# Observation of Hypernuclear Gamma-Ray Transitions in ${}^{7}_{\Lambda}$Li and ${}^{9}_{\Lambda}$Be

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$\gamma$-ray transitions of energy $2.034 \pm 0.023$ MeV in the hypernucleus ${}^{7}_{\Lambda}$Li and 3.079 $\pm 0.040$ MeV in the hypernucleus ${}^{9}_{\Lambda}$Be are observed. In both cases, the energy of the $\gamma$ ray in the hypernucleus ${}^{A}_{\Lambda}Z$ is very close to the energy of the first excited state of the nuclear core. The $\gamma$ rays are interpreted as arising from core transitions in the presence of the $\Lambda$ particle. The size of the shift places limits on the strength of the $\Lambda N$ spin-dependent interaction.

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In an experiment at the Brookhaven alternating-gradient synchrotron (AGS), $\gamma$-ray transitions in the hypernuclei ${}^{7}_{\Lambda}$Li and ${}^{9}_{\Lambda}$Be have been established for the first time. The $\gamma$ rays were observed in coincidence with hypernuclei which had been positively identified through their formation reaction $(K^-,\pi^-)$. In addition, a $\gamma$-ray peak interpreted as resulting from transitions in ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He has been observed, confirming the results of a previous experiment[1] with stopped kaons.

Observing electromagnetic transitions between hypernuclear levels is a powerful tool to investigate hypernuclear structure, for the same reasons as in the nuclear case. The resolution obtained by $\gamma$-ray detection in NaI scintillators is roughly an order of magnitude better than that of currently available hypernuclear magnetic spectrometers.[2] The improved energy resolution of the present experiment gives a corresponding improvement in sensitivity to the small, spin-dependent parts of the $\Lambda N$ interaction.

Hypernuclei are formed with use of $K^-$ mesons at 820 MeV/$c$ in the hypernuclear spectrometer[2,3] at the AGS. A neutron in the nucleus is converted to a $\Lambda$ particle forming a hypernucleus with the emission of a pion. An accurate measurement of the kaon and pion momenta permits a calculation of the energy spectrum of the hypernuclear states excited. Thus, $\gamma$-ray spectra are obtained as a function of hypernuclear excitation. In this experiment, resolution in excitation energy was 7 MeV full width at half maximum. Kinematic and geometric reconstruction of the event eliminates the very large background arising from kaon decays and results in a sample of hypernuclei with low background contamination. A major source of background in the $\gamma$-ray spectra in the region of bound hypernuclear states arises from the weak decay of the hypernucleus.

The 8-g/cm$^2$ Li target was surrounded by an array of six 12.7-cm-diam by 7.6-cm-thick NaI crystals at 11.4 cm from the target center and two 20.3-cm-diam by 15.2-cm-thick NaI crystals at 20 cm from the target. The combined photopeak efficiency of the six smaller detectors was 6% at 2 MeV; in this measurement the 12.7-cm $\times$ 7.6-cm detectors accounted for most of the detection efficiency.

Radioactive sources $^{203}$Hg, $^{56}$Co, and natural thorium were placed in the vicinity of the target, providing calibration $\gamma$ rays at 0.279, 0.511, 0.847, 1.238, and 2.615 MeV. The sources were embedded in plastic scintillation counters so that the $\beta$ particles accompanying the calibration $\gamma$ rays could be detected and used to mark the event. Calibration $\gamma$ rays were recorded in all NaI detectors during the beam pulse to monitor rate-dependent variations of the energy calibration and line shape.

Figure 1(a) shows the $\gamma$-ray spectrum observed in coincidence with the bound-state region of ${}^7_\Lambda$Li defined as $-2$ to 6 MeV excitation. The binding energy of the $\Lambda$ particle in the hypernuclear ground state determined in a photographic emulsion experiment[4] ($5.58 \pm 0.03$ MeV) has been used to determine zero excitation energy. The first threshold for particle emission is ${}^7_\Lambda\mathrm{Li} \to {}^5_\Lambda\mathrm{He} + d$ at 3.94 MeV excitation. One obvious peak is observed in the spectrum aside from the 0.511-MeV positron-annihilation $\gamma$ ray. The energy of the $\gamma$ ray is $2.034 \pm 0.023$ MeV. The error is derived from a least-squares peak fit and includes an additional systematic error estimated from the observation of the 0.511-MeV annihilation peak and a 3.5-MeV nuclear $\gamma$ ray from $^6$Li in our spectra. The full energy peak contains 85 events and its width is consistent with the experimental resolution of 120 keV.

Evidence which supports the hypernuclear origin of the $\gamma$ ray is as follows: (a) Based on the known efficiency of the NaI array, at least one quarter of the bound-state events are accompanied by the $\gamma$ ray. (b) It does not appear in coincidence with other regions of excitation energy. (c) There are no 2-MeV nuclear $\gamma$ rays for $A \leq 7$.

Referring to Fig. 1, the interpretation of this $\gamma$ ray is straightforward. The inset diagram in the figure, which is adapted from the review article[5] of Dalitz and Gal, shows the known energy levels of the $^6$Li core. The addition to the core of a $\Lambda$ in an $s_{1/2}$ state splits the core states into hypernuclear doublets. The expected relative population of the hypernuclear states in the $(K^-,\pi^-)$ reaction at 0° is shown in brackets and is based on $^7$Li,$^6$Li fractional parentage. We identify the observed 2-MeV $\gamma$ ray with the strongest expected $\gamma$ ray, the $\frac{5}{2}^+$ to ground-state transition. The energy of the $\gamma$ ray is only slightly shifted from the 2.18 MeV excitation of the $^6$Li core state. Note that the 2.18-MeV $^6$Li core state decays to $\alpha + d$ and not by $\gamma$ emission. The additional binding provided by the $\Lambda$ particle makes the hypernuclear state particle stable.

The observed shift is consistent with a small value of the two-body spin-orbit interactions $(\vec{\sigma}_\Lambda \pm \vec{\sigma}_n)\vec{l}_{n\Lambda}$. The related one-body spin-orbit in-

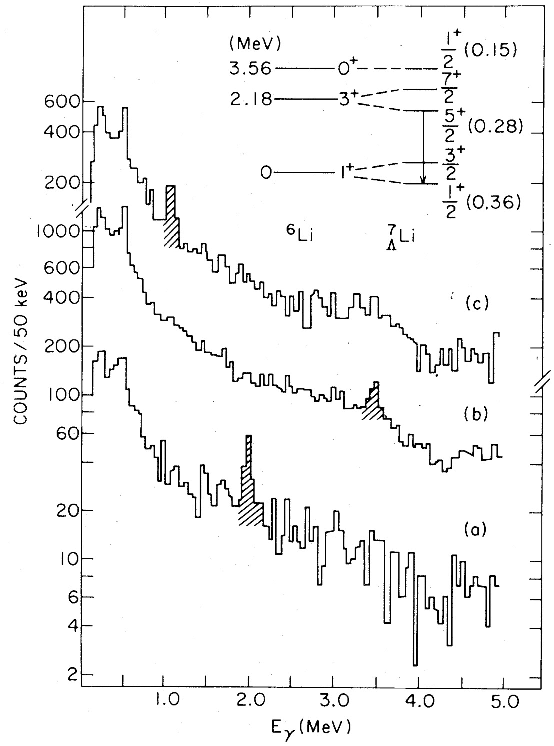


FIG. 1. Gamma-ray energy spectra observed in coincidence with the $^7$Li$(K^-,\pi^-)$ reaction at 0° for $P_K = 820$ MeV/$c$, for $10^{10}$ kaons on target. Spectra are shown for excitation-energy intervals of (a) $-2$ to 6 MeV, (b) 6 to 22 MeV, and (c) 22 to 39 MeV. The inset shows the energy spectrum of excited states of $^6$Li which give rise to doublets in the hypernucleus ${}^7_\Lambda$Li. Expected relative populations of the ${}^7_\Lambda$Li hypernuclear states in the $(K^-,\pi^-)$ reaction at 0° are shown in brackets.

teraction $\vec{\sigma}_\Lambda \cdot \vec{l}_\Lambda$ has been shown to be small by previous experiments, e.g., by the ${}^{13}_{\Lambda}$C spectrum.[3] Earlier model calculations,[5] using large spin-orbit terms derived from ground-state binding energies, predicted a value of 1.35 MeV for the $\frac{5}{2}$-$\frac{1}{2}$ transition, i.e., a shift of 0.8 MeV with respect to the core level spacing compared with the observed shift of 0.15 MeV. In view of the smallness of the observed shift it may be necessary to consider other effects besides the four two-body spin-dependent terms included by Dalitz and Gal,[5] e.g., many-body forces,[6,7] $\Lambda$-$\Sigma$ mixing,[7] or clustering effects.[8] The central $\Lambda N$ interaction will contribute to an energy shift if the radius of the hypernucleus is different in the initial and final states. This last effect is opposite to the observed shift in ${}^{7}_{\Lambda}$Li.

No other unambiguous peaks appear in the observed bound-state spectrum, Fig. 1(a). The ground-state hypernuclear doublet in ${}^{7}_{\Lambda}$Li is split primarily by the spin-spin $\Lambda n$ interaction because of the ${}^3S$ nature of the ${}^6$Li ground state. Considering the known[1] ground-state doublet splitting in $s$-shell hypernuclei where only the spin-spin interaction is effective, we expect the $\frac{1}{2}^+$ state to be the ${}^{7}_{\Lambda}$Li ground state and a calculation[9] extrapolates a doublet splitting of approximately 500 keV. Both $\frac{1}{2}^+$ and $\frac{3}{2}^+$ members of the ground-state multiplet will be populated from the $\frac{5}{2}^+$ level near 2 MeV, but the transition to the $\frac{3}{2}^+$ level is expected to be relatively weak because angular momentum recoupling favors the $\frac{1}{2}^+$ state. Thus the spin-flip $\gamma$ transition connecting the ground-state doublet members will also be weak, unless the $\frac{3}{2}^+$ level is fed by other transitions. One possibility is the $\frac{1}{2}^+$ $T=1$ level supposed to be near 3.5 MeV. This level may or may not be bound since its expected energy lies near the particle threshold of 3.94 MeV.

The spectrum of Fig. 1(a) is not of sufficient quality near 3 MeV to establish the presence of a 3-MeV $\gamma$ ray of the expected intensity; however, neither is that transition ruled out by our data. On the other hand, the annihilation peak near 511 keV seems unusually broad in the bound-state excitation-energy cut. This broadening might be due to the hypernuclear ground-state doublet transition or the presence of nuclear lines from ${}^7$Be* or ${}^7$Li* formed by hypernuclear decay. Calculations lead us to expect the nuclear contribution to be small.[10]

Herrera *et al.*[11] have reported a $\gamma$ ray at 789 keV, observed in a forward $(K,\pi)$ reaction at $P_K \approx 1.7$ GeV/$c$ on ${}^7$Li. The present experiment has about 40 times greater sensitivity due to greater flux and detector solid angle. We see no evidence for a $\gamma$-ray transition at this energy.

The threshold for ${}^{7}_{\Lambda}\mathrm{Li} \to \Lambda + {}^6\mathrm{Li}$ is at $5.58 \pm 0.03$ MeV. In coincidence with a region of ${}^{7}_{\Lambda}$Li excitation energy above this threshold (6 to 22 MeV) a $\gamma$ ray of energy $3.546 \pm 0.043$ MeV is observed [Fig. 1(b)]. This $\gamma$ ray is attributed to a nuclear transition in ${}^6$Li. The $\Lambda$ escapes from ${}^{7}_{\Lambda}$Li leaving the ${}^6$Li nucleus in an excited state; the 3.56-MeV, $T=1$, $0^+$ state of ${}^6$Li, which is forbidden to decay to $\alpha + d$ by parity conservation, emits the $\gamma$ ray. Observation of this nuclear $\gamma$ ray provides an additional energy calibration.

The thresholds for ${}^{7}_{\Lambda}\mathrm{Li} \to {}^{4}_{\Lambda}\mathrm{He} + {}^3\mathrm{H}$ and ${}^{7}_{\Lambda}\mathrm{Li} \to {}^{4}_{\Lambda}\mathrm{H} + {}^3\mathrm{He}$ are at $18.98 \pm 0.05$ MeV and at $19.33 \pm 0.05$ MeV, respectively. In coincidence with a region of ${}^{7}_{\Lambda}$Li excitation energy above this threshold (22 to 39 MeV) a $\gamma$-ray peak of energy $1.108 \pm 0.010$ MeV is observed [Fig. 1(c)]. The peak is absent below this threshold. Bedjidian *et al.*[1] have reported a $\gamma$-ray transition of energy $1.04 \pm 0.04$ MeV in ${}^{4}_{\Lambda}$H and a $\gamma$-ray transition of energy 1.14 $\pm$ 0.04 MeV in ${}^{4}_{\Lambda}$He. These $\gamma$ rays are ascribed to spin-flip transitions of the $\Lambda$ particle. The peak observed in the present experiment is near the average of the two energies reported by Bedjidian *et al.*; our experimental resolution of 84 keV is insufficient to resolve these reported lines.

The excitation spectrum of the hypernucleus ${}^{9}_{\Lambda}$Be was obtained with a flux of $1.9 \times 10^{10}$ $K^-$ on an 8-g/cm$^2$ target. In coincidence with the bound-state region of the spectrum defined as $-2$ to $+5$ MeV excitation, a $\gamma$-ray peak of energy 3.079 $\pm$ 0.040 MeV is observed (Fig. 2). We interpret this peak as being due to unresolved transitions from both members of the hypernuclear doublet built on the first excited state of ${}^8$Be (Fig. 2). The first excited state of ${}^8$Be lies at 2.94 MeV and decays into two $\alpha$ particles: The additional binding provided by the presence of the $\Lambda$ makes the hypernuclear doublet particle stable. The ground state and first excited state of ${}^8$Be differ in orbital angular momentum but have the same spin structure. Unlike the ${}^{7}_{\Lambda}$Li case, both members of the doublet are predicted to be excited with roughly equal intensity.[5] 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 and more direct constraint on the two-body $\Lambda N$ spin-orbit interaction. The observed $\gamma$-ray peak has width $150 \pm 30$ keV compared to our estimated resolu-

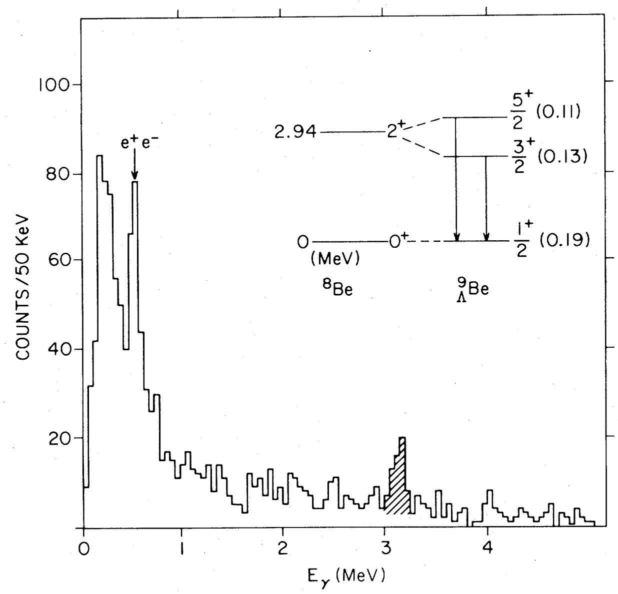


FIG. 2. Gamma-ray energy spectrum observed in coincidence with the bound-state region of the $^9_\Lambda$Be excitation-energy spectrum, for $^9$Be($K^-, \pi^-$) at 0°, with $1.9 \times 10^{10}$ kaons on the target. The inset shows the energy levels for $^8$Be, as known up to 3 MeV from experiment, and expected levels in $^9_\Lambda$Be. The numbers in brackets are the relative formation rates for the reaction $K^- + {}^9\text{Be} \rightarrow \pi^- + {}^9_\Lambda\text{Be}^*$ at 0°.

tion of ≈ 160 keV. If both members of the doublet are excited with equal intensity, as expected from their coefficients of fractional parentage,[5] the doublet splitting is less than 100 keV with 95% confidence. This measurement has provided valuable constraints for a revision[8] of the Dalitz and Gal evaluation of the $\Lambda N$ effective interaction in the nuclear $p$ shell.

In summary, the present experiment establishes $\gamma$-ray transitions in $p$-shell hypernuclei providing new information about the $\Lambda N$ interaction. An experiment is in preparation to continue these studies using germanium detectors to observe the $\gamma$-ray transition between members of hypernuclear doublets, thus directly measuring the spin dependence of the interaction.

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[1]M. Bedjidian, E. Descroix, J. Y. Grossiord, A. Guichard, M. Gusakow, M. Jacquin, M. J. Kudla, H. Piekarz, J. Piekarz, J. R. Pizzi, and J. Pniewski, Phys. Lett. 83B, 252 (1979).

[2]M. May, in *Proceedings of the International Conference on Hypernuclear and Kaon Physics* (Max-Planck Institut für Kernphysik, Heidelberg, 1982, p. 63; H. Piekarz, *ibid.*, p. 37.

[3]M. May, H. Piekarz, R. E. Chrien, S. Chen, D. Maurizio, H. Palevsky, R. Sutter, Y. Xu, P. Barnes, B. Bassalleck, N. J. Colella, R. Eisenstein, R. Grace, P. Pile, F. Takeutchi, W. Wharton, M. Deutsch, J. Piekarz, S. Bart, R. Hackenburg, E. V. Hungerford, B. Mayes, L. Pinsky, R. Cester, and R. L. Stearns, Phys. Rev. Lett. 47, 1106 (1981).

[4]M. Juric, G. Bohm, J. Klabuhn, U. Krecker, F. Wasotzki, G. Coremans-Bertrand, J. Sacton, G. Wilquet, T. Cantwell, F. Esmael, A. Montwill, D. H. Davis, D. Kielczewska, T. Pniewski, T. Tymieniecka, and J. Zakrzewski, Nucl. Phys. B52, 1 (1973).

[5]R. H. Dalitz and A. Gal, Ann. Phys. (N.Y.) 116, 167 (1978).

[6]A. Gal, J. M. Soper, and R. H. Dalitz, Ann. Phys. (N.Y.) 113, 79 (1978).

[7]B. F. Gibson and D. R. Lehman, in *Proceedings of the International Conference on Hypernuclear and Kaon Physics* (Max-Planck Institut für Kernphysik, Heidelberg, 1982), p. 161.

[8]Toshio Motoba, Hiroharu Bando, and Koyomi Ikeda, Prog. Theor. Phys. 70, 1 (1983).

[9]D. J. Millener, A. Gal, and C. B. Dover, to be published.

[10]A. Gal, private communication.

[11]J. C. Herrera, J. J. Kolata, H. Kraner, C. L. Wang, R. Allen, D. Crockley, A. Hassan, A. Kanofsky, and G. Lazo, Phys. Rev. Lett. 40, 158 (1978).