8$ MeV, a peak at 2.034 ± 0.023 MeV is observed. In this peak nearly 100 events are observed; at this energy the net photopeak efficiency of the array is about 10%. The peak is observed in no other excitation region, and no nuclear γ rays exist near 2 MeV for $A < 7$. Hence this peak may be unambiguously assigned to the $5/2^+ \rightarrow 1/2^+$ transition in ${}^{\Lambda}_7\text{Li}$. It is interesting to observe that the corresponding $3^+ \rightarrow 1^+$ transition in the ${}^6\text{Li}$ nucleus occurs by α -d breakup. The presence of the Λ stabilizes the system against breakup, thus permitting the observation of the γ ray.

c) No peaks, save that due to 511 radiation, is observed in the cut for $4 < E_x < 10$ MeV.

d) A peak at 3.56 MeV appears for $10 < E_x < 16$ MeV. Here there is sufficient energy for Λ emission to populate ${}^6\text{Li}$ excited states. The lowest such state is the 3.56 T=1 level; hence the peak represents a nuclear line.

In the case of ${}^{\Lambda}_9\text{Be}$ (not shown here), of especial interest is the doublet near 3 MeV, built in the $L=2$ 2^+ core state of ${}^8\text{Be}$. In the ${}^{\Lambda}_9\text{Be}$ spectrum we see a γ ray consistent with the deexcitation of the $3/2^+$, $5/2^+$ doublet to the ${}^{\Lambda}_9\text{Be}$ ground state with a transition energy of 3.089 ± 0.04 MeV. In this case the doublet members are expected to be equally populated. Since the nuclear core in this case has $S=0$, the spin-spin interaction would be absent, and the splitting would be expected to be largely a measure of the $S_{\Lambda} \cdot l_N$ interaction. The observation of a single, unresolved peak places severe constraints on the value of S_{Λ} . If one ignores the small effects expected from the tensor and spin-spin terms in this case the absolute value of S_{Λ} would be constrained, from our experiment, to be less than 0.04 MeV.

In view of our failure to observe the spin-flip transitions, an improvement in the experimental techniques was called for.

Fortunately there have been rapid developments in the application of high resolution germanium diode detectors to high rate situations. Quite large intrinsic n-type germanium detectors are now available with reasonably good timing characteristics and excellent efficiencies at very low energies. Furthermore, portable germanium detectors have been developed for commercial applications. These are capable of operating in any orientation; they have small liquid nitrogen dewars and capable of being closely packed around a target.

These detectors have a high photopeak efficiency from below 20 keV to about 200 keV, with the efficiency falling by a factor of 3 at 500 keV. The measured photopeak efficiency of the 6 detector array at 120 keV, averaged over an extended target is 3%, when the detectors are 10 cm from the median plane. Special care is taken to achieve a narrow beam waist in the y direction, so that these detectors can be placed as near to the target as possible.

It should also be noted that for γ -ray energies of less than about 50 keV there will be severe competition from the Λ weak decay mode; the Λ lifetime is on the order of 10^{-10} seconds. Thus our "window of sensitivity" extends from perhaps 50 keV to perhaps 300 keV, where the efficiency falls rapidly. However the M-1 spin flip rates are low enough that the γ -rays will not suffer Doppler broadening, the recoiling nucleus having come to rest prior to γ -emission.

The hostile environment caused by the proximity of a beam of about 10^6 particles/sec, mostly pions, near the detectors requires some special treatment. We have adopted the use of a standard spectroscopy amplifier operated with short pulse shaping time constants (0.25 μ sec), whose output is coupled to a gated integrator. This combination gives a high rate handling capability, yet allows for the relatively slow charge collection of the germanium crystals.

The beam is surrounded by a halo of decay muons which deposit a large amount of energy in the detector. Typically we observe in excess of 5×10^3 /sec muon-induced events in each crystal, each depositing about 50 MeV of γ -equivalent ionization. The preamplifier must be able to handle the average current of 10 nano-amperes through the beam spill. This can be accomplished by a reduction in the input feedback resistor from the typically used 2×10^9 ohms to 500×10^6 ohms. The amplifier must be able to recover from overload pulses quickly, to be able to handle succeeding events without excessive base line distortions. A highly stable pulser is injected into the preamplifier to monitor gain stability and resolution through the beam spill. With our rates of $\approx 1.2 \times 10^6$ total beam particles, we achieve signal processing efficiencies of 50 to 60%, defined as peak events which lie within a resolution width of 4 keV compared to all events.

Fig. 4. Ge timing curves.

Fig. 5. $\Lambda^{10}\text{B}$ excitation spectrum. A and B regions are cuts chosen to represent the bound state region (B) and a background region (A). The sample is 3.7 gms/cm² of $\Lambda^{10}\text{B}$.

Germanium timing is crucial for low accidental background. We use a constant fraction discriminator set at a level of ≈ 5 mV. Timing curves characteristic of 80 keV (^{133}Ba) and 1332 keV (^{60}Co) radiation are shown in Fig. 4, as measured under actual beam conditions. As is evident, the time distributions are strong functions of γ -ray energy, ranging from ≈ 30 ns FWHM at 80 keV to ≈ 5 ns for 1.3 MeV.

The first experiments with targets of ^{10}B and ^{16}O have been completed and the results are being analyzed. Some preliminary conclusions have been drawn and are presented here.

Figure 5 shows the excitation energy spectrum obtained for a 3.7 gm/cm² target of 93% enriched ^{10}B . The bound state region is delineated, with the arrow pointing at the ground state. At a 5° spectrometer setting a production cross section of 46 $\mu\text{b/sr}$ is expected from DWBA calculations.

A spectrum from $\Lambda^{10}\text{B}$, obtained with the following cuts, is shown in Fig. 6a:

- a) the excitation energy has been constrained between -12 and +6 MeV,
- b) the time is constrained to an acceptance window of 35 nanoseconds,
- c) the data are binned in 2 keV γ -ray energy intervals.

A candidate for the M-1 spin-flip transition is seen near $E_\gamma = 160$ keV. It is interesting to note that this is very close to the prediction for $\Lambda^{10}\text{B}$ of Millener et al., and if verified, would constitute a strong confirmation of his analysis. Further supporting evidence is presented by Fig. 6b, which shows the spectrum obtained with the same time cut, but for the excitation region below the bound state region, and hence represents background. Similarly, no peak is seen for $E_{\text{ex}} > 12$ MeV. Thus the peak satisfies our requirements for hypernuclear radiation.

Heavier hypernuclear systems can be investigated and more complex spectra obtained if we can refine our tools and improve

Fig. 6a,b. Ge spectra obtained from cuts of regions A (background, right) and B (bound state, left) of Fig. 5.

our overall efficiency factor, which is now at one in a billion. Increases in kaon intensity will help only if we can learn to handle the increased rates, or cut down on pion contamination or both. Progress in this exciting and wide-open field depends on solving these immense experimental difficulties and on the continued availability of kaon beams. We need "kaon factories" such as are proposed at Los Alamos, Vancouver, or in Europe. Perhaps photoproduction of hypernuclei can be exploited at the new electron accelerators. The future should be very interesting in this field.

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REFERENCES

1. B. Povh, Rep. Prog. Phys. 39, 823 (1976).
2. C. B. Dover and G. E. Walker, "The Interaction of Kaons with Nucleons and Nuclei", Phys. Reports 89 (1982).
3. W. Bruckner et al., Phys. Lett. 73B, 157 (1978); A. Bouyssy, Phys. Lett. 84B, 41 (1979); M. May et al., Phys. Rev. Lett. 47, 1106 (1981); M. May et al., Phys. Rev. Lett. 51, 2085 (1983).
4. R. Bertini et al., Proc. Intern. Conf. on Hypernuclear and Kaon Physics, Heidelberg, MP1H-1982-V20, p. 1.
5. M. Bedjidian et al., Phys. Lett. 83B, 252 (1979) and references contained therein.
6. R. H. Dalitz and A. Gal, Ann. Phys. (N.Y.) 116, 167 (1978).
7. D. J. Millener, private communication (1984).