A Study of Hypernuclei Using the (π^+,K^+) Reaction

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The (π^+,K^+) reaction was used to study lambda hypernuclear states from ^{9}Be, ^{12}C, ^{13}C, ^{16}O, ^{28}Si, ^{40}Ca, ^{51}V and ^{89}Y targets. Ground state excitations were seen for all targets as well as clear indications for the Λ populating bound shell model single-particle states. The data will be compared with DWBA calculations of Dover and Millener[1).

§1. Introduction

The study of hypernuclei has generally been done using either the in-flight or stopped K^- strangeness exchange reaction (K^-,π^-). Due to the small momentum transfer allowed by the in-flight (K^-,π^-) reaction it has been most successful for populating the so-called substitutional states--where the Λ-particle is substituted for an outer shell neutron taking the quantum number of the neutron. The stopped (K^-,π^-) reaction has a fixed momentum transfer of about 300 MeV/c and can be used to populate the non-substitutional natural parity states in hypernuclei. Most of the known properties of hypernuclei--binding energies, spin-dependent parameters and lifetime information--have been obtained using these reactions at CERN or at Brookhaven National Laboratory (BNL). The information, however, for the most part has been limited to light s-p shell hypernuclei.

The (π^+,K^+) reaction involves a momentum transfer >300 MeV/c and is particularly suited for populating non-substitutional, $\Delta L>0$, natural parity states. The usefulness of the (π^+,K^+) reaction was predicted by Dover et al.[2)] and was demonstrated by Milner et al.[3)] in 1985 for the $^{12}_{\Lambda}C$ case. Since that time (π^+,K^+) experiments at both BNL and KEK have been done using a variety of targets. This paper describes the results of the BNL experiment[4)] which were first reported by Chrien[5)] at the 1987 PANIC Meeting held in Kyoto. The results presented here supercede the preliminary results reported earlier but should not be considered final since the data analysis is still in progress.

§2. The Experimental Setup

2.1 The spectrometer system

The BNL hypernuclear spectrometer system[3)] was used to collect the (π^+,K^+) data. The system uses the end elements of the LESB-I beam line in conjunction with drift chambers and timing scintillators to define the phase space of the incoming pion beam. Although pion intensities up to 10^8 per AGS beam spill were available, the pion intensity was limited to about 10^7/spill by detector and trigger rate limitations. The outgoing K^+ was momentum analyzed in a second rotatable spectrometer (Moby Dick) using drift chamber and time-of-flight information. Although the (π^+,K^+) differential cross sections peak at 0 degrees in the lab, the experiment was run at a 10 degree K^+ angle in order to avoid unacceptable background

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conditions caused by pion beam interactions with the material downstream of the target. A 1038 MeV/c pion momentum was chosen--close to the theoretical maximum cross section for making hypernuclei with the (π^+,K^+) reaction[2]. A thin lead absorber was placed in the pion beam for some parts of the experiment so that the positron contamination in the beam could be evaluated. The proton contamination in the beam was for the most part eliminated by the LESB-I velocity selector.

2.2 Targets

A summary of some of the relevant target parameters is shown in Table I below. With the exception of ^{12}C, which was run at various times during the run, the targets are listed in the chronological order in which they were run.

Table I. Target Parameters.

Target	Thickness (g/cm^2)	$\langle P_\pi \rangle$ (MeV/c)	Run Time (hrs)	π^+ Intensity/ Spill at Target
^{12}C**	2-4	1031.4-1034.4	13.5	$0.2\text{-}1\times10^7$
^{9}Be	2.35	1034.7	27	2×10^6
^{16}O***	3.0	1033.5	43.4	2×10^6
^{28}Si*	4.0	1033.3	73.3	2×10^6
^{40}Ca*	4.13	1033.3	109.5	$0.2\text{-}1\times10^7$
^{89}Y	3.95	1033.7	88	1×10^7
^{51}V	3.48	1024.6	23	1×10^7
#^{13}C**	2.0	1032.0	23	1×10^7

*natural target; **scintillator live target; ***H_2O target; P_0 for kaon spectrometer = 700 MeV/c; θ_{lab} = 10 deg; #ran in tandem with ^{51}V, benzene live target ($^{13}C_6H_6$) with 1.4 g/cm^2 teflon window on either side.

Note that the energy of the pion beam at the target center varied from about 1025 to 1035 MeV/c but was below the nominal 1050 MeV/c quoted in ref. 5.

For the ^{13}C, ^{51}V, ^{40}Ca and ^{89}Y targets, a 6 mm thick lucite Cerenkov detector was placed just downstream of the target in order to veto pion beam events which did not interact in the target. By using a vertex selection which included only the lucite volume, a $_\Lambda{}^{12}C$ spectrum could be generated from the carbon in the lucite. For these targets an in-situ check of the missing mass resolution as well as the energy scale was available. Figure 1 shows such a spectrum for the ^{89}Y case. The dashed line represents a fit to the peaks with a 2.5 MeV/c^2 fwhm resolution.

§3. The Results

3.1 The p-shell targets

Four p-shell targets were examined: ^{9}Be, ^{12}C, ^{13}C, and ^{16}O. All had previously been studied using the (K^-,π^-) reaction either at CERN or BNL or both. The spectroscopy of the p-shell hypernuclei was studied theoretically by Auerbach et al.[6] and is well understood. Dover and Millener's[1] DWBA calculation for the (π^+,K^+) cases following the Auerbach et al.[6] formalism reproduces the observed features of the data rather well in the regions below zero binding for the Λ particle.

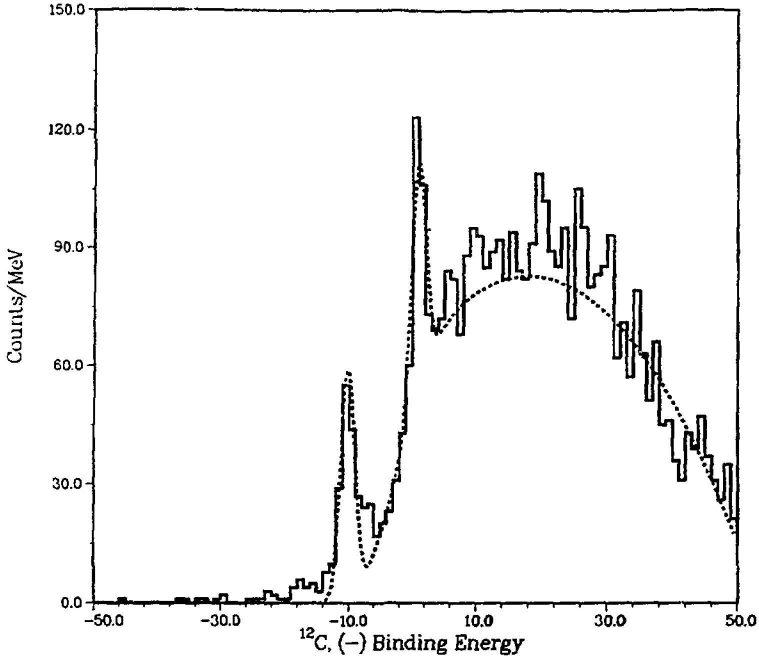

Fig. 1. The $_{\Lambda}{}^{12}C$ spectrum generated from a vertex cut which included only the lucite Cerenkov detector downstream of the ^{89}Y target. Oxygen in the lucite can be seen as shoulders on either side of the ground state peak. The roll-off of the quasi-free spectrum is due to the K^+ spectrometer acceptance.

Motoba et al.[7] have included the continuum states for $B_\Lambda < 0$ as well as the bound states. Their calculations were based on a DWIA formalism and reproduce the preliminary data of ref. 5 rather well. For the ^9Be case Motoba et al.[8] predicted the $_{\Lambda}{}^9Be$ spectrum for the $^9Be(\pi^+,K^+)$ reaction based on an alpha cluster model calculation. Their cluster model predicts the existence of a state (based on a 1^- core) which should appear around $B_\Lambda = 0$. This state is not predicted to be populated with any appreciable strength in the shell model calculation of Millener and Dover[1]. The preliminary data of ref. 5 gave some indication for the existence of this state. The present analysis of the experimental data, however, does not support the existence of the state; in fact there is a minimum in the data at this point. The cluster model calculation for this case was discussed in some detail by Bando and by Yamada in these proceedings.

3.2 The heavier targets: ^{28}Si, ^{40}Ca, ^{51}V, and ^{89}Y

The spectra for the heavier targets, for the most part, display the same simple structure as is seen in the lighter targets. The principal strength goes to those Λ states (s,p,d,f...) coupled to the outer neutron shell hole state which was created when the Λ was produced. Table II summarizes the observed Λ states for the $B_\Lambda > 0$ case (bound states). As can be seen, as the atomic number of target nucleus increases, the higher Λ orbitals become bound.

Table II. Observed Bound States.

Target	Valence Neutron Shell	Λ States with $B_\Lambda > 0$
^{28}Si	$d_{5/2}$	s,p
^{40}Ca	$d_{3/2}$	s,p,d
^{51}V	$f_{7/2}$	s,p,d
^{89}Y	$g_{9/2}$	s,p,d,f

Since the present analysis of the data is still in progress the hypernuclear spectra will not be published in these proceedings since they have already been published in a preliminary form in ref. 5. The gross features of the data remain unchanged from that presented in ref. 5. In the present analysis, however, the statistics have been increased by about 20% and the background reduced to below 0.1 μb/sr-MeV (negligible). Furthermore, the peaks in the spectra for all targets are now better defined and, in fact, for the ^{51}V case the ground state peak can easily be seen.

The most spectacular (π^+,K^+) spectra remains that of ^{89}Y. Here five Λ single-particle shell model states are observed to be occupied and can be assigned to an s,p,d,f or g Λ coupled to a $f_{7/2}$ neutron hole state. All the states, with the exception of the g state, are bound with respect to Λ emission; however, only the s and possibly the p states are bound with respect to proton emission. The DWBA shell model calculations of Millener and Dover[1] and the DWIA calculations of Motoba et al.[7] reproduce the gross features of the data rather well.

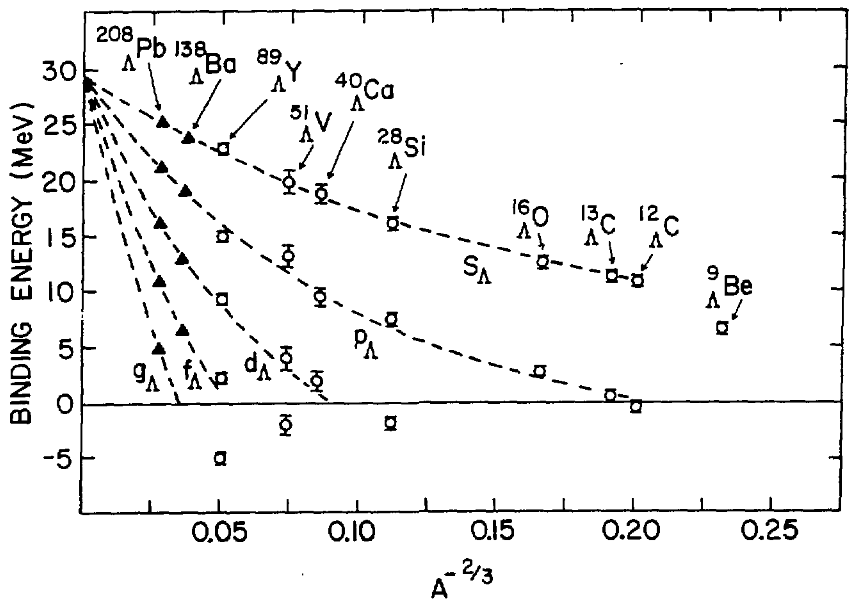

Fig. 2. Binding Energy vs $A^{-2/3}$. The open circles represent the measured Λ binding energy for each of the targets (preliminary) in this experiment with the core nucleus in its ground state. The dashed line as well as the triangles are the result of a calculation[9].

§4. Conclusion

The plots shown in Fig. 2 represent data derived from this experiment only. The Λ binding energy for the various single-particle orbitals coupled to the ground state core nucleus is shown as a function of $A^{-2/3}$ for the target nucleus. The dashed line represents the result of a theoretical calculation taken from ref. 9 (see also ref. 10). As can be seen from the data, they are fit rather well by the theory which binds the Λ in a Woods-Saxon potential with a depth which is independent of either atomic number or the orbital angular momentum of the Λ.

It will be interesting to see if the fit remains good as one goes to heavier nuclei. Their predictions for ^{138}Ba and ^{208}Pb are shown in the figure. Since the Λ particle is a distinguishable particle in the nucleus and is therefore not required to obey the Pauli Principle, it can populate deep shell model states, "providing a 'textbook' example of single particle structure in nuclear physics." The quote is taken from ref. 10.

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