Observation of Λ-Hypernuclei in the Reaction $^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$

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The observation of Λ-hypernuclear levels in $^{12}_{\Lambda}C$ by associated production through the (π^+,K^+) reaction is reported. The $^{12}_{\Lambda}C$ excitation-energy spectra were recorded at laboratory scattering angles of 5.6°, 10.3°, and 15.2°. They show two major peaks—one attributed to the ground state, and one about 11 MeV higher. These results are compared to the strangeness-exchanging (K^-,π^-) reaction. The measured cross sections are compared to relativistic distorted-wave Born-approximation calculations.

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In the past, Λ-hypernuclear levels have been studied[1,2] primarily by use of the strangeness-exchanging (K^-,π^-) reaction through the elementary process $K^-+n\rightarrow\Lambda+\pi^-$. The kinematic properties of this reaction are appealing because for a K^- momentum of about 550 MeV/c, the momentum transferred to the residual nucleus is close to zero.[3] In practice, experiments have been done at somewhat higher K^- momenta, in the range 700–800 MeV/c, to take advantage of the maximum in the elementary cross section and to avoid excessive kaon decay losses. Even at these higher momenta the momentum transfer of about 80 MeV/c at 0° is small compared to the Fermi-momentum distribution of the nucleons. Thus the cross sections for the formation of Λ-substitutional states, in which the Λ assumes the same quantum numbers as the neutron it replaces, can be quite large, approaching 1 mb/sr at 0°.

Nonsubstitutional states involve orbital angular momentum transfer, and are formed preferentially at higher values of momentum transfer. High spin states of "stretched" configurations, in which the particle and hole coupling has maximum angular momentum, are of considerable interest in medium and heavy nuclei. Because of momentum-matching considerations, it would not be expected that these states are easily formed in (K^-,π^-) reactions. It is interesting, therefore, to explore alternative reaction mechanisms such as the associated production of hyperons by the (π^+,K^+) reaction.

This Letter is a report on the first study of Λ-hypernuclear excitations using the qualitatively different endoergic reaction $A(\pi^+,K^+)_\Lambda A^*$. This reaction involves a much larger momentum transfer of about 330 MeV/c and is complementary to the (K^-,π^-) reaction discussed above. The viability of this reaction is illustrated in a study of ^{12}C$(\pi^+, K^+)^{12}_\Lambda$C*, and a comparison of the results with a previous ^{12}C$(K^-,\pi^-)^{12}_\Lambda$C* measurement is made.

The reaction ^{12}C$(\pi^+,K^+)^{12}_\Lambda$C* was studied at the low-energy separated beam line of the Brookhaven National Laboratory alternating gradient synchrotron. The experimental system is similar to that used for (K^-,π^-) reaction studies,[4] with the addition of a liquid-nitrogen threshold Čerenkov detector as a pion veto at the rear of the kaon spectrometer. The pion spectrometer consisted of QDQQ (Q, quadrupole; D, dipole) elements comprising the end of the beam line, followed by a kaon spectrometer with a QQDQQ sequence. A scattering target was placed between the two spectrometers. The kaon spectrometer had a length of 7 m, a solid angle of 20 msr, and a 6% full width at half maximum momentum acceptance. The dispersions of the pion and kaon spectrometers were 1.7 and 2.5 cm/%, respectively. The incident pion rate was limited to 4×10^6 pions per beam spill by the counting electronics. The incident pion beam momentum, 1054 MeV/c, was selected to take advantage of the maximum in the elementary cross section for $\pi^+ + n \rightarrow \Lambda + K^+$.[5]

Data were taken for kaon spectrometer settings of 716 and 728 MeV/c. These central momenta are known from a floating-wire study of the kaon spectrometer; the beam line and pion spectrometer were calibrated by reference to the kaon spectrometer settings with use of π^+ elastic scattering. Trigger rates of up to 100 per spill were acceptable, and data were recorded on magnetic tape for off-line analysis.

Excitation-energy ($E_{\rm ex}$) spectra recorded for $^{12}_\Lambda$C for laboratory angles of 5.6°, 10.3°, and 15.2° are shown in Fig. 1. These angles are the centroids of the empirically determined kaon spectrometer acceptances corresponding to spectrometer angle settings of 5°, 10°, and 15°, with a software-restricted solid angle of 8.6 msr. An examination of these figures reveals the presence of at least two peaks together with a broad distribution characteristic of the quasifree $\pi^+ + n \rightarrow \Lambda + K^+$ process and also containing background components due to pole-face scattering, particle misidentification, and perhaps other contributions. The peak shown at $E_{\rm ex}=0$ MeV is believed to be the ground state of $^{12}_\Lambda$C. The spectra as shown have been shifted by 4 MeV in the direction of increasing excitation so as to place this peak at zero excitation. This error in the energy scale is attributable to calibration errors in the measurement of the field line integrals for the rear (or kaon analyzing) dipole. The effect of the calibration error is accentuated in this experiment because of the large momentum difference in the settings of the pion and kaon dipoles. Since there are no bound states in $^{12}_\Lambda$C expected to be strongly produced in the (π^+,K^+) reaction, other than the ground state, we feel that this identification is justified.

In the corresponding (K^-,π^-) reaction, the 1^- ground state is produced by a $\Delta L=1$ transition that transforms a $p_{3/2}$ neutron into an $s_{1/2}$ lambda. The 11-MeV peak seen in that reaction is believed to consist[1] of several unresolved contributions with spin and parity of 0^+ and 2^+ arising from the components $({}_\Lambda p_{3/2,1/2} \otimes {}_n p^{-1}_{3/2,1/2})$. Because the momentum transfer in the (K^-,π^-) reaction is small, the $\Delta L=0$, $J^\pi=0^+$ substitutional component dominates at 0°, while at larger angles, the ground state and 11-MeV substitutional state are populated with compar-

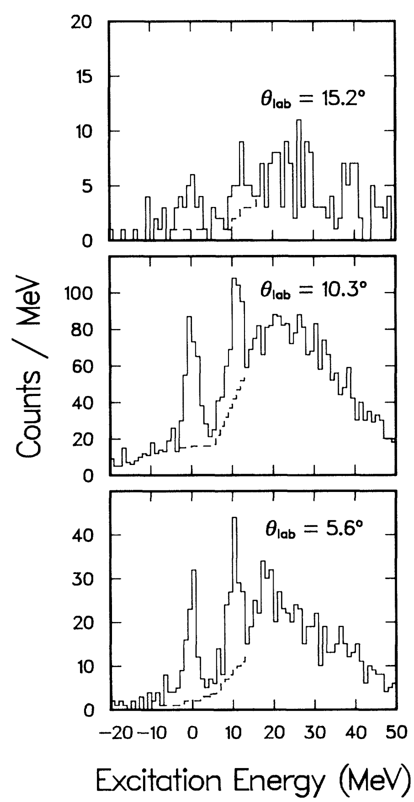

FIG. 1. Excitation-energy ($E_{\rm ex}$) spectra for $^{12}_\Lambda$C excited in the (π^+,K^+) reaction at laboratory angles of 5.6°, 10.3°, and 15.2°. The data are grouped in 1-MeV bins. The incident pion momentum is 1054 MeV/c. These spectra have been shifted 4 MeV to the right as described in the text. The dashed lines show the assumed background, obtained by extrapolation from the continuum region to the region of discrete states.

able intensities. In contrast, the higher momentum transfer in the (π^+,K^+) reaction does not favor the substitutional state, so that the 0- and 11-MeV peaks are expected to be of comparable strength at all angles. The spectra of Fig. 1 confirm this expectation. Similarly, the observed peak at 11 MeV for the (π^+,K^+) reaction is believed to consist mainly of 2^+ states.

The experimental differential cross sections for the two peaks (Fig. 2) are determined absolutely, and are not normalized to any other reaction. However, cross sections for (π^+,π^+) elastic scattering collected in the same experiment agree with previous results.[6] In addition to the statistical uncertainties shown for the data points, the following systematic uncertainties exist: (1) drift-chamber efficiency ($\pm 10\%$); (2) e^+ and μ^+ contamination of the π^+ beam ($\pm 20\%$); (3) subtraction of estimated background under the peaks ($\pm 10\%$); and (4) uncertainty in kaon decay-length corrections ($\pm 10\%$). For $P_{\text{beam}} = 1054$ MeV/c the e^+ contamination of the π^+ beam could not be observed because the time-of-flight resolution was insufficient to distinguish the two components. But at $P_{\text{beam}} = 716$ MeV/c, the time-of-flight distribution revealed a 30% e^+ component in the π^+ beam. The percentage of e^+ contamination is known to fall with rising momentum,[7] so that the e^+ component is estimated to be $(15 \pm 15)\%$ at $P_{\text{beam}} = 1054$ MeV/c. The μ^+ component is estimated to be $(5 \pm 5)\%$.[7]

Differential cross sections for the (π^+,K^+) reaction on several nuclides have been calculated by Dover, Ludeking, and Walker[5] using a distorted-wave Born-approximation (DWBA) code. However, these calculations did not include an average over the Fermi-momentum distribution of the neutrons. Because the elementary cross-section peak near 1050-MeV/c incident pion momentum is narrow, the Fermi broadening must be taken into account.

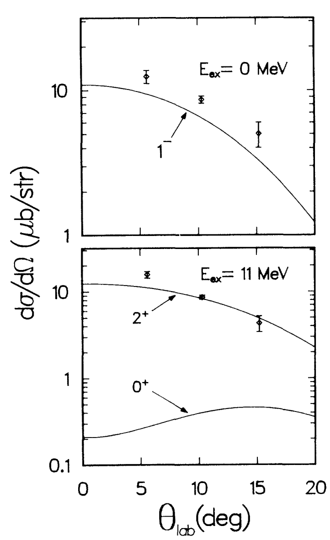

FIG. 2. Differential cross sections for the multiplet peaks near 0 and 11 MeV in E_{ex}. The $E_{\text{ex}} = 0$ MeV group is composed of two $J^\pi = 1^-$ states separated by $\simeq 2$ MeV, while the 11-MeV group contains contributions from three $J^\pi = 2^+$ states in a 2-MeV interval (see Ref. 9). The curves represent calculations performed with a DWBA computer code, CHUCK (Ref. 8).

Shown as curves in Fig. 2 are DWBA predictions for the $J^\pi = 1^-$ ground state and the $J^\pi = 0^+, 2^+$ states in the excited peak calculated with the program CHUCK,[8] and with use of nuclear structure information as reported in the work of Auerbach *et al.*[9] For this calculation the π^+ and K^+ distorted waves are described by optical-model parameters which fit the kaon[10] and pion[6] scattering data for ^{12}C. (These are substantially different from those available to Dover, Ludeking, and Walker.) The effect of Fermi averaging was approximated by the averaging of the elementary foward differential cross sections for $\pi^- + p \rightarrow \Lambda + K^0$ (equivalent to $\pi^+ + n \rightarrow \Lambda + K^+$ by charge independence) over several types of Fermi-momentum distributions for ^{12}C: (a) uniform, with $P_{\max} = 220$ MeV/c; (b) Gaussian; and (c) Woods-Saxon.[9] The results are almost identical and produced a reduction in the cross section at the peak from 0.95 to 0.50 mb/sr. The DWBA calculations shown in Fig. 2 include this factor. Also depicted in this figure is the predicted cross section for the 0^+ level population, which illustrates the relative weakness of this component. In contrast, for the (K^-,π^-) reaction at a laboratory angle of 10°, the $J^\pi = 0^+$ component was predicted to be about one-half of the total multiplet peak strength.[11] The general agreement between the predicted cross sections and the experimental data indicates that the salient features of this reaction mechanism are reasonably well understood.

In the 5.9° spectrum it is interesting to note weak evidence for a peak appearing near an excitation of about 20 MeV. There are several excitations which might plausibly appear at that energy; the deeply lying $({}_\Lambda s_{1/2} \otimes {}_n s_{1/2}^{-1})$ substitutional state is one and the $({}_\Lambda d_{5/2,3/2} \otimes {}_n p_{3/2,1/2}^{-1})$ is another. DWBA predictions strongly favor the latter candidate, but a definite identification awaits further experimental work. Since the quasifree spectrum in the (π^+,K^+) reaction is broader than the more peaked distribution in the quasifree region of the (K^-,π^-) reaction, such continuum hypernuclear states, if they exist, might be more clearly observed in the (π^+,K^+) reaction.[5]

In conclusion, is has been demonstrated that associated production of hypernuclei in discrete states of excitation can be achieved by application of the (π^+,K^+) reaction. Although the observed cross sections are significantly lower than for states in the (K^-,π^-) reaction, they are more than compensated by the larger available incident particle intensity, which produces higher event rates. A comparison of the observed cross sections with theoretical predictions is satisfactory. Calculations indicate that the larger momentum transfer of the (π^+,K^+) reaction predominantly matches to states of higher spin, implying the feasibility of populating "stretched" hypernuclear configurations. The (π^+,K^+) reaction is thus an important spectroscopic tool, complementary to the (K^-,π^-) reaction, and offers the possibility of extending detailed hypernuclear studies to heavier nuclei, beyond the p shell.

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[1]R. E. Chrien *et al.*, Phys. Lett. **89B**, 31 (1979).

[2]G. C. Bonazzola *et al.*, Phys. Rev. Lett. **34**, 683 (1975); W. Brückner *et al.*, Phys. Lett. **55B**, 107 (1975).

[3]H. Feshbach and A. K. Kerman, *Preludes in Theoretical Physics* (North-Holland, Amsterdam, 1965), p. 260.

[4]P. H. Pile, in *Intersections between Particle and Nuclear Physics—1984,* edited by R. Mischke, AIP Conference Proceedings No. 123 (American Institute of Physics, New York, 1984), p. 814.

[5]C. B. Dover, L. Ludeking, and G. E. Walker, Phys. Rev. C **22**, 2073 (1980).

[6]D. Marlow *et al.*, Phys. Rev. C **30**, 1662 (1984).

[7]J. F. Amann *et al.*, Los Alamos National Laboratory Report No. LA9486-MS, 1982 (unpublished).

[8]P. D. Kunz, unpublished.

[9]E. H. Auerbach, A. J. Baltz, C. B. Dover, A. Gal, S. H. Kahana, L. Ludeking, and D. J. Millener, Ann. Phys. (N.Y.) **148**, 381 (1983).

[10]D. Marlow *et al.*, Phys. Rev. C **25**, 2619 (1982).

[11]C. B. Dover, A. Gal, G. E. Walker, and R. H. Dalitz, Phys. Lett. **89B**, 26 (1979).