Observation of Characteristic γ Radiation from the $(K^-, \pi^-\gamma)$ Reaction on Light Nuclei

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Characteristic γ radiation produced in the reaction $^7\mathrm{Li}(K^-, \pi^-\gamma)$ at a kaon momentum of 1.7 GeV/c has been analyzed with Ge(Li) detectors. A transition at 789 ± 4 keV is a candidate for a new hypernuclear γ-ray line. The intensity of this transition corresponds to a c.m. forward-angle production cross section of 48 ± 12 μb for the reaction $^7\mathrm{Li}(K^-, \pi^-\gamma)$. Several γ-ray lines observed with ^{6}Li, Be, B, C, and O targets could be ascribed to ordinary nuclear transitions.

The investigation of excited states of hypernuclei, i.e., of bound structures containing nucleons and one or more strange hyperons, may be expected to improve our understanding of the nucleon-hyperon interaction. A hypernucleus is produced in the (K^-, π^-) reaction when the incident kaon converts a neutron inside the target nucleus to a Λ hyperon $(K^- + n \rightarrow \pi^- + \Lambda)$, which is subsequently captured by the nucleus. Previous hypernuclear γ-ray experiments,[1,2] which resulted in the identification of one transition ascribed to $^4_\Lambda\mathrm{H}^*$, were performed with stopped K^- mesons. In this case, the momentum transferred to the Λ is rather large (~250 MeV/c) and therefore the probability that the resultant hypernucleus will decay by emitting several nucleons before reaching a more stable configuration is enhanced. On the other hand, at $P_K \simeq 510$ MeV/c the momentum transfer can be reduced to zero,[3] but then high-lying states of the hypernuclear system are predominantly formed.[4] A further advantage of low momentum transfer is the fact that the hypernuclear γ-ray lines will not be severely Doppler broadened.

The present experiment was designed to search for electromagnetic transitions between low-lying states of light hypernuclei, using an immediately available, intense, medium-energy kaon beam of momentum $P_K = 1.7$ GeV/c at the Brookhaven National Laboratory alternating-gradient synchrotron (AGS). The 0° momentum transfer for this beam is 130 MeV/c. In this Letter, we report primarily results obtained with a ^{7}Li target. Preliminary analysis of data obtained with ^{6}Li, Be, B, C, and O, targets indicates several γ-lines, which, however, can be ascribed to ordinary nuclear transitions.

A schematic of the experimental setup, which used Beam 5 at the AGS, is shown in Fig. 1. The incident beam was defined by the scintillators B_1–B_3 and the veto counter A. The 3.75-cm-diam aperture in A defined a maximum beam size but the acutal beam diameter, measured with a photographic emulsion, was 2.5 cm. The first threshold gas Cherenkov counter C_1 rejected pion or other light-particle contamination in the beam, and the liquid-cell differential Cherenkov counter C_2 identified kaons and provided additional pion rejection. Although the ratio $\pi/K = 10$ in Beam 5, the pion contamination in our logic gate was less than 0.05%. The incident momentum (1.7 GeV/c, $\Delta P/P = \pm 1\%$) was chosen to be as low as practical without too much sacrifice of intensity. Typically, 800 K^- mesons were deliv-

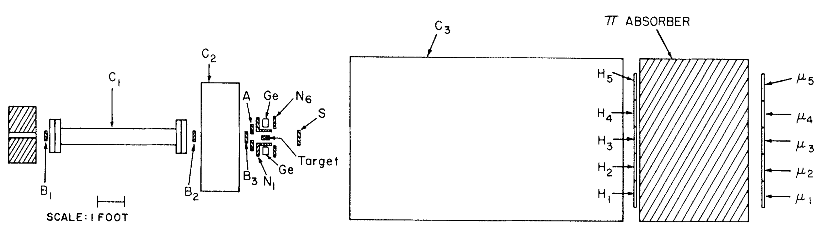

FIG. 1. Schematic diagram of the experimental setup.

ered onto the target per AGS pulse.

Outgoing particles were detected by the scintillator S (which defined a lab scattering angle of $\pm 9.5°$), the second threshold gas Cherenkov counter C_3 (which identified pions with momentum > 1.2 GeV/c), and the hodoscope counters H_1–H_5. Since muons from K^- decays after C_2 resemble (K, π) events and hence constitute a major source of background, it was necessary to eliminate such events with the veto counters μ_1–μ_5 placed behind a 1.25-m steel wall. This absorber thickness was sufficient to eliminate all pions from the beam, but it also prevented some low-energy muons from reaching the veto counters so that suppression of the $K^- \to \mu^- + \nu$ mode was incomplete.

Another and even more important contribution to the background is the 21% branch $K^- \to \pi^- + \pi^0$, which is not rejected by the μ counters. In this case, the subsequent decay of the π^0 into two γ rays also provides $(K^-, \pi^-\gamma)$ coincidence events which are only partially suppressed by the momentum restrictions on the outgoing π^- particle. Though such high-energy γ rays are not easily detected by the Ge(Li) detectors, pair production in neighboring material results in a strong, diffuse source of the 511-keV γ rays which are the major component of target-out spectra [Fig. 2(b)]. As a measure of the background, we note that $K\pi$ triggers, defined by

$$K\pi = B_1 B_2 B_3 \overline{A} \overline{C}_1 C_2 S C_3 H \overline{\mu}$$

(where H and μ represent "OR" logic of H_1–H_5 and μ_1–μ_5, respectively), occurred for 6.0% of incident kaons with no target, and 6.4% with a ^{7}Li target in place.

The target was a 5-cm-diam by 12.5-cm-long cylinder of isotopically separated Li metal (> 99% ^{7}Li), encased under vacuum in a polystyrene container. γ rays were detected by two 15%-efficient [relative to NaI(Tl) at 1332 keV] Ge(Li) detectors placed at 90° to the beam. These detectors were surrounded by veto counters N_1–N_6 which rejected events in which charged particles penetrated either detector. In addition, the γ-ray coincidence circuitry was disabled for 10 μs following each such charged-particle event to allow the detectors to recover. Typical coincidence rates were $K\pi = 500$ triggers/pulse and $K\pi\overline{N}\gamma = 0.45$ events/pulse for each detector. From the effective $K\pi\gamma$ resolving time of < 0.5 μs and the Ge(Li) singles counting rate of ~500 per pulse, we compute an "accidentals" rate of $\lesssim 0.12$ counts/pulse, compared to the observed "target-out"

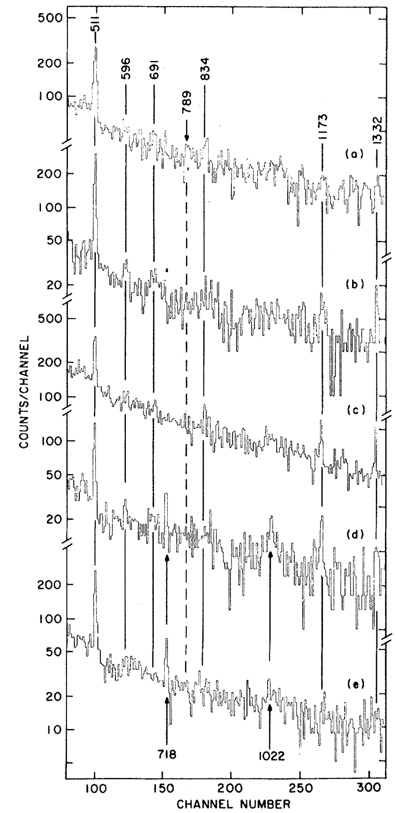

FIG. 2. γ-ray spectra observed in the present experiment. (a) ^{7}Li target, 4.83×10^8 K^-; (b) no target, 4.66×10^8 K^-; (c) ^{7}Li target, 1.00×10^8 π^-; (d) B target, 3.01×10^8 K^-; (e) C target, 4.24×10^8 K^-. The energies of various γ rays are indicated in keV. Note the absence of the 789-keV γ ray in all but the first spectrum.

counting rate of 0.17 counts/pulse. (Note that this comparison should be quite valid, since the γ-ray singles rate, as well as the rate of $K\pi$ triggers, did not depend to first order on whether a target was in place.) In addition, "true" $K\pi\gamma$ (511 keV) events are expected in the "target-out" spectrum due to the $(K^-, \pi^-[\pi_0 \to 2\gamma])$ process discussed above.

The spectrum obtained with the ^{7}Li target in place, after ~ 6×10^4 AGS pulses, is shown in Fig. 2(a). In addition to the 511-keV line from positron annihilation and the 834.81-keV calibration line from an indigenous ^{54}Mn source, three other lines are present in this spectrum between 500 and 1000 keV at the 3 standard deviation (S.D.) level. These were measured to be 600, 681, and 789 keV all with an uncertainty of ± 4 keV. The first of these lines, which also occurs in the "target-out" spectrum [Fig. 2(b)], corresponds to inelastic excitation of the 596-keV first excited state of ^{74}Ge via neutral-particle scattering in the detector.[5] The 681-keV line also has a counterpart in the "target-out" spectrum which is quite broad but nonetheless shows some evidence of superimposed narrow structure near 680 keV. In this case, the line is due to inelastic excitation of the 690-keV first excited state of ^{72}Ge.[5] Furthermore, a narrow 689-keV line is also observed in a spectrum taken with 1.7-keV/c pions incident on ^{7}Li [Fig. 2(c)]. Because of the difference in the measured energies of these γ rays, it is possible that the 681-keV line from ^{7}Li is a hypernuclear γ ray. However, the evidence from present data is inconclusive, at best. Finally, the 789-keV γ-ray does not appear in either the "target-out" spectrum [Fig. 2(b)] or the pion-induced spectrum [Fig. 2(c)]. Furthermore, no 789-keV line was observed with any of the other targets used in this experiment,[6] and no nuclear γ ray of this energy is expected from likely light- to medium-mass contaminants. Therefore, this line must be considered to be an excellent candidate for a new hypernuclear γ ray.

It should be mentioned that Bedjidian *et al.*[2] initially reported a 750-keV hypernuclear γ ray from their analysis of a low-resolution NaI(Tl) spectrum obtained with negative kaons stopping in ^{7}Li. They subsequently retracted this assignment when it was noticed that much of the intensity of the line was due to kaon interactions in their C moderator. We have observed[6] that the 718-keV nuclear γ ray from the first excited state of ^{10}B is very strongly produced in the $(K^-, \pi^-\gamma)$ reaction on C at 1.7 GeV/c [Fig. 2(e)]. The 750-keV energy reported by Bedjidian *et al.* then suggests the possibility that part of this line may be due to our 789-keV γ ray. In addition, the 1021.8-keV transition from the second excited state of ^{10}B was also seen with the C target in place [Fig. 2(e)]. This observation, combined with the data presented in Ref. 1, leads to the conclusion that at least part of the intensity of the "1.08-MeV" hypernuclear line reported in Ref. 2 was actually due to the ^{10}B nuclear line. This result demonstrates the utility of high-resolution Ge(Li) spectrometry for disentangling these complex γ-ray spectra. Of course, the Doppler effect restricts such high-resolution experiments to the low-momentum-transfer case.

The γ-ray spectrum above 1 MeV [Fig. 2(a)] shows no evidence for any peaks at the 3-S.D. level. However, the 1173- and 1332-keV γ rays from ^{60}Co are visible in the "target-out" and pion-induced spectra [Figs. 2(b) and 2(c)] and counterparts for the first of these lines can be found at the 2-S.D. level in Fig. 2(a). A 2-S.D. peak at 1119 keV also appears in both spectra, and there is some evidence for a broad structure near 1.25 MeV which may not be present in the "target-out" or pion-induced spectra. However, none of these structures can be considered as a good candidate for a hypernuclear γ ray on the basis of present data.

TABLE I. Forward-angle production cross sections for γ rays observed in this experiment.

Target	$\bar{E}_\gamma$ (keV)	Source	σ (μb)
^{7}Li	789	^{7}Li*	48 ± 12
B	718	^{10}B*	30 ± 6
B	1021	^{10}B*	35 ± 9
C	718	^{10}B*	33 ± 8
C	1021	^{10}B*	28 ± 9

The forward-angle cross section for the (K^-, π^-) reaction corresponding to the observed intensity of the 789-keV line was computed, using the efficiency of the Ge(Li) detector measured with calibrated sources. Corrections were applied for the π^- detection efficiency (84%) and the (negligible) dead time of the coincidence circuitry. The resulting value was $\sigma = 48 \pm 12$ μb (integrated over the angle subtended by counter S), where the quoted error is purely statistical and does not include possible systematic errors. The most important such error is likely to be the assumption that the (π^-,γ) angular correlation is isotropic. The effect of anisotropy will be somewhat damped by the fact that the ^{7}Li target represents a poor-geometry source of γ radiation. Nevertheless, isotropy was explicitly assumed in the integration over the source dimensions. The forward-angle production cross sections for all γ-ray lines observed in this experiment are listed in Table I.

In conclusion, we have observed a 789-keV line from the reaction ^{7}Li$(K^-, \pi^-\gamma)$ which is an excellent candidate for a new hypernuclear γ ray. The corresponding forward-angle cross section for the (K^-, π^-) reaction is $\sigma_{\text{c.m.}} = 48 \pm 12$ μb under the assumption of isotropy in the $\pi^-\gamma$ angular correlation. This γ ray, if it is in fact hypernuclear, may correspond to the predicted[7] $\frac{5}{2}^+ \to \frac{1}{2}^+$ $E2$ transition in ^{7}Li and hence give information on the sign and magnitude of spin-dependent terms in the ΛN potential. One potentially interesting experiment would then be to measure the mean life of the 789-keV state which is expected to be about

200 ps, i.e., approximately the same as the lifetime of the free Λ particle. In any event, the present experiment provides an upper limit of about 20 μb for the 0° production cross section of other γ-emitting hypernuclear states in the (K^-, π^-) reaction at 1.7 GeV/c, and demonstrates conclusively that present technology is sufficient to measure such small cross sections in particle-γ coincidence experiments with currently available kaon beams.

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Difference in Analyzing Powers for (p,t) Reactions Due to a Phase Change of Interference between Direct and Indirect Processes in Two-Nucleon Transfer Reactions

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A marked difference between analyzing powers for reactions ^{128}Te$(p,t)^{126}$Te(2_1^+) and ^{110}Pd$(p,t)^{108}$Pd(2_1^+) with polarized protons has been observed, while the ground-state transitions have shown similar analyzing powers. The difference is accounted for as a result of a phase change of the interference between direct and inelastic multistep processes in two-neutron pickup reactions. The origin of this phase change is elucidated on the basis of the microscope description of the collective quadrupole oscillation of nuclei.

The interference between a direct process and inelastic multistep processes (nucleon transfer followed by inelastic scattering and the inverse) in two-nucleon transfer reactions is quite sensitive to the nuclear structure involved. The neutron-number (N) dependence of this type of interference in excitation of the first 2^+ (2_1^+) states has been extensively studied for the nuclei of $N \approx 82-50$ by using (p,t) reactions on the isotopes of $^{A+2}$Nd$(A+2=150-142)$,[1,2] Te$(A+2=130-122)$,[3,4] Sn(118, 116),[3,5] Cd(116–112),[3,5] and Pd(110–104).[5,6] In consequence, a phase change from constructive to destructive interference has been found in the Pd isotopes.[6] The phase change has been interpreted as a result of a sign change of the form factor of the direct transfer process in going from Te, Sn, and Cd to Pd isotopes on the basis of the BCS and quasiparticle-RPA (random-phase approximation) model.[6,7]

The experimental and theoretical results mentioned above are all due to the measurements of the differential cross sections of the (p,t) reactions leading to the ground states (0_g^+) and the 2_1^+ states. Measurements of analyzing powers for $(p_{\rm pol},t)$ reactions leading to the same 2_1^+ states are expected to provide a sensitive probe to detect whether the nature of the interference is constructive or destructive. Such measurements are of fundamental importance in understanding the microscopic structure of vibrational characters[5] of nuclei as well as the reaction dynamics of the processes.

Analyzing powers for the reactions ^{128}Te$(p_{\rm pol},t)^{126}$Te$(0_g^+$ and $2_1^+)$ and ^{110}Pd$(p_{\rm pol},t)^{108}$Pd$(0_g^+$ and $2_1^+)$ were measured at $E_p=22.0$ MeV. The nuclei ^{128}Te and ^{110}Pd were chosen as targets because the previous measurements of the differential cross sections showed that the ^{128}Te$(p,t)^{126}$Te(2_1^+) transition[3,4] had constructive interference while ^{110}Pd$(p,t)^{108}$Pd(2_1^+)[6] had destructive. A polarized proton beam was produced with a Lamb-shift ion source[8] and was accelerated with the University of Tsukuba 12UD Pelletron. The beam intensity was about 50 nA on target and