Study of Hypernuclei by Associated Production

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Data obtained by the associated production of Λ hypernuclei through the (π^+,K^+) reaction are presented for a wide range of mass numbers. The special features which make this reaction useful are pointed out. The reaction is shown to be an excellent probe of Λ single-particle states, as demonstrated by the excitation of deeply bound states which are interpreted as the weak coupling of a Λ to neutron-hole states of the core. The Λ binding energies and ground-state production cross sections for ${}^{9}_{\Lambda}\mathrm{Be}$, ${}^{12}_{\Lambda}\mathrm{C}$, ${}^{16}_{\Lambda}\mathrm{O}$, ${}^{28}_{\Lambda}\mathrm{Si}$, ${}^{40}_{\Lambda}\mathrm{Ca}$, ${}^{51}_{\Lambda}\mathrm{V}$, and ${}^{89}_{\Lambda}\mathrm{Y}$ are presented.

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The production of hypernuclei by the strangeness-exchanging (K^-,π^-) reaction for both in-flight and stopped kaon configurations was previously shown to be useful for the light hypernuclear systems in the s and p shells.[1] The purpose of this paper is to demonstrate the advantages of another process, the associated production reaction, (π^+,K^+), for producing both light and heavy hypernuclei. The practicality of the associated production reaction was first demonstrated at Brookhaven National Laboratory for the case of ${}^{12}_{\Lambda}\mathrm{C}$.[2] In this paper we present production cross sections and energies for hypernuclei ranging from ${}^{9}_{\Lambda}\mathrm{Be}$ to ${}^{89}_{\Lambda}\mathrm{Y}$, and in so doing demonstrate the utility of the associated production technique for examining hypernuclei across the whole available mass range. The method is shown to be effective in determining the positions of Λ single-particle states and consequently allows a precise evaluation of the detailed parameters of the Λ-nucleus potential, including its geometry, nonlocality, and density dependence.[3]

The elementary (π^-,K^0) reaction on protons displays a maximum near 1050 MeV/c in the incident pion momentum. Accordingly, this momentum was chosen with the expectation that the corresponding charge-conjugate (π^+,K^+) reaction will produce Λ hypernuclei with the maximum cross section. Because of the relatively high momentum transfer of 350 MeV/c, the reaction preferentially transfers the highest orbital angular momentum, l_N+l_Λ, and excites the highest-spin states of a given particle-hole configuration resulting from the transformation of a neutron into a Λ hyperon. The reaction mechanism has been extensively discussed by Dover, Ludeking, and Walker,[4] and by Bandō and Motoba.[5] It follows that the outstanding characteristic of the (π^+,K^+) reaction is its selectivity in picking out the series of states in which the Λ shell-model orbitals $(s,p,d,f,g,\dots)$ couple to the high-spin valence neutron-hole states produced when the neutron is transformed into a Λ hyperon. The fact that other members of the multiplets are only weakly excited leads to a simple spectrum of well-separated peaks (a) if the target valence hole strength is concentrated into one or a few nuclear configurations and (b) if the spin splitting of the Λ multi-

TABLE I. A summary of the experimental running conditions and targets used. The incident beam momentum was $p_\pi=1048$ MeV/c. The data were taken at $\theta_{\mathrm{lab}}=10°$ with the spectrometer set for $p_K=700$ MeV/c.

Target	Thickness (g/cm^2)	Run time (h)	π^+ intensity on target (per spill)[a]
^{9}Be	2.35	27	2×10^6
^{12}C	2.0	13.5	2×10^6
^{16}O[b]	3.0	43.4	2×10^6
^{28}Si[c]	4.03	73.3	2×10^6
^{40}Ca[c]	4.13	109.5	(2 and 10)$\times10^6$
^{51}V[d]	3.48	23	10×10^6
^{89}Y	3.95	88	10×10^6

[a]The AGS beam spill length for this experiment was about 1.2 s with a 2.9-s repetition rate.

[b]In water.

[c]Natural target.

[d]Run in tandem with a ^{13}C target.

plets is small. Because the Λ hyperon is uninhibited by the Pauli principle, it is free to occupy any shell-model orbital, and it is therefore an unsurpassed probe of nuclear single-particle states.

The experiment described here was performed using the low-energy separated beam (LESB1) at the Brookhaven Na-

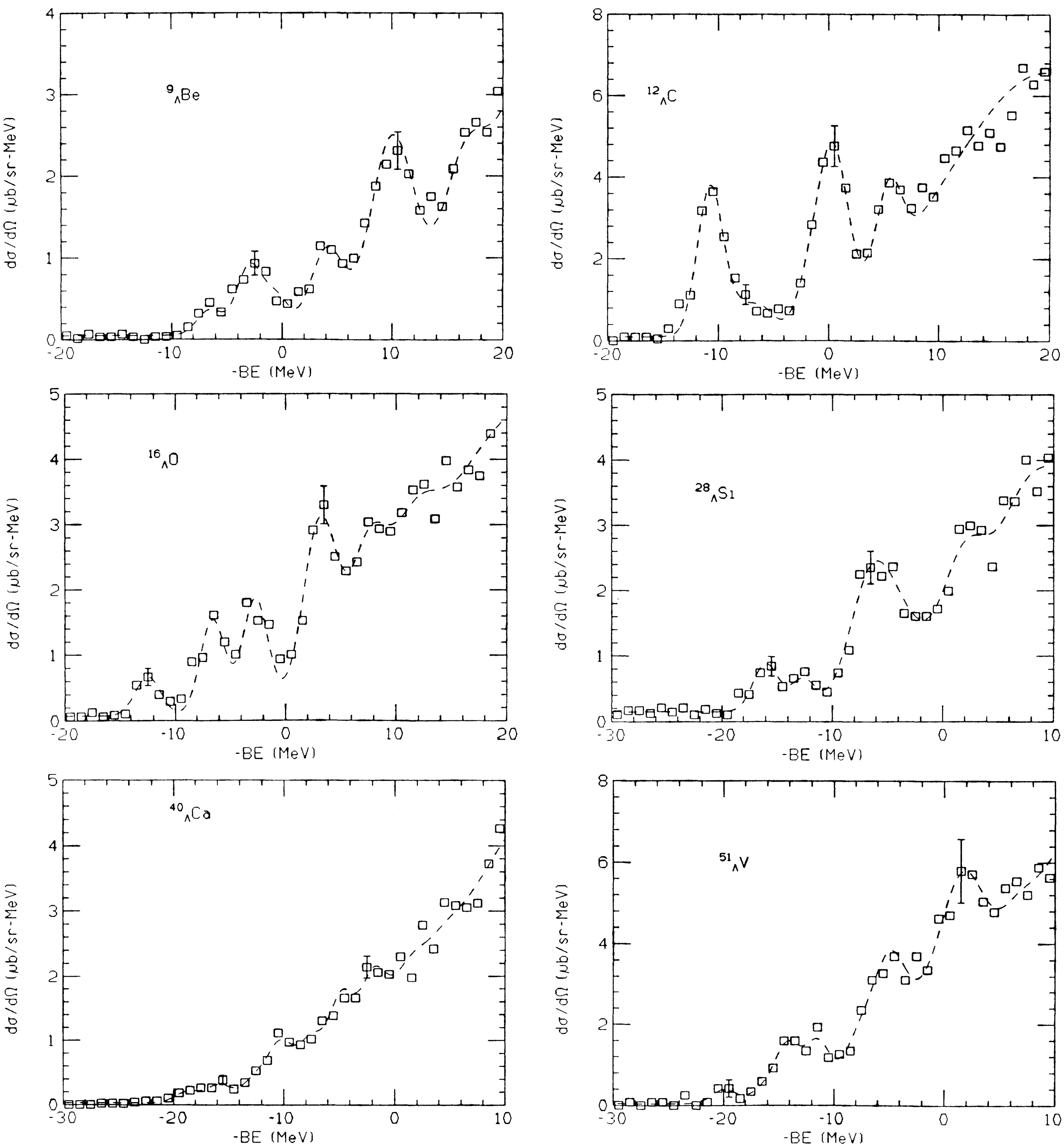

FIG. 1. The least-squares-fitted spectra obtained in this experiment for targets of Be, C, O, Si, Ca, and V. The cross sections shown refer to the laboratory frame and are plotted against the negative of the Λ-particle binding energy.

tional Laboratory Alternating Gradient Synchrotron (AGS). Table I displays the relevant experimental conditions. The system uses the end elements of the beam line, together with tracking chambers and scintillators, to determine the phase space and flux of the incident pion beam. Although more than 10^8 pions were available in each AGS spill, only about 10^7 could be used due to detector rate limitations. The Moby-Dick spectrometer[2,6] set at $\theta = 10°$ was used to analyze the emerging K^+ momentum. High-rate drift chambers and timing scintillators were used to track and identify the particles. Higher-rate runs shown in Table I were necessary to measure the small cross sections associated with ground-state production in the heavier targets. In order to reduce the on-line trigger rate to an acceptable level for these runs, a Lucite Čerenkov veto counter was placed just downstream of the target. The carbon present in this detector, isolated with a suitable vertex cut in the analysis, allowed continuous monitoring of the system resolution function and cross-section scale. A 4.7-mm Pb filter was inserted at the mass slit of the beam separator for part of the run to allow a determination of the positron contamination of the π^+ beam (less than 10%).

For the ^{12}C target, a scintillation counter was used and the large signal associated with the decay of a bound hyperon provided an optional spectrum (not shown) with a large measure of quasifree-reaction suppression.

The results of this experiment are displayed in Figs. 1 and 2, where the data have been binned into 1-MeV histograms. Many of the targets produced spectra with characteristic peaks which can be plausibly ascribed to particle-hole excitations. The theoretical interpretation of (π^+,K^+) spectra has been described in some detail by Milner *et al.*[2] and by Peng.[7] This is based on distorted-wave Born-approximation calculations which include a Fermi averaging of the elementary cross section, optical-model potentials fitted to the 800-MeV/c π^+ and K^+ elastic-scattering data of Marlow *et al.*,[8] and experimental values for the neutron pickup strengths from the targets.

The results of these calculations, with Λ single-particle energies from a Λ-nucleus potential based on the energies of the most prominent experimental peaks, were used to provide a set of initial parameters for least-squares fits of the experimental spectra. For all but one of the targets, a Gaussian resolution function with a full width at half maximum of about 3 MeV, corresponding to the spectrometer resolution, was assumed for the Λ bound states. The ^{51}V target was run in tandem with a ^{13}C target and the additional target energy loss degraded the resolution to approximately 4 MeV. A broad distribution of fragmented particle-hole states is expected to lie below the principal peaks expected in Figs. 1 and 2. This distribution was approximated by the tail of a Gaussian extending from the "quasifree" Λ production region down into the bound-state region.

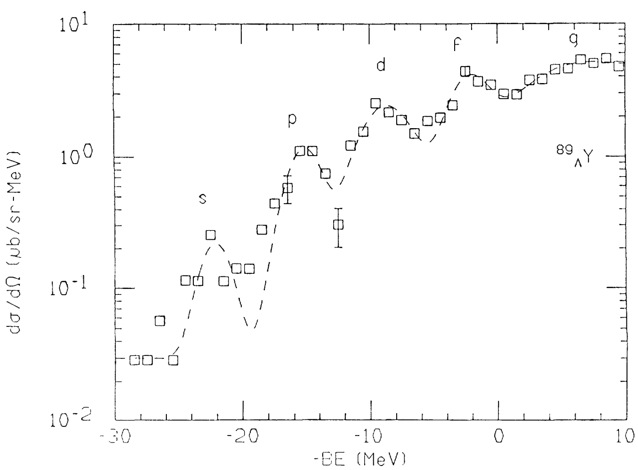

FIG. 2. The least-squares-fitted spectrum obtained in this experiment for Y. The relative positions of the Λ single-particle states, as labeled, are in agreement with the particle-hole assignments expected from the DWBA analysis.

Because of these assumptions, the curves of the figures should be regarded only as guides to the eye. The agreement with distorted-wave Born-approximation (DWBA) estimated cross sections is reasonably good for all targets. A more detailed comparison with DWBA predictions is underway and will be published separately. In addition to the targets listed here, data were taken with a ^{13}C benzene liquid scintillator; the large background present because of the target windows of this sample precluded an unambiguous interpretation of this case.

In Table II are summarized the ground-state or s-shell binding energies for the seven targets shown, as well as the (π^+,K^+) production cross sections in the laboratory frame. It is instructive to compare the present results to a (K^-,π^-) survey reported by Bertini *et al.*,[9] which includes many of the same targets. In the latter work, the spectra are dominated by the substitutional 0^+ configuration, which lies near threshold for Λ binding, and there is little population of bound Λ states. In contrast, the (π^+,K^+) data presented here provide an unambiguous description of Λ binding energies as a function of mass number.

TABLE II. The measured s-shell Λ binding energies and ground-state production cross sections in the laboratory frame.

Nucleus	BE (MeV)	σ (μb/sr)
$^{9}_{\Lambda}$Be	6.49 ± 0.68	0.87 ± 0.34
$^{12}_{\Lambda}$C	10.75 ± 0.10	10.36 ± 0.61
$^{16}_{\Lambda}$O	12.50 ± 0.35	1.68 ± 0.36
$^{28}_{\Lambda}$Si	16.00 ± 0.29	2.06 ± 0.34
$^{40}_{\Lambda}$Ca	18.70 ± 1.1	0.48 ± 0.28
$^{51}_{\Lambda}$V	19.9 ± 1.0	1.00 ± 0.56
$^{89}_{\Lambda}$Y	22.1 ± 1.6	0.54 ± 0.38

The ${}^{89}_{\Lambda}$Y spectrum, shown in more detail in Fig. 2, illustrates particularly well the main features of the (π^+,K^+) studies. The selectivity of this reaction preferentially highlights the states in which the Λ in the s, p, d, f, or g state is coupled to the dominant $g_{9/2}$ target hole strength. This spectrum is a good example of a case in which the Λ single-particle states are distinct; this is due to the sharp localization of neutron-hole strength in the core nucleus. It is interesting to contrast this case with that of ${}^{40}_{\Lambda}$Ca in Fig. 1. For ${}^{40}_{\Lambda}$Ca the $d_{3/2}$ and particularly the $d_{5/2}$ hole strengths are highly fragmented and widely spread.

The sharply localized peaks apparent in the case of ${}^{89}_{\Lambda}$Y provide exceptionally clear evidence for the validity of the nuclear shell model for deeply bound states. Such an example is not available for conventional nuclear physics. There the determination of single-particle energies for deeply bound states is difficult because of the large spreading and escape widths associated with the deep hole excitation.[10,11] In this experiment the lack of Pauli blocking for the Λ particle allows it to occupy freely any shell-model orbital. Detailed discussions of the nuclear structure for all the targets presented here will be given in a future publication.

The results of this experiment are amenable to interpretation with a wide variety of theoretical tools. Detailed models of hypernuclear structure and the reaction mechanisms of production and decay can be tested against the base of data provided here. Such topics as the effect of ΛNN three-body interactions or the density-dependent two-body interaction are now open for study. Future applications such as the production of polarized hypernuclei,[12] hypernuclear weak decay process, and $(\pi^+,K^+\gamma)$ experiments await the provision of suitable beams and high-resolution spectrometers for such studies.

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