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Observation of Levels in ${}^{13}_{\Lambda}$C, ${}^{14}_{\Lambda}$N, and ${}^{18}_{\Lambda}$O Hypernuclei

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The spectra of levels in the hypernuclei ${}^{13}_{\Lambda}$C, ${}^{14}_{\Lambda}$N, and ${}^{18}_{\Lambda}$O, excited by 800-MeV/c kaons in the (K^-,π^-) reaction, have been observed at the Brookhaven alternating-gradient synchrotron. Data were recorded for scattering angles from 0° to 25°, corresponding to momentum transfers from 50 to 330 MeV/c. The levels are interpreted in terms of a Λ hyperon coupled to a strangeness-zero nuclear core. The results provide insights into the properties of the Λ-nucleon and Λ-nucleus interactions.

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Through use of the strangeness-exchanging (K^-, π^-) reaction, levels of the hypernuclei ${}^{13}_{\Lambda}$C, ${}^{14}_{\Lambda}$N, and ${}^{18}_{\Lambda}$O have been studied for the first time in an experiment done at the Brookhaven alternating-gradient synchrotron. A schematic description of the structure of these states is given in this paper. A comprehensive theoretical treatment of the structure of the levels in ${}^{13}_{\Lambda}$C and their excitation is presented in the accompanying Letter.[1]

The experimental apparatus used the hypernuclear spectrometer which has been previously described.[2] The momentum of the incident kaon beam was ~800 MeV/c. Approximately 10^4 kaons/sec were incident on the target, where the π/K ratio was approximately 15 to 1. For the ~2-g/cm^2 targets used in these experiments the energy resolution for the observed hypernuclear states was approximately 2.5 MeV. The pion spectrometer is rotatable up to angles of 35° with respect to the beam direction, and the resulting angular distributions are useful in establishing the character of the states observed.

For the ${}^{13}_{\Lambda}$C measurement, the target was a liquid scintillator of benzene containing ^{13}C enriched to 99%. The target signal due to hypernuclear decay is crucial at spectrometer angles where kaon decay and (K, π) reactions are kinematically indistinguishable; however, a loss of a factor of 2 in efficiency results from imposing this restriction. The imposition of this restriction did not change the observed spectrum shape. The ^{18}O was in the form of water and the ^{14}N was in the form of liquid nitrogen. Protons present in the benzene and water targets do not contribute to the hypernuclear signal.

The excitation spectra of ${}^{13}_{\Lambda}$C were measured at spectrometer angles of 0°, 5°, 10°, 15°, and 25°. For ${}^{14}_{\Lambda}$N and ${}^{18}_{\Lambda}$O only 0° spectra were obtained. Because of the spectrometer acceptance, the effective scattering angle at the 0° spectrometer setting can be shown to be 3.7°. At other angles the effective scattering is virtually the same as the spectrometer setting.

Representative spectra are shown in Fig. 1, where they are also compared to our previous results[2] from (K^-, π^-) on ^{12}C. The absolute cross-section scales shown in the figure were arrived at after due consideration of detector efficiencies, spectrometer acceptance, and data cuts. They have been checked against the expected kaon two-body decay rate and against kaon-nucleon and kaon-nucleus scattering data.[3] It should be noted that the ^{12}C cross sections shown represent a correction of our previously published results.[2] The figure illustrates the main features of the data, which may be understood by a few simple considerations following from the strangeness-exchange reaction,

$$K^- + n \rightarrow \pi^- + \Lambda .$$

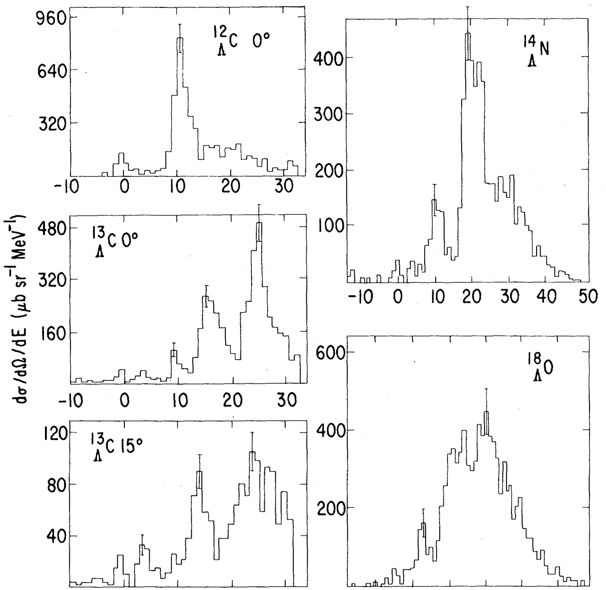

FIG. 1. Excitation spectra for ${}^{13}_{\Lambda}$C(0° and 15°), ${}^{14}_{\Lambda}$N, and ${}^{18}_{\Lambda}$O. These spectra have been corrected for the spectrometer acceptance as determined from Monte Carlo calculations. Representative error bars are shown; these do not include an estimated 20% systematic error. Shown for comparison is a spectrum for ${}^{12}_{\Lambda}$C based on Ref. 2.

At sufficiently low momentum transfer q (in this experiment q varied from 50 to 330 MeV/c), the above reaction will result in a substantial coherent excitation of the target nucleons.[4] Such excitations are related in character to the states excited in (p, d) pickup reactions. To a first approximation, the hypernuclear levels can be thought of as resulting from Λ hyperons coupled to core-excited states with a sizable neutron hole character: (n^{-1}, Λ).

In the case of ^{12}C studied previously,[2] the natural interpretation of the major peaks is that they are particle-hole excitations of the types $({}_n p_{3/2}{}^{-1} \otimes {}_\Lambda p_{3/2,1/2})_{0^+,2^+}$ $(E_x = 11$ MeV), and $({}_n p_{3/2}{}^{-1} \otimes {}_\Lambda s_{1/2})_{1^-}$ $(E_x = 0)$. The ~11 MeV difference between them, which is shown in Fig. 1, is just the p- to s-shell energy difference for the Λ. States of spin 0^+ can be termed "substitutional"; the neutron hole and Λ particle have identical quantum numbers. At small scattering angles such states are evidently preferentially excited, while at larger angles alternative spin couplings of the Λ and hole, resulting from orbital angular momentum transfer $\Delta L \neq 0$, are important.[5]

For the other nuclei, which are not spin or isospin saturated, the spectra are richer. The (K^-, π^-) reaction on a target of isospin T results in hypernuclear states with isospin $T \pm \frac{1}{2}$; for instance, states of $T=0$ and $T=1$ are formed in the reaction ${}^{13}\mathrm{C}(K^-, \pi^-){}^{13}_{\Lambda}\mathrm{C}$. Nevertheless the simple interpretation outlined for ${}^{12}_{\Lambda}$C is still applicable.

To interpret the data of Fig. 1, reference to the core states excited in the neutron pickup reactions may be found in Refs. 6–9. Coupling a Λ in the p or s shell with these core states gives a natural interpretation of the spectra in the figure. For ${}^{13}_{\Lambda}$C, the peak at zero excitation energy (the scale of excitation energy of Fig. 1 has been derived from the known binding energy for ${}^{13}_{\Lambda}$C, determined from emulsion studies)[10] is clearly the ${}^{13}_{\Lambda}$C ground state with the configuration $({}_n p_{1/2}{}^{-1} \otimes {}_\Lambda s_{1/2})$; i.e., an $s_{1/2}$ Λ coupled to the ^{12}C ground-state core. The next highest peak is interpreted as the $l=0$ Λ coupled to the $J=2^+$, $T=0$ state of ^{12}C at 4.4 MeV. The excitation energy corresponding to the Λ (p-s) shell spacing is 10.4 MeV; hence at 0° near this energy we see the substitutional state $({}_n p_{1/2}{}^{-1} \otimes {}_\Lambda p_{1/2})$; i.e., a $p_{1/2}$ Λ coupled to the ^{12}C ground-state core. However, at large angles, the structure near 10.4 MeV persists and suggests a sizable $\Delta L = 2$ component. Thus at 15° this peak must be largely of the form $({}_n p_{1/2}{}^{-1} \otimes {}_\Lambda p_{3/2})$. In Fig. 2 the angular variations of selected regions of the spectra encompassing the peaks are shown in the ${}^{13}_{\Lambda}$C case. The "peaks" at 0 and 4.4 MeV display the preference for angles greater than 0° which might be expected for the $\Delta L = 1$ transitions. In contrast, the peak near 10.4 MeV displays a stronger intensity near 0°; the behavior with angle suggests a $\Delta L = 2$ component of that multiplet. At 15° that component is dominant; the energy difference for the 10.4-MeV peak between the 0° and 15° spectra is found to be

$$\Delta E_{0-15^\circ} = 0.36 \pm 0.3 \text{ MeV}.$$

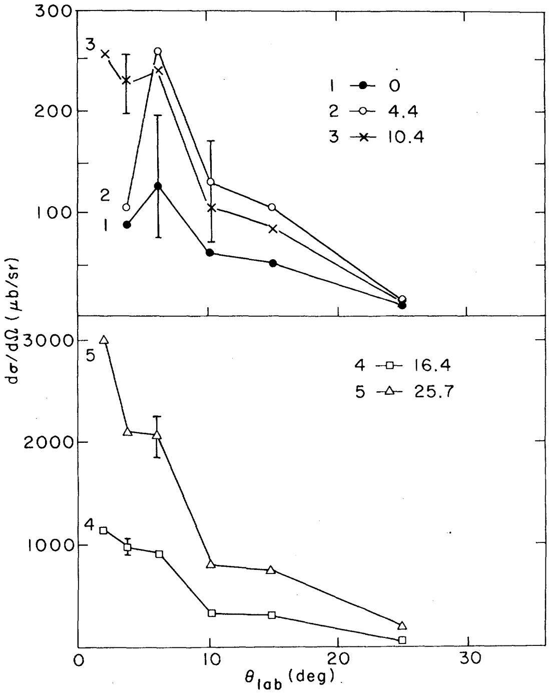

FIG. 2. Angular distributions for ^{13}C$(K^-, \pi^-){}^{13}_{\Lambda}$C are shown for energy cuts located around the five major peaks of Fig. 1. It is emphasized that each cut may contain several component states and, for the excitations above Λ threshold, a quasifree component. For the higher energy peaks the nominal 0° spectrometer data have been subdivided to obtain 2° and 4° points, based on trajectory reconstruction. The $d\sigma/d\Omega$ shown is actually $\langle (d^2\sigma/d\Omega\, dE)\rangle \Delta E_i$, $i = 1$–5, where the ΔE_i intervals bracket the apparent "peaks" of Fig. 1.

As shown by the authors of Ref. 1, the absence of a shift between these peaks is a *direct* demonstration of the weakness of the Λ spin-orbit force, since the comparison is between the $p_{1/2}$ and $p_{3/2}$ Λ's coupled to the 0^+ ^{12}C ground-state core. The weakness of the Λ spin-orbit force was previously hypothesized by the Heidelberg-Saclay-Strasbourg collaboration at CERN, on the basis of more indirect evidence.[11]

At higher energies we see two major peaks. Near 16.4 MeV, a peak is seen which plausibly encompasses the following configurations: $({}_n p_{3/2}{}^{-1}(4.4) \otimes {}_\Lambda p_{3/2})$, $({}_n p_{3/2}{}^{-1}(15.1) \otimes {}_\Lambda s_{1/2})$, and $({}_n p_{3/2}{}^{-1}(16.1) \otimes {}_\Lambda s_{1/2})$. It is clear that at 0° the energy spacing of the states deviates from the weak-coupling limit, which would place the 16.4-MeV peak at $4.4 + 10.4 = 14.8$ MeV. This difference is indicative of the Λ residual interaction. The peak shifts in position between 0° and 15°,

$$\Delta E_{0^\circ - 15^\circ} = 1.7 \pm 0.39 \text{ MeV}.$$

An explanation for this shift may be in the splitting between the $\frac{1}{2}^-$ and $\frac{5}{2}^-$ members of the $({}_n p_{3/2}{}^{-1} \otimes {}_\Lambda p_{1/2,3/2})$ multiplet, as is described in Ref. 1. However, the splitting may also be influenced by components with the Λ in the s state. Near 25 MeV, a peak is found near the expected position of the multiplets formed from a $p_{3/2}$ Λ particle coupled to the $T=1$ states of ^{12}C at 15.1 and 16.1 MeV. The first $T=1$ channel for particle instability is 15.8 MeV for ${}^{13}_{\Lambda}\text{C} \rightarrow p + {}^{12}_{\Lambda}\text{B}$; the rearrangement required for the decay gives these excited hypernuclear states a relatively narrow width.[12]

The angular distributions of Fig. 2 support the above interpretation. The $\Delta L = 1$ character for the two "peaks" at lowest excitation energy contrast sharply with the forward peaking for the $\Delta L = 0$ substitutional states represented in the three higher peaks. Nevertheless the falloff with angle for those peaks is mitigated by the presence of $\Delta L = 2$ components in the multiplets which are contained in these peaks, and by the core excitations.

The spectra for ${}^{14}_{\Lambda}$N and ${}^{18}_{\Lambda}$O may be interpreted in similar terms. The ground-state B_Λ for ${}^{14}_{\Lambda}$N has not been observed; however, B_Λ for the mirror nuclide ${}^{14}_{\Lambda}$C is known to be 12.17 ± 0.33 MeV.[10] We have assumed this value in constructing the excitation energy scale for ${}^{14}_{\Lambda}$N. The lowest energy peak seen in the case of ${}^{14}_{\Lambda}$N lies at an excitation energy of 10.5 MeV and is plausibly assigned to the $({}_np_{1/2}{}^{-1} \otimes {}_{\Lambda}p_{1/2})$ substitutional state. The states with the Λ residing in the s shell are not strongly excited at 0° and are not obvious in the spectrum. Most prominent are the p-neutron hole states near 20 MeV. In the case of ${}^{18}_{\Lambda}$O, the ground-state Λ binding energy is not known, and we have assumed $B_{\Lambda} = 18$ MeV to construct the excitation spectrum. With use of the 10.5-MeV Λ p- to s-shell energy difference, and the 9-MeV d-to-p energy difference, the peak near 20 MeV can be assigned to the $({}_nd_{5/2}{}^{-1} \otimes {}_{\Lambda}d_{5/2})$ substitutional state, while near 12 MeV one sees the $d_{5/2}$ neutron-hole state coupled to the p-shell Λ. Near 12 MeV in energy will also be a state $({}_np_{1/2}{}^{-1} \otimes {}_{\Lambda}p_{1/2})$, based on the 3-MeV state in ^{17}O.

States with configurations corresponding to the $T = \frac{3}{2}$ states of the ^{17}O core coupled to a $p_{1/2}$ or $p_{3/2}$ Λ may be expected near 22 and 27 MeV, respectively. Qualitatively the observed ${}^{18}_{\Lambda}$O spectrum is in good agreement with the expectations of this simple model.

In summary, we have observed levels in the hypernuclei ${}^{13}_{\Lambda}$C, ${}^{14}_{\Lambda}$N, and ${}^{18}_{\Lambda}$O, and measured the cross sections for the (K^-, π^-) reaction in these nuclei from 0° to 25°. The spectra show variations with angle which are interpreted as changes in the population of the various states in the Λ-nucleus multiplets as the orbital angular momentum transfer is varied. The consequent shifts in peak positions allow measurement of spin-dependent splittings much smaller than experimental resolution.

The observed levels for these hypernuclei can be understood in terms of a model in which the Λ is loosely coupled to an excited-core nucleus, and the core excitations are obtained from the results of neutron pickup reactions. The sensitivity of these data to the Λ-nucleus interaction is contained in the deviations from this picture, which give the spin-orbit and residual interactions for the Λ.

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