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EXPERIMENTS WITH Λ HYPERNUCLEI

Morgan May

Brookhaven National Laboratory, Upton, New York, 11973, USA

Abstract

Recent observations of hypernuclear bound states in experiments at the Brookhaven National Laboratory Alternate Gradient Synchrotron are described. Gamma rays from hypernuclei have been observed in coincidence with a (K^-,π^-) energy difference spectrum. The energy resolution and purity of the (K^-,π^-) spectrum demonstrates the hypernuclear origin of the gamma rays. The case of $_{\Lambda}{}^{7}Li$ is discussed in detail as it represents the first successful application of the technique. Experiments of this kind can benefit greatly from the increased kaon beam intensity that will be available at LAMPF II.

Introduction

The study of hypernuclei elucidates the difference between the nucleon nucleon and the hyperon nucleon interactions, and the consequences of these differences for nuclear structure. Ultimately these differences must be understood in terms of the substructure of baryons.

Observing electromagnetic transitions between hypernuclear levels is a powerful tool to investigate hypernuclear structure for the same reasons as it is in the nuclear case. The resolution available in γ-ray detection is roughly 100 times better than the resolution of currently available magnetic spectrometers.

In our experiment the γ rays are observed in coincidence with a pure sample of hypernuclear events in a narrow range of excitation energy selected by a magnetic spectrometer. This technique gives the necessary background rejection. However the double coincidence nature of the experiment makes the overall detection efficiency low. Experiments of this type will benefit greatly from the increased kaon beam intensity available at LAMPF II. Beam purity and halo must be improved so that the background rates in the γ detectors are not significantly higher than at present beam intensities.

Core Excited States in Λ Hypernuclei

The particle-stable excited states of Λ hypernuclei decay to the hypernuclear ground state by γ-ray emission. In most cases, the decay of the Λ particle (free lifetime 2.5 10^{-10} seconds) takes place after all γ transitions have occurred. The particle-stable states are in general core-excited states: the lambda is in an s orbit and the ^{A-1}Z nuclear core is in one of its excited states. Core excited states are split into doublets depending on the orientation of the lambda spin with respect to the angular momentum of the core. Promotion of the lambda particle to a p state requires about 10 MeV and usually brings the system above the threshold for particle emission.

The energy levels of hypernuclei depend on the Λ-n interaction and on the wave functions of the nuclear core states. In the core excited states the Λ occupies an orbit from which a nucleon would be excluded by the Pauli principle. The distinguishability of the lambda particle thus may make hypernuclear structure sensitive to characteristics of the nuclear wave function to which other processes are not.

For the core excited states of hypernuclei in the p shell, the interaction of the $s_{1/2}$ Λ particle with the p nucleons gives rise to four possible two-body spin terms. The lambda and the nucleon can be in a spin singlet or triplet state and in the triplet case, the total spin can couple to the orbital angular momentum to give total angular momentum 0, 1, or 2. Gal, Soper and Dalitz[1] characterize the four terms as spin-spin, symmetric and anti-symmetric spin orbit $(\sigma_\Lambda \pm \sigma_n)\ell_{\Lambda n}$, and tensor interactions. The spin orbit interaction may alternatively be divided into a part depending on the lambda spin $(\sigma_\Lambda \cdot \ell_n)$ and an induced spin orbit interaction $(\sigma_n \cdot \ell_n)$. The presence of only four two-body terms makes the determination of the complete Λn interaction a highly attractive goal. Deviation from this description will then test the knowledge of the core nuclear wave function and the presence of three-body interactions.

Formation of Λ Hypernuclei

The strangeness exchange reaction $K^- \ {}^AZ \rightarrow \pi^- \ {}_\Lambda^AZ$ is used to form hypernuclei. A neutron in the nucleus is converted to a Λ particle with relatively low momentum transfer; the Λ binds to the nuclear core forming a hypernucleus. Since this is a two-body reaction, an accurate measurement of the K^- and π^- momenta permits the calculation of the energy of the hypernucleus. The spectrum of hypernuclear states is observed by a missing mass technique. In our experiments at Brookhaven,[2,3] the K^- momentum is 800 MeV/c resulting in 730 MeV/c π^- at 0°. Momentum resolution of 2 10^{-3} is sufficient to resolve hypernuclear levels 3 MeV apart. Kaon and pion trajectory measurements are overconstrained so that the very large background of two-body kaon decays can be eliminated by geometric and kinematic requirements resulting in a pure sample of hypernuclear events.

Figure 1 shows the apparatus which consists of focussing magnetic spectrometers composed of quadrupole and dipole magnets to measure the kaon and pion momenta. Multiwire proportional counters determine the particle trajectories. A scintillation counter hodoscope is used for the position measurement at the furthest upstream position because of the high instantaneous rates (10^7 particles per second). Cerenkov counters and time-of-flight provide particle identification.

Bound States Observed in ${}_{\Lambda}^{13}C$

Figure 2 shows the spectrum of hypernuclear states observed[3] in ${}_{\Lambda}^{13}C$ using the (K^{-},π^{-}) energy difference technique described above. A ${}^{13}C_6H_6$ scintillation counter was used as the target at the Brookhaven hypernuclear spectrometer. The measured binding energy of the hypernuclear ground state (labeled 1 in the figure) agrees with the value observed in a photographic emulsion experiment.[4] The threshold for $\Lambda^{13}C \rightarrow \Lambda + {}^{12}C$ is at 11.69±.12 MeV excitation.[4] Thus only peaks 2 and 3 are excited bound states.

Peak 2 lies at 4.4±.3 MeV excitation. It is interpreted as a core excited state; the ${}^{12}C$ core is in its 4.44 MeV excited state and the Λ is bound to the core in an s state. A precise measurement of the difference in the excitation energy of the hypernuclear state and the corresponding core state is needed to determine the fine structure of the Λ nucleus interaction.

The peak labeled 3 in fig. 2 has dominant composition $(p_{1/2})_{\Lambda}$ with the ${}^{12}C$ core in its ground state. In a spectrum taken at 15° which results in momentum transfer near the maximum of the L=2 transition amplitude, we observe another state with dominant composition $(p_{3/2})_{\Lambda}\ {}^{12}C$ (ground state). The difference in energy of these two states determines the Λ nucleus spin orbit interaction $\varepsilon(p_{1/2})_{\Lambda} - \varepsilon(p_{3/2})_{\Lambda} = .36 \pm .3$ MeV. A more rigorous analysis confirms that the splitting of these states is in fact due to only the spin orbit interaction. This measurement confirms the conclusion[5] of the Heidelberg-CERN-Saclay-Strassbourg collaboration concerning the weak spin dependence of the Λ nucleus interaction.

Thus, the spin dependence of the Λ nucleus interaction and the effects of the 1s lambda particle on the nuclear core in the core excited states both appear to give rise to effects less than 300 KeV. To study these effects, much better energy resolution is needed than is available in current magnetic spectrometer experiments.

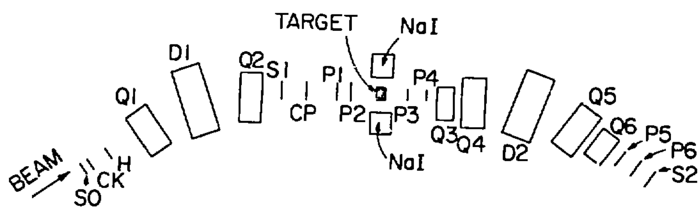

Figure 1 The hypernuclear spectrometer at Brookhaven. Quadrupole magnets Q1-Q6, dipole magnets D1 and D2. Multiwire proportional chambers P1-P6, scintillation counters S0-S2, Cerenkov counters CK and CP, scintillation counter hodoscope H. The target is surrounded by sodium iodide detectors NaI.

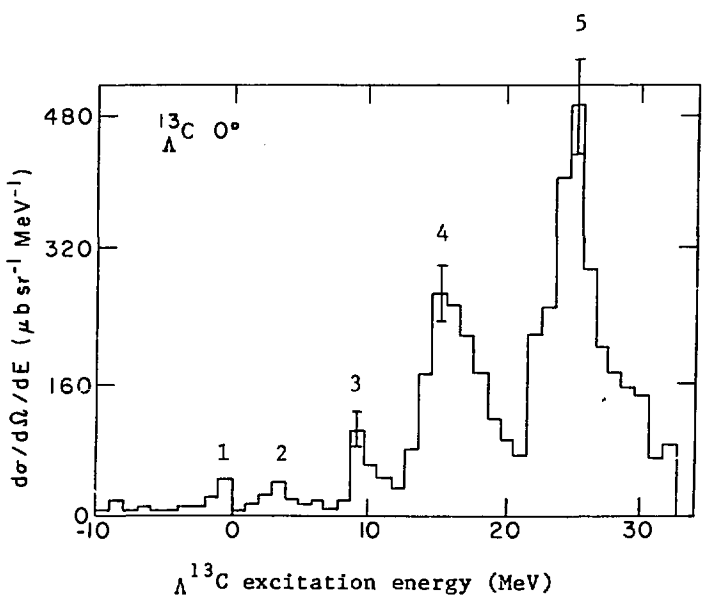

Figure 2 $_{\Lambda}^{13}C$ excitation energy spectrum observed in the reaction $^{13}C(K^-,\pi^-)_{\Lambda}^{13}C$ at 0° with p_K = 800 MeV/c.

KπY Coincidence Experiment

Observation of γ rays emitted in the deexcitation of hypernuclear bound states can provide excellent energy resolution. Standard techniques using sodium iodide crystals can give 65 KeV resolution for 1 MeV γ rays. Observation of the γ rays in coincidence with a pure sample of hypernuclei in a narrow interval of excitation energy gives powerful background rejection.

An 8 gm/cm^2 ^7Li target was exposed to an 820 MeV/c K^- meson beam of intensity 10^5 K^- per pulse at the Brookhaven AGS. Resolution in hypernuclear excitation energy was 7 MeV fwhm. The target was surrounded by an array of six 5" diameter by 3" thick NaI crystals at 4.5" from the target center and two 8" diameter by 6" thick NaI crystals at 8" from the target. The rates in each detector were greater than 10^5 per second. The combined photopeak efficiency of the six 5" x 3" detectors was 8% at 2 MeV; in this measurement the 5" x 3" detectors accounted for most of the detection efficiency.

For a total flux of 10^{10} K^- on target we observed 117,000 $_\Lambda{}^7Li$ hypernuclei. Of these, 59,000 were accompanied by a signal in at least one of the NaI detectors. Of these, 1400 events corresponded to excited hypernuclear bound states. In coincidence with these we observed 100 hypernuclear γ rays in a peak at 2 MeV.

$_\Lambda{}^7Li$ Hypernuclear γ Ray

The excitation energy spectrum of the hypernucleus $_\Lambda{}^7Li$ taken with resolution 7 MeV fwhm is shown in fig. 3. The excitation energy spectrum of this hypernucleus in the (K^-,π^-) reaction was first observed at CERN.[6] The measured binding energy of the Λ particle in the hypernuclear ground state agrees well with the value 5.58 ± .03 MeV determined in a photographic emulsion experiment.[7] The threshold for $_\Lambda{}^7Li \rightarrow {}_\Lambda{}^5He + d$ is at 3.94 MeV excitation.[7] Figure 4 shows the γ-ray spectrum observed in coincidence with the bound state

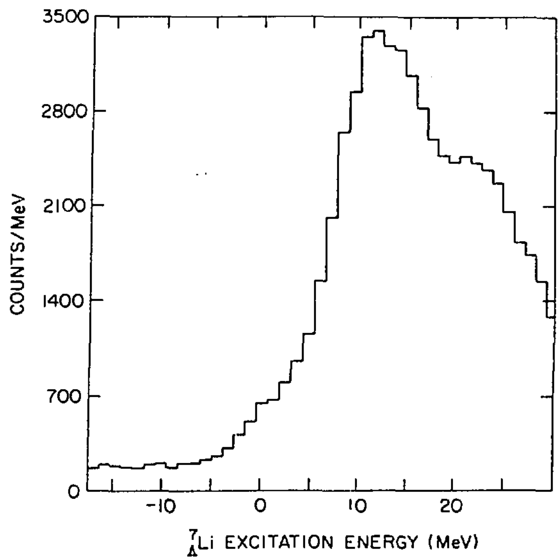

Figure 3 $_{\Lambda}{}^{7}$Li excitation energy spectrum observed in the reaction ^{7}Li$(K^-,\pi^-)_{\Lambda}{}^{7}$Li at 0° with p_K = 820 MeV/c.

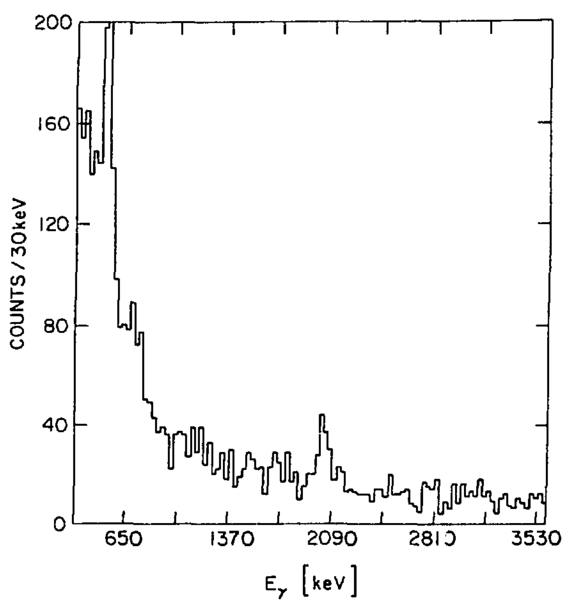

Figure 4 Gamma-ray energy spectrum observed in coincidence with $_{\Lambda}{}^{7}$Li excitation energy interval -2. to 6. MeV.

region of the spectrum defined as 2 ± 4 MeV excitation. One clear peak is observed in the spectrum aside from the .511 MeV positron annihilation γ ray. The energy of this γ ray is slightly above 2 MeV. The data presented here are preliminary. Our final analysis of the data will constrain the γ energy to within 20 KeV.

Figure 5 shows the γ-ray spectrum for several different regions of hypernuclear excitation energy. It is clear from the figure that the 2 MeV γ ray is associated only with the bound state region of ${}_{\Lambda}^{7}Li$. To fully establish this γ ray as resulting from a hypernuclear transition we must eliminate the possibility of nuclear origin. The hypernucleus decays releasing up to 180 MeV energy from the Λ conversion. Coincident γ rays may be emitted by the resulting nuclear fragments. However, there are no nuclear 2 MeV γ rays for $A < 7$. Thus the observed γ ray indisputably results from a hypernuclear transition.

Refering to fig. 6, the interpretation of this γ ray is straightforward. Figure 6 shows the energy levels of the ${}^{6}Li$ core and the resulting hypernuclear doublets in ${}_{\Lambda}^{7}Li$, and is adapted from the review article of Dalitz and Gal.[8] The relative population of the hypernuclear states in the (K^-,π^-) reaction at 0° is shown in brackets and is based on ${}^{7}Li$, ${}^{6}Li$ fractional parentage. We identify the observed 2 MeV γ ray with the strongest γ ray in the spectrum, the $5/2^+$ to ground state transition. The energy of the γ ray is only slightly perturbed from the 2.18 MeV excitation of the ${}^{6}Li$ core state.

A nuclear γ ray observed in the ${}_{\Lambda}^{7}Li$ experiment provides energy and timing calibration. The γ-ray spectrum observed in coincidence with ${}_{\Lambda}^{7}Li$ excitation energy in the interval 11 to 20 MeV shows a 3.56 MeV ${}^{6}Li$ nuclear γ ray. In this region of excitation the Λ can escape from the hypernucleus leaving the core in an excited state. The first excited state of ${}^{6}Li$ at 2.18 MeV does not emit γ rays because of its αd decay; both parity and isospin conservation forbid the decay of the 3.56 MeV state of ${}^{6}Li$ into αd.

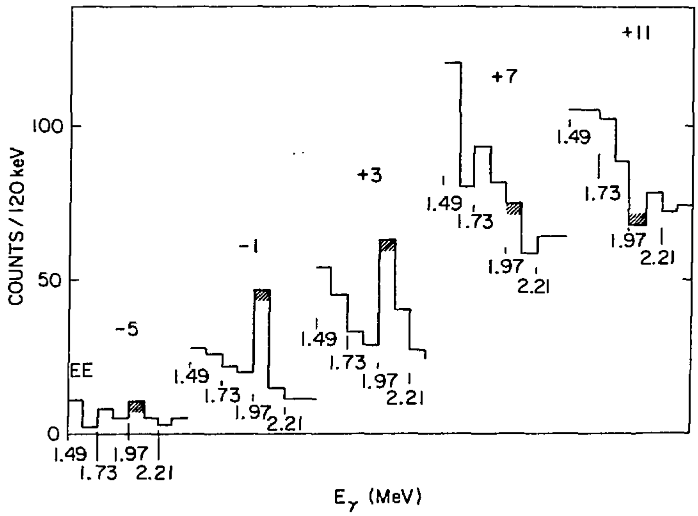

Figure 5 Gamma-ray energy spectra observed in coincidence with ${}_{\Lambda}^{7}Li$ excitation energy intervals. The central value of excitation energy (EE) is indicated above each spectrum. Excitation energy intervals are ± 2 MeV about the central value.

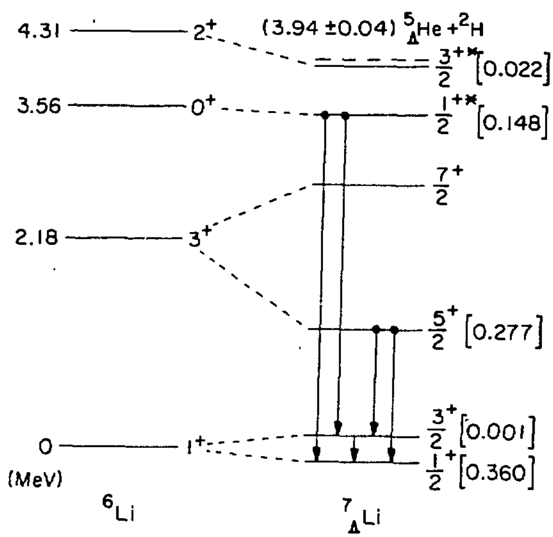

Figure 6 Energy spectrum of excited states of ${}^{6}Li$; the states of the ${}^{6}Li$ core give rise to doublets in the hypernucleus ${}_{\Lambda}^{7}Li$. Expected relative populations of the ${}_{\Lambda}^{7}Li$ hypernuclear states in the (K^{-},π^{-}) reaction at 0° are shown in brackets.

Based on a fit to the ground state binding energies of the p shell hypernuclei, Dalitz, Gal and Soper[1] estimated the parameters of the Λ-n interaction. They obtained a large value for the Λ-n spin orbit interaction $\sigma_\Lambda \cdot \ell_n$ and a correspondingly large shift for the $5/2^+$ excitation energy relative to the core state energy. They predicted[8] 1.35 MeV for the energy of the $5/2^+$ to ground state transition which we observed at 2 MeV. This problem may be attributed to the limitations of the data available at the time of their calculation. Inclusion of the energies of a few excited level, as well as the ground state energies, will result in an accurate determination of the interaction.

In addition to the transition observed in $_\Lambda{}^7Li$, hypernuclear γ rays in $_\Lambda{}^9Be$ and $_\Lambda{}^{16}O$ were also observed. These γ rays are interpreted, similarly to the $_\Lambda{}^7Li$ case, as transitions between core excited states (in fact the most copiously formed stable excited states) and the hypernuclear ground state; also as in $_\Lambda{}^7Li$, in both cases the energy of the γ ray is only slightly displaced from the energy of the excited state in the nuclear core.

The first excited state of ^8Be has excitation energy 2.94 MeV. We observe a γ-ray full energy peak in $_\Lambda{}^9Be$ of energy 3.08 MeV (preliminary data). We interpret this as being due to unresolved transitions from both members of the hypernuclear doublet built on the first excited state of ^8Be. The small energy difference between the hypernuclear excitation and the core excitation once again indicates weak spin dependence. Since we are, in this case, observing transitions from both members of a doublet to the ground state, the lack of apparent broadening of the peak from our known energy resolution gives an additional constraint on the spin dependence.

The hypernuclear γ ray observed in $_\Lambda{}^{16}O$ at roughly 6.5 MeV (preliminary data) likewise is only slightly displaced from the 6.18 MeV excitation energy of the ^{15}O core state on which it is based.

There are a small number of fundamental measurements to be made which will define the spin dependence of the lambda nucleus interaction. Once these measurements are completed, there will remain the problem of relating the effective lambda-nucleon interaction in hypernuclei to the free lambda nucleon interaction. In hypernuclei we can measure spin dependent effects giving rise to energy splittings as small as 50 keV. Experiments studying the lambda nucleon interaction by lambda proton scattering will not be sensitive to such subtle effects in the foreseeable future.

Acknowledgement

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