First Observation of the $p_\Lambda \rightarrow s_\Lambda$ γ-Ray Transition in $^{13}_{\Lambda}$C

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The spectrum of excited states in the hypernucleus $^{13}_{\Lambda}$C was studied at the Brookhaven Alternate Gradient Synchrotron using the (K^-, π^-) reaction on an enriched ^{13}C target. γ rays coincident with the $p_{1/2\Lambda}$ state were observed using two large sodium iodide detectors. We interpret them as arising from the $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$ transition in $^{13}_{\Lambda}$C. This represents the first direct observation of a γ ray associated with the transition of a hyperon between major nuclear shells. [S0031-9007(97)03270-5]

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In an experiment at the Brookhaven National Laboratory Alternate Gradient Synchrotron (AGS), we have searched for γ-ray transitions in $^{13}_{\Lambda}$C. The hypernucleus $^{13}_{\Lambda}$C may be thought of as a lambda particle bound to ^{12}C; for this reason it is an especially interesting and simple system. The p states for the Λ particle lie about 11 MeV above the s_Λ state [1] and are predicted to be particle stable. We report on the detection of γ rays that we ascribe to the transition $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$. This is the first observation of a γ ray due to a Λ-particle transition between major nuclear shells. The single particle levels in nuclei are basic to the shell model; yet because of the Pauli principle and the particle instability of hole states, pure transitions between them are not observed. The $p_\Lambda - s_\Lambda$ spacing is therefore of fundamental interest for hypernuclear physics.

The spin-orbit splitting, which is such a prominent feature in nuclei, has yet to be observed in Λ hypernuclei, presumably because of its small magnitude. The Λ-nucleus spin-orbit interaction could be determined in a direct way by a high statistics measurement of γ rays from both the $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$ and the $p_{3/2\Lambda} \rightarrow s_{1/2\Lambda}$ transitions in $^{13}_{\Lambda}$C. Because of angular momentum conservation, the $p_{1/2\Lambda}$ or $p_{3/2\Lambda}$ state can be selectively excited by choosing the momentum transfer in the production reaction [1]. The goal of subsequently making this higher statistics measurement was an additional motivation for the experiment.

In this work, the $^{13}_{\Lambda}$C hypernuclei were formed using the reaction

$$K^- + {}^{13}\text{C} \rightarrow {}^{13}_{\Lambda}\text{C} + \pi^- \tag{1}$$

with $p_{K^-} = 750$ MeV/c. For this experiment the low energy separated beam II (LESB-II) at the AGS provided a flux of 5×10^4 K^- in a pulse of duration of 1 sec. The beam consisted of 9% kaons, the remainder being mostly π^-. Particle identification was achieved using time-of-flight and lucite Cherenkov counters of a total internal reflection type. All events with a K^- entering the target region and a π^- exiting were recorded. Also recorded were the γ-ray calibration events described below, and a prescaled sample of events where the only requirement was a beam K^-. The momenta and trajectories of the K^- and π^- were determined using focusing spectrometers instrumented with drift chambers. The pion spectrometer can be rotated to vary the production angle ($\theta_{K\pi}$). For a drawing and detailed description of the beam line and spectrometer, see Ref. [2]. The present experiment corresponds to values of $\theta_{K\pi}$ near 0°, which results predominantly in the excitation of the $p_{1/2\Lambda}$ state.

The target consisted of two scintillation counters containing ^{13}C with 99% isotopic purity. The scintillating material consisted of 200 gm of $^{13}C_6H_6$ with a small amount of wavelength shifter added. Each target counter was 2 cm thick. The $^{13}C_6H_6$ was synthesized [3] from $^{13}CO_2$, which was commercially available. The hypernucleus decays [4] by the weak interaction roughly 0.25 ns after its formation, resulting in a large signal in the target scintillation counter. The large pulse height in the target scintillator is a major characteristic used in defining a hypernuclear event.

The spectrum of states of $^{13}_{\Lambda}C$ is obtained from the missing mass in the (K^-, π^-) reaction. The main background is due to the decay of beam kaons to pions and muons. The constraints used in the software to separate signal from background are (a) the pion and kaon tracks are required to intersect within the target, (b) the kaon track at the spectrometer exit, when traced back through the magnetic field, is required to be consistent with the kaon track measured at the spectrometer entrance, and (c) the pulse height in the ^{13}C scintillation target is required to be at least three times minimum ionizing; this is a very effective cut for removing background, but results in a loss of approximately 1/3 of the real events. In addition, events that satisfied energy and momentum conservation for kaon decays were rejected.

Figure 1 shows the excitation energy spectrum obtained. The lower histogram (shaded) is of events in which at least 0.5 MeV was deposited in one of the γ-ray detectors; the analysis requirements have been made sufficiently stringent to remove almost all background. For the upper histogram (dashed), the cuts have been relaxed and there is no requirement placed on the γ-ray detector. The rising background below zero, where no counts are expected, is due primarily to $K^- \rightarrow \pi^- + \pi^0$ decays. The energy scale is adjusted so that the ground state of the hypernucleus is at zero; the expected energy resolution is $\approx$3 MeV FWHM. The data shown result from 4.7×10^9 K^-. We search for γ rays in coincidence with the state labeled p_Λ. The properties of this excited state have been established through previously measured angular distributions and theoretical analysis [1].

Sodium iodide (NaI) γ-ray detectors 20.3 cm in diameter and 15.2 cm thick were placed approximately

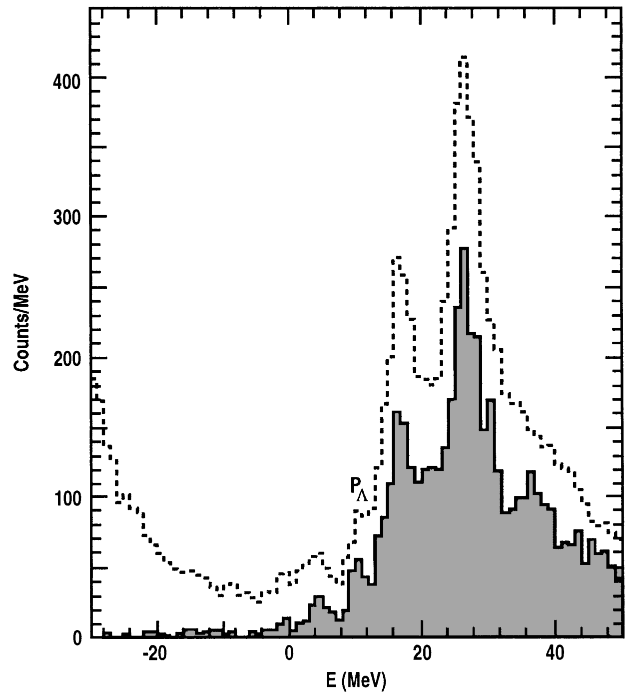

FIG. 1. Excitation energy spectrum in the reaction $K^- + {}^{13}C \rightarrow {}^{13}_{\Lambda}C + \pi^-$. The p_Λ excited state is indicated. The upper histogram (dashed) is the data use to generate the γ-ray spectrum and was subject to the same requirements as Fig. 2 and Fig. 3; it is divided by 5. The rising background below zero, where no counts are expected, is due primarily to $K^- \rightarrow \pi^- + \pi^0$ decays. The lower histogram (shaded) has been subject to tighter cuts and also to the requirement of a signal of more than 0.5 MeV in one of the NaI detectors; very little decay background remains.

10 cm above and below the ^{13}C target. The NaI detector responses were compensated for spatial uniformity based on a map made using a 6.13 MeV γ-ray source. Each detector was viewed by three Hamamatsu R1911 photomultiplier tubes. The last two stages of each tube had individual power supplies to minimize rate-dependent gain changes. Typical rates were 3×10^5 counts per second above 0.5 MeV in each detector; more than 10^4 of the counts were above 15 MeV beyond the range of the analog-to-digital converter. These large pluses were due primarily to a beam halo particle passing through the detector and depositing approximately 100 MeV. They resulted in an effective dead time of, typically, 35% for our system.

The bases were constructed using temperature compensated resistors. Passive filters were used to shorten the pulses [5]. The resolution of each detector was better than 300 keV FWHM measured [6] under beam-off conditions at 10.5 MeV; resolution under beam conditions was better than 350 keV. The back surfaces of the NaI crystals subtended 5% of the solid angle. Full energy detection efficiency times solid angle was approximately 1% per crystal [6].

Veto counters made of 7.6 cm thick cylinders of plastic scintillator surrounded each NaI detector. Plastic scintillation counters 6.4 mm thick covering the front face of each NaI detector identified charged particles. These counters were useful for diagnostic purposes but the final γ-ray spectrum does not include this requirement.

Calibration and monitoring techniques were developed to maintain gain stability and resolution of the NaI detector during variable running conditions. For calibration at 1.17 and 1.33 MeV, specially prepared ^{60}Co sources were mounted on small scintillation counters which detected the β decay electrons. Using the β signal as a trigger, calibration spectra were recorded which permitted continuous monitoring during and between the beam bursts. This was essential to maintaining good energy resolution. Data taken simultaneously with the β as a trigger were used to correct gains as a function of time and also to measure rate-dependent dead time due to pulse pileup. The gain as measured by the ^{60}Co data changed by less than 0.5% from beam-on to beam-off. The average run-to-run variation of the gain was 1.5%.

A 6.13 MeV calibration γ ray was produced by a ^{244}Cm-^{13}C source [7] through the reaction $\alpha + {}^{13}\mathrm{C} \rightarrow {}^{16}\mathrm{O}^* + n$. A source producing 9.00 MeV γ rays through neutron capture on ^{58}Ni was developed for this experiment. Measurements taken periodically with these sources were used in the calibration, though this was not possible when the beam was on target.

Figure 2 shows the γ-ray energy spectrum obtained in coincidence with the peak in the excitation spectrum labeled p_Λ in Fig. 1. The cuts in the (K^-, π^-) reconstruction are the same as for the upper histogram of Fig. 1. The peak near 11 MeV is identified as the $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$ transition. Because of the low statistics, 400 keV binning is used. The peak shown contains both the one escape and full energy peak which should be of roughly equal intensity [6]. The peak contains 16 $\pm$ 4 events; based on the known solid-angle efficiency, dead time losses and an estimation of the background in the missing mass spectrum 20 $\pm$ 5 events are expected if the p_Λ state decays exclusively by γ-ray emission to the ground state. The spectrum falls off sharply above the peak as expected; the continuum below the peak is the sum of the Compton tail and some low energy background.

The energy of the $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$ γ-ray transition determined from the spectrum is 10.95 $\pm$ 0.1 $\pm$ 0.2 MeV. Included in the systematic error (0.2 MeV) is the uncertainty in extrapolating from the highest measured calibration point at 9 MeV. The systematic error could be significantly reduced in a future experiment by frequent calibration at γ-ray energies bracketing 11 MeV.

It is known that the Λ binding energy in the $^{13}_{\Lambda}$C ground state is 11.69 $\pm$ 0.12 MeV [8]. For excitation energies greater than 16.2 MeV, therefore, the Λ can escape leaving the ^{12}C core in the 4.44 MeV first excited state. We have observed this nuclear γ ray in coincidence with the appropriate region of excitation energy. The observed energy is 4.46 $\pm$ 0.05 MeV, confirming the accuracy of the calibration.

Figure 3 shows the fraction of events in each 1 MeV bin of excitation energy that were in coincidence with a γ ray near 11 MeV, where "near 11 MeV" is defined as being within 0.7 MeV of the central energy of the observed γ-ray peak. A clear peak is observed near 11 MeV excitation energy, and no significant rate is associated with other parts of the excitation spectrum. The fact that the observed γ ray occurs only in association with the p_Λ

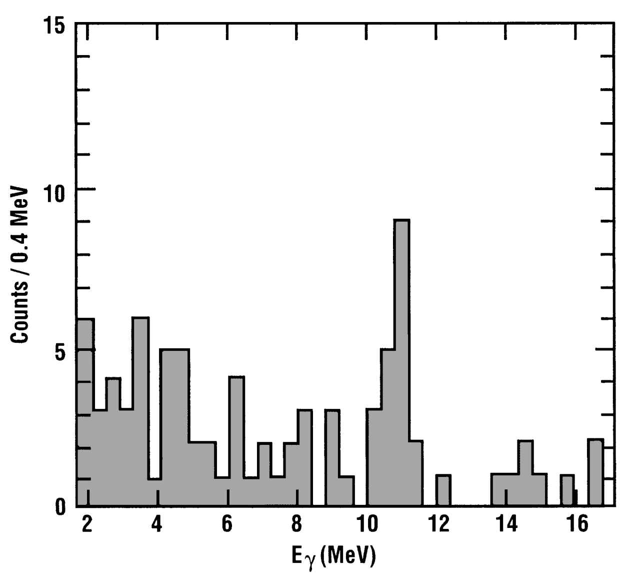

FIG. 2. The γ-ray energy spectrum in coincidence with the p_Λ state of $^{13}_{\Lambda}$C.

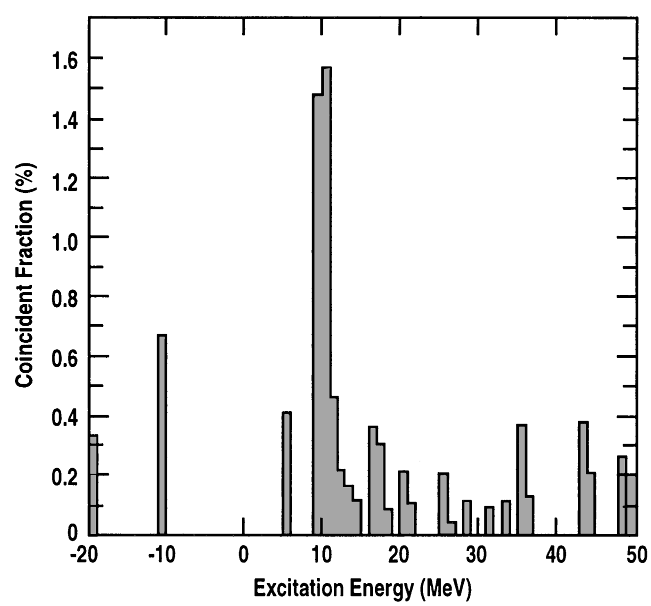

FIG. 3. Fraction events in each bin of excitation energy that were in coincidence with an 11 MeV γ ray.

state, and at a rate consistent with expectations, is evidence for its resulting from the $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$.

It is interesting to note that 11 MeV is an especially clean region for coincident γ rays: The raw spectrum of γ rays falls off sharply above 7 MeV due to the scarcity of neutron capture γ rays above this energy; and when the excitation energy is below Λ-escape threshold, the continuum due to π^0 showers from Λ decay is not present.

A previous experiment [1] obtained a value of 10.4 MeV for the $p_\Lambda - s_\Lambda$ splitting in ${}^{13}_{\Lambda}C$ by magnetic analysis of the (K^-, π^-) formation reaction. The energy resolution in present experiment is an order of magnitude better due to detection of the γ ray.

Given the binding energy of the ${}^{13}_{\Lambda}C$ ground state, our result of 10.9 MeV for the γ-ray energy implies that the $p_{1/2\Lambda}$ state is bound by 0.74 MeV. For comparison we can look at the neighboring hypernucleus ${}^{12}_{\Lambda}C$. The energy of the p_Λ state in ${}^{12}_{\Lambda}C$ is quoted as 11 MeV in a formation reaction experiment [9] and as 9.8 to 10.6 MeV in an analysis of proton emission in an emulsion experiment [10].

If a higher statistics measurement were to be performed, γ rays due to other transitions in ${}^{13}_{\Lambda}C$ could be observed. Both the 4.44 MeV 2^+ state and the 15.1 MeV $T = 1$ state of ${}^{12}C$ have prominent γ-ray transitions to the ground state. In ${}^{13}_{\Lambda}C$ these may occur as γ-ray transitions of the ${}^{12}C$ in the presence of the Λ particle [11]. Of more immediate interest to the present work is the possibility of searching for the γ rays associated with the $p_\Lambda \rightarrow s_\Lambda$ transition at larger momentum transfer. At values of $\theta_{K\pi}$ near 15°, the higher momentum transfer involved should preferentially excite the $p_{3/2\Lambda}$ state, although with significantly smaller cross section [1]. If this γ ray could be observed, knowledge of the splitting, combined with the present results, would provide a direct measurement of the Λ spin-orbit interaction; at present, only upper limits for its magnitude are known [12]. Plans are being made for a new experiment [13] to observe ${}^{13}_{\Lambda}C$ γ rays using a large, highly segmented NaI detector which would permit greater utilization of the high intensity beam which has become available at the AGS. A γ-ray detector with a faster decay time and comparable resolution to NaI would be ideal, but so far such scintillators [14] are still in the development stage.

It is interesting to note that an analogous γ-ray transition is expected to occur in the double hypernucleus ${}^{14}_{\Lambda\Lambda}C$. In this case, the $p_\Lambda \rightarrow s_\Lambda$ transition will occur in the presence of a second Λ in the s state. This γ ray would carry information about the $\Lambda\Lambda$ interaction.

In summary, we have made the first observation of the γ-ray transition $p_{1/2\Lambda} \rightarrow s_{1/2\Lambda}$ in ${}^{13}_{\Lambda}C$. In this particular (and rather special) case, the p_Λ excitations are particle stable, and the observation of a γ-ray transition of the Λ particle between major nuclear shells has been achieved.

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