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RECENT HYPERNUCLEAR RESEARCH AT THE BROOKHAVEN AGS*

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Abstract: Recent AGS experiments contributing to our knowledge of hypernuclei are reviewed. These experiments have suggested new areas of research on hypernuclei. With the proper beam line facilities, the AGS will be able to perform experiments in these areas and provide a transition to the future era of "kaon factories".

Introduction: Why are hypernuclei interesting?

The study of hypernuclei started a little more than 30 years ago, when the first evidence for stable hypernuclear formation was discovered by Danysz and Pniewski[1]. Yet today, hypernuclei are still considered a "frontier area" of nuclear physics and worthy of study. The rate of progress through these three decades has been relatively slow, compared to other fields of research, and this slow rate is largely attributable to the lack of suitably intense beams for producing strange particles.

The study of hypernuclei--that is, nuclei in which one or more of the nucleons have been replaced by hyperons--allows us to study the effective interaction between baryons and how that interaction is influenced by the additional strangeness degrees of freedom that hyperons possess.

It is probable that the quark structure of the baryons plays an important role in the theoretical description of these strongly interacting systems, and that one must consider quark and gluon contributions to the boson exchanges. It is thus of interest to compare the interaction of strange and non-strange baryons and arrive at a more fundamental understanding of hadronic forces.

At the present time, the research in hypernuclei is at a critical phase, one in which decisions affecting its future must be taken. During the seventies and early eighties kaon beam lines for hypernuclear studies were created

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at the CERN PS (1973) and the BNL AGS (1978). At the beginning of the present decade, a kaon line at the 12 GeV KEK accelerator was commissioned (1980), and a low momentum line at CERN was tested (1980). Because of conflicting priorities among particle and nuclear physics programs, the CERN program has been terminated and only the BNL AGS line and the KEK K-2 line remain active. Thus very limited facilities exist for hypernuclear research[2]. One may legitimately conclude that there is a mismatch between the facilities capable of performing this research, and the interest in it.

Hypernuclear Spectroscopy

For about 20 years our knowledge of hypernuclei was obtained through emulsions or bubble chambers, and they were identified by the characteristic decay through fragmentation. From a measurement of the decay products of light nuclei, a consistent picture of the binding energy of the hypernucleus in its ground state could be obtained. The Λ-hypernuclear binding energy shows a smooth dependence on A, changing only gradually, and showing little dependence on nuclear structure (Fig. 1).

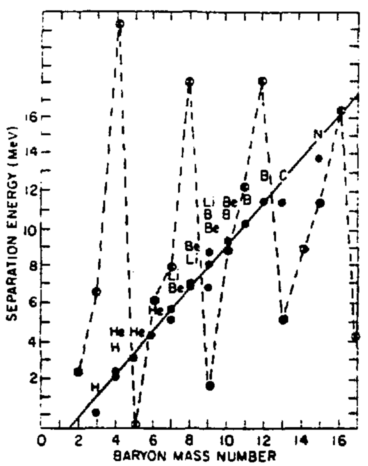

Fig. 1. Neutron (X) and lambda (•) separation energies compared (Ref. 3).

This illustrates one very important difference between hypernuclei and ordinary nuclei. Since the Λ hyperon carries a strangeness quantum number of −1, it is uninhibited by the Pauli principle and may occupy any nuclear orbit, whether filled with other nucleons or not. Thus in any Λ-hypernucleus, the ground state is one in which the Λ is found in the lowest, or 1s shell. The Λ separation energy will reflect only the depth of the nuclear well and will not depend at all on the extent of filling of the orbitals by other nucleons.

From emulsion data a value of 30 MeV is obtained for the single particle Λ potential well depth, V_0. This value of

30 MeV is significantly smaller than for the nuclear case, where $V_0 \approx 50$ MeV for low energy neutrons, and provided the first evidence that the Λ-nucleus interaction is significantly different from the nucleon-nucleus interaction. When, in the 1970's, more intense beams of K-mesons became available to experimenters, sophisticated counter experiments could be done to widen our knowledge of hypernuclei. Almost all of the experimental work in this area has been done at the CERN proton synchrotron and the Brookhaven AGS, using the strangeness exchanging (K,π) interaction. Extensive reviews have been given outlining our knowledge of Λ hypernuclei based on these experiments[3]. It is sufficient to observe, for present purposes, that our knowledge of the light hypernuclei, especially the p-shell Λ-hypernuclei, is on a sound basis. Shell-model calculations of these systems, using a reasonable Λ-N effective interaction, are in good agreement with experimental observations[4]. The outstanding fact about this interaction, which has emerged from these experiments, is the near zero value which is inferred for the Λ-nucleus spin orbit interaction[5].

Several recent experiments have recently been performed at the Brookhaven AGS which have had a significant impact on our knowledge of these systems and which, moreover, point the way to the study of more complicated systems. I would like here to describe several of these. It should be emphasized that these experiments were made possible by a close collaboration of a number of user groups from universities and national laboratories. These user groups have made essential contributions to the development of the hypernuclear spectrometer and to the evolution of the research in this area. These contributions are explicitly listed in a recent report[6].

Electromagnetic Transitions in Λ-Hypernuclei

The fact that the spin-dependent Λ-nuclear interactions appear to be small places severe demands on the magnetic resolving power of hypernuclear spectrometers. In fact it does not appear to be practical to construct instruments, operating with available beam intensities, capable of resolving hypernuclear multiplets. Electromagnetic transitions detected in coincidence with the (K,π) reaction, however, allow the separation of specifically selected final states in a hypernuclear system whose initial state is

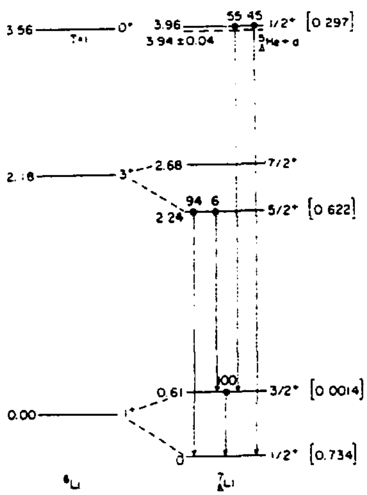

Fig. 2. Level scheme for $_{\Lambda}{}^{7}Li$, and expected electromagnetic transitions.

reasonably well defined by the spectrometer. These $(K^-,\pi^-\gamma)$ experiments were made possible at BNL by a modification of the original Moby Dick spectrometer, which allow kaon intensities of up to 2×10^5 kaon/spill on target.

The $(K^-,\pi^-\gamma)$ technique has made possible a complete characterization of the Λ-N effective 2-body interaction in the p-shell. In p-shell hypernuclei there are only a relatively few bound states which qualify for γ-emission and so the spectra are relatively simple[7]. Most of the excitations available for study belong to the configuration $\{(1S)^4{}_N(1P)^{A-5}{}_N(1S)_\Lambda\}$; that is, the Λ is present in the s-shell, and the reaction proceeds via an orbital angular momentum transfer, $\Delta L=1$.

A sample calculation of the transitions to be expected from the Λ-hypernucleus is shown in the level scheme for $_{\Lambda}{}^{7}Li$, Fig. 2. In this case, the γ-ray transitions can be divided into two classes, depending on the role of the Λ:

1) spin-flip doublet transitions - These are M1 transitions connecting the members of the hypernuclear doublet built on a core state. In this type the Λ spin is flipped with respect to the core spin.

2) core transitions - In this type the γ-ray transition connects core states, and the Λ plays the role of a spectator (whose presence, however, perturbs the core states).

Dalitz and Gal[7], and more recently Millener et al.[8], have performed a phenomenological analysis using a Λ-N potential model to determine a set of four P_NS_Λ two-body matrix elements to describe the spin-dependent ΛN interaction in the p-shell. The two-body interaction can be expressed as follows:

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)\underline{S}_N \cdot \underline{S}_\Lambda + V_\Lambda(r)\underline{\ell}_{N\Lambda} \cdot \underline{S}_\Lambda + V_N\underline{\ell}_{N\Lambda} \cdot \underline{S}_N + V_T(r)S_{12}$$

with $\ell_{N\Lambda}$ the relative orbital angular momentum, and

$$S_{12} = 3(\underline{\sigma}_\Lambda\cdot r)(\underline{\sigma}_\Lambda\cdot r) - \sigma_{\underline{N}}\cdot\underline{\sigma}_\Lambda;\ r = |\underline{r}_N-\underline{r}_\Lambda|.$$

The potential parameters are referred to as the overall central potential V, the spin-spin term Δ, the Λ spin orbit S_Λ, the induced nuclear spin-orbit S_N, and the tensor T. These parameters are assumed constant across the p-shell. The average central interaction has no effect on spectra, while the S_N (induced spin orbit) affects the spacing of the core states.

Measurements of several hypernuclei ranging across the p-shell can serve to fix these parameters unambiguously. The Λ spin-orbit parameter S_Λ is known to be small and negative from previous (K,π) results of CERN[9] and Brookhaven[10]. The most uncertain parameter is T, which has been estimated by Millener et al. to be small and positive. As Dalitz and Gal have previously observed, the most promising test for T comes from measuring hypernuclear doublet separations in the heavier p-shell hypernuclei, where the coefficient of T in the expression above is the largest.

In AGS experiment 760 core transitions (type 2 above) were observed for the first time in the $(K^-,\pi\gamma)$ reaction with an array of NaI detectors in ${}_\Lambda^7Li$ and ${}_\Lambda^9Be$ hypernuclei[11]. The spectra are illustrated in Figs. 3-5.

These spectra are readily interpretable as follows:

a) In the excitation spectrum, below the hypernuclear gs, no peaks, except for the ever-present 511 keV annihilation, are observed.

b) In the region $-2<E_x<8$ MeV, a peak at 2.034 ± 0.023 MeV is observed. In this peak nearly 100 events are observed; at this energy the net photopeak efficiency of the array is about 10%. The peak is observed in no other excitation region, and no nuclear γ rays exist near 2 MeV for $A\leq7$. Hence this peak may be unambiguously assigned to the $5/2^+\to1/2^+$ transition in ${}_\Lambda^7Li$. It is interesting to observe that the corresponding $3^+\to1^+$ transition in the ^6Li nucleus occurs by α-d breakup. The presence of the Λ stabilizes the system against breakup, thus permitting the observation of the γ ray.

c) No peaks, save that due to 511 radiation, are observed in the cut for $4<E_x<10$ MeV.

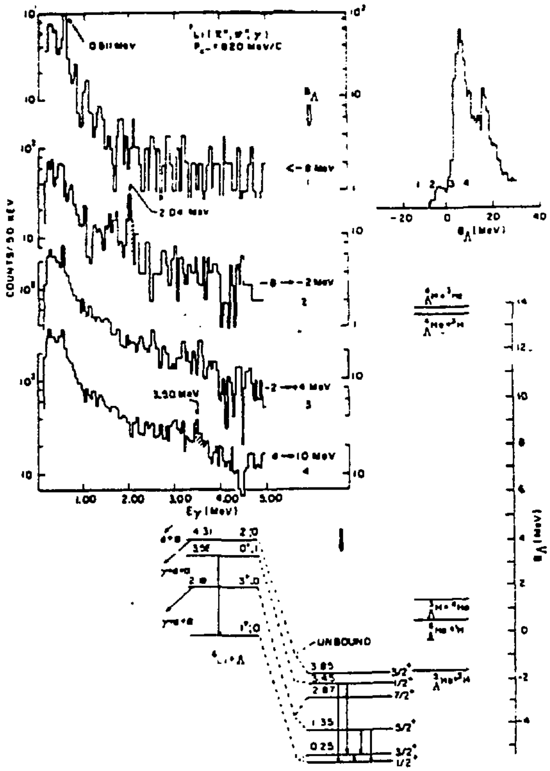

Fig. 3. Gamma-ray spectra obtained for $_{\Lambda}{}^{7}Li$ in the bound state region.

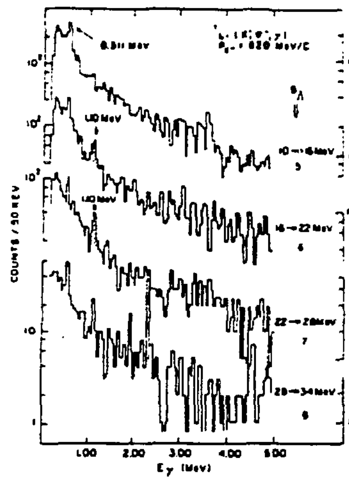

Fig. 4. Gamma-ray spectra obtained for $_{\Lambda}{}^{7}Li$ in a region of high excitation.

d) A peak at 3.56 MeV appears for $10<E_x<16$ MeV. Here there is sufficient energy for Λ emission to populate ^{6}Li excited states. The lowest such state is the 3.56 T=1 level; hence the peak represents a nuclear line.

e) The next figure, 4, shows the regions of higher excitations. For $E_x>22$ MeV, the $_{\Lambda}{}^{7}Li$ system can break up into A=4 and A=3 fragments. A peak at 1.10 ± 0.04 MeV appears. This peak nicely confirms the observation of the 1.04 and 1.15 MeV γ rays reported by Piekarz and his collaborators in the $_{\Lambda}{}^{4}H$ and $_{\Lambda}{}^{4}He$ systems.

In the $_{\Lambda}{}^{9}Be$ spectrum we see a γ ray consistent with the deexcitation of the $3/2^{+}$, $5/2^{+}$ doublet to the $_{\Lambda}{}^{9}Be$ ground state with a transition energy of 3.089 ± 0.04 MeV. In this case the doublet members are expected to be equally populated. Since the nuclear core in this case has S=0, the spin-

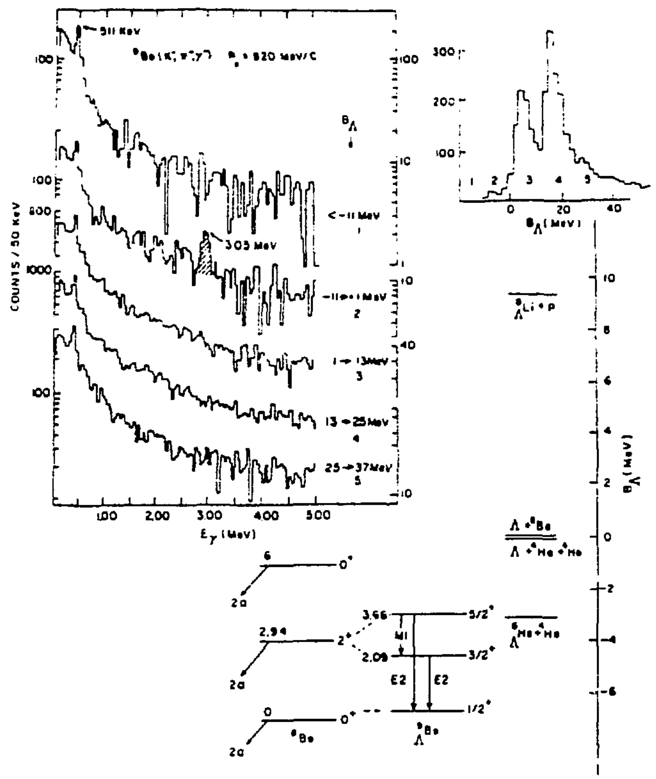

Fig. 5. Gamma-ray spectra obtained for $_{\Lambda}^{9}Be$.

spin interaction would be absent, and the splitting would be expected to be largely a measure of the $\underline{S_\Lambda} \cdot \underline{\ell_N}$ interaction. The observation of a single, unresolved peak places severe constraints on the value of S_Λ. If one ignores the small effects expected from the tensor and spin-spin terms in this case the absolute value of S_Λ would be constrained, from our experiment, to be less than 0.04 MeV.

High Resolution Studies

In view of our failure to observe the spin-flip transitions, an improvement in the experimental techniques was called for. Since the doublet splittings are determined by the sum of several spin-dependent terms of varying sign, it might be expected that cancellation effects would make the doublet separations quite small in some cases. We also concluded that because of high singles rates inherent in these experiments, it was not practical to use large sodium iodide detectors for radiation much below 511 keV in energy.

Fortunately there have been rapid developments in the application of high resolution germanium diode detectors to high rate situations. Quite large intrinsic n-type germanium detectors are now available with reasonably good timing characteristics and excellent efficiencies at very low energies. Furthermore, portable germanium detectors have been developed for commercial applications. These are capable of operating in any orientation; they have small liquid nitrogen dewars and are capable of being closely packed around a target. We used an array of 6 n-type intrinsic Ge detectors, of the closed-end coaxial type, 50 mm in diameter by 40 mm thick.

It should be noted that for γ-ray energies of less than about 50 keV there will be severe competition from the Λ weak decay mode; the Λ lifetime is on the order of 10^{-10} seconds. Thus our "window of sensitivity" extends from perhaps 50 keV to perhaps 300 keV, where the efficiency falls rapidly. However the M1 spin flip rates are low enough that the γ rays will not suffer Doppler broadening, the recoiling nucleus having come to rest prior to γ-emission.

The hostile environment caused by the proximity of a beam of about 10^6 particles/s, mostly pions, near the detectors requires some special treatment. We have adopted the use of a standard spectroscopy amplifier operated with short pulse shaping time constants (0.25 μs), whose output is coupled to a gated integrator. This combination gives a high rate handling capability, yet allows for the relatively slow charge collection of the germanium crystals.

The beam is surrounded by a halo of decay muons which deposit a large amount of energy in the detector. Typically we observe in excess of 5×10^3/s muon-induced events in each crystal, each depositing about 50 MeV of γ-equivalent ionization. The preamplifier must be able to handle the average current--about 10 nano-amperes through the beam spill--without blocking due to base line shift.

A demonstration that the system can indeed detect γ rays under these adverse conditions is demonstrated in Fig. 6, which shows the spectrum obtained for the inelastic excitation of the 478 keV state of ^{7}Li, in the reaction (π,π'γ). Here the γ ray is emitted promptly from the moving Li fragment and is hence Doppler-broadened, consistent with the expected momentum transfer at 15°.

The effects of this harsh environment are mitigated somewhat by the <u>extreme simplicity</u> of the γ-ray spectra expected from p-shell hypernuclei. For the case of $_\Lambda^{10}$B, only the members of the (1^-,2^-) ground state doublet, among the negative parity levels, will be particle stable, and the 2^- level

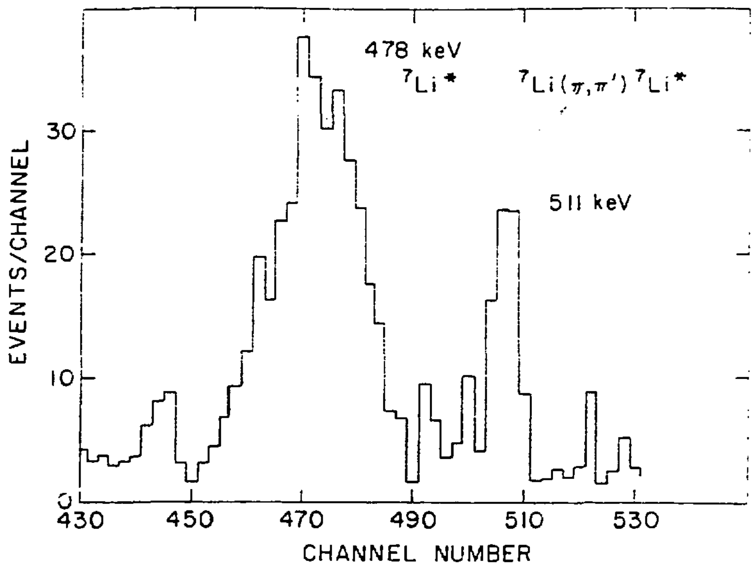

Fig. 6. Detection of the γ-ray from the $^{7}Li(\pi,\pi'\gamma)$ reaction.

will be populated in the (K^-,π^-) reaction with an expected cross section of about 50 μb/sr.

The doublet splitting for $_{\Lambda}{}^{19}B$, in Millener's treatment[8] is given by

$$E(2^-) - E(1^-) = 0.62\Delta + 1.36\ S_\Lambda + 0.055\ S_N - 1.49T$$

$$\approx 170\ \text{keV for} \begin{cases} \Delta = 0.5 \\ S_\Lambda = -0.04 \\ S_N = -0.08 \\ T = 0.04 \end{cases}$$

Figure 7 shows the region near 170 keV for a time coincidence window 80 ns wide. The figure shows two hypernuclear excitation regions: at the left, corresponding to bound states; at the right, an unbound region. The appearance of the peak near 160 keV, quite close to Millener's prediction, is strong evidence that his standard interaction is a good parameterization of the effective Λ-N interaction in the p-shell.

The results for these two γ-ray experiments have provided important constraints on the p-shell Λ-nuclear effective interaction and offer hope that in the future, heavier hypernuclei might be examined with these techniques. The principal limitation, obvious from Fig. 7, is counting rate.

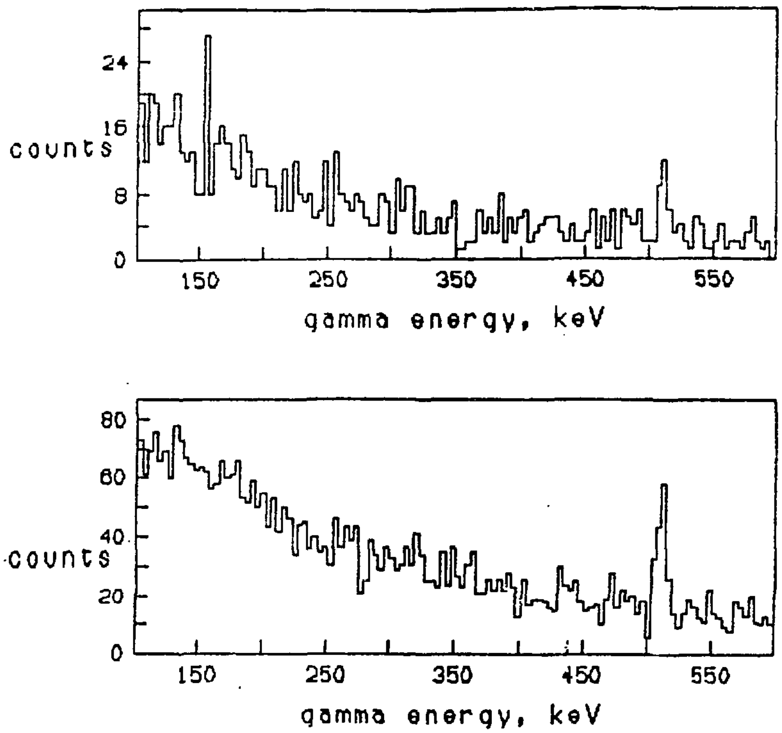

Fig. 7. The γ-ray spectrum from ${}_{\Lambda}^{10}B$ in the (a) bound state region, $-12<B_{\Lambda}<+6$ MeV and (b) from the region $6<B_{\Lambda}<24$ MeV. The (K,π) coincidence window is 80 ns wide.

Clearly future advances in applying these techniques depend on access to kaon beams of improved intensity and purity.

Associated Production of Hypernuclei

It has been pointed out that in the exoergic (K^-,π^-) reaction, the kinematics allow zero momentum transfer to the recoiling hypernucleus near P_K = 530 MeV/c. However, over quite a range of P_K from 500 to over 1000 MeV/c, the momentum transfer is small compared to the Fermi momentum characteristic of nucleons in the nucleus. High spin states formed of "stretched" configurations, in which the particle and hole coupling have maximum angular momentum, are of considerable interest in medium and heavy nuclei. These states are not easily formed in (K^-,π^-) reactions at small angles because of momentum matching considerations. Another obvious need is to reach ground states of Λ-hypernuclei in the s-d shell, which have high spin values.

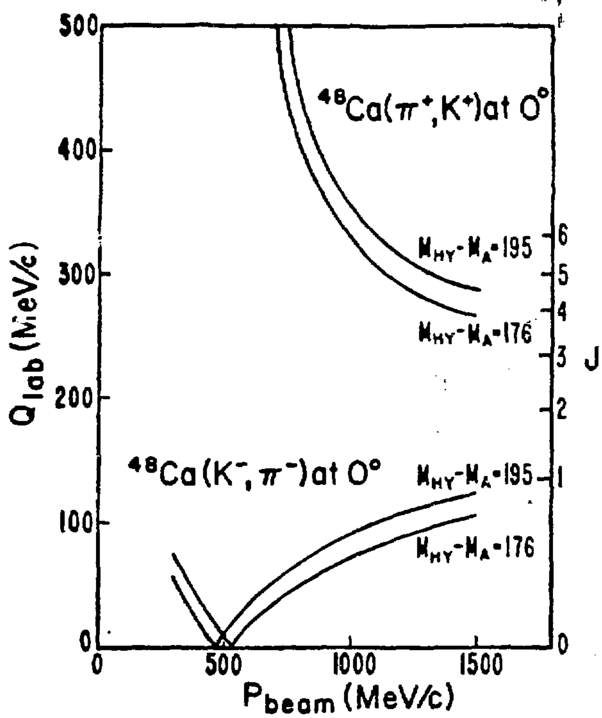

Fig. 8. Kinematics of (π^+,K^+) compared to (K^-,π^-) for a ^{48}Ca target.

It is of some interest, therefore, to explore the use of alternative reaction mechanisms to reach such states.

One such alternative reaction involves the associated production of hyperons, namely the (π^+,K^+) reaction. The kinematics of (π^+,K^+) is compared to the complementary (K^-,π^-) reaction in Fig. 8 for a ^{48}Ca target nucleus[12]. One sees immediately that the momentum transfer is much higher over the whole incident momentum range from threshold, ≈700 MeV/c, to 1500 MeV/c. The figure shows the momentum match to states of various angular momenta, J. It is clear that the (π^+,K^+) preferentially produces states of higher spin than is the case for (K^-,π^-).

The use of the (π^+,K^+) reaction to form hypernuclei was tested recently at the AGS in experiment 758 on ^{12}C.[13] This nucleus was chosen since it had been well studied at Brookhaven with the (K^-,π^-) reaction[14]. In that reaction, two peaks are clearly seen; the lower excitation peak is identified as the 1^- gs, produced by a $\Delta L=1$ transition which transforms a $p_{3/2}$ neutron into an $s_{1/2}$ Λ. Near 11 MeV is seen a peak which consists of several unresolved contributions with spins 0^+ and 2^+ arising from the components $[n^{-1}(p_{3/2}),\ \Lambda(p_{3/2})]$ and $[n^{-1}(p_{3/2}),\ \Lambda(p_{1/2})]$. The smallness of the Λ-nucleus spin-orbit interaction causes this complex of states to be nearly degenerate in energy. In using the (π^+,K^+) reaction to investigate ${}_{\Lambda}^{12}$C one would expect to populate more effectively the <u>higher</u> spin members of the multiplet components.

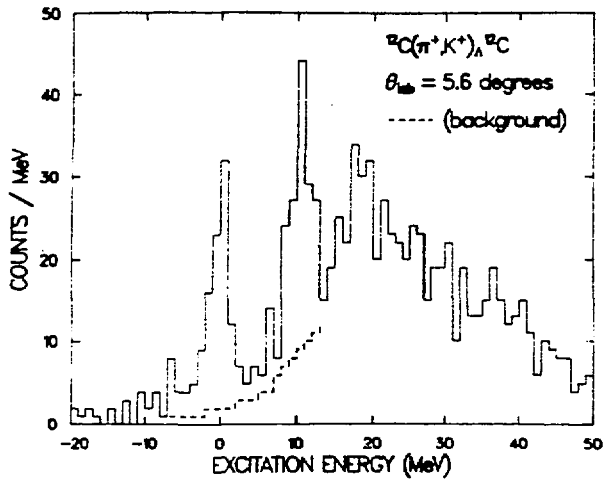

Fig. 9. Spectrum from the (π^+,K^+) reaction on ^{12}C.

The experiment was performed at 1050 MeV/c incident pion momentum to take advantage of the maximum in the elementary cross section for $\pi^+ + n \to K^+ + \Lambda$. Data were recorded at spectrometer settings of 5°, 10°, and 15°. The data are shown at 5° angles as binned into 1 MeV excitation energy regions, in Fig. 9. An examination of these shows the presence of at least two peaks together with a broad distribution characteristic of the quasi-free $\pi^+ + n \to \Lambda + K^+$ process. The two peaks observed are reminiscent of the peaks observed for carbon in the complementary (K^-,π^-) reaction.

Plots of the angular distributions obtained from the present experiment compared to DWBA calculations are shown in Fig. 10. A good agreement is evident after the DWBA predicted cross sections have been reduced by a factor of two to account for Fermi broadening.

These results confirm the feasibility of the (π^+,K^+) reaction as a spectroscopic tool for investigating hypernuclei. The overall running times for the accumulation of these spectra are roughly the same as those experienced for (K^-,π^-). It is evident that the inherently lower cross sections have been compensated by the higher particle flux, and that the background components induced by the higher flux are manageable. In view of the recent successful detection of electromagnetic radiation for p-shell hypernuclei, it is natural to consider the extension of the present experiment to $(\pi^+,K^+\gamma)$ reactions. Thus possibilities for a much more expanded field of hypernuclear research have been opened up. A beam line in the range of 1 to 2 GeV/c pion momentum, and a flux up to 10^7 particles/spill would allow the effective exploitation of this tool.

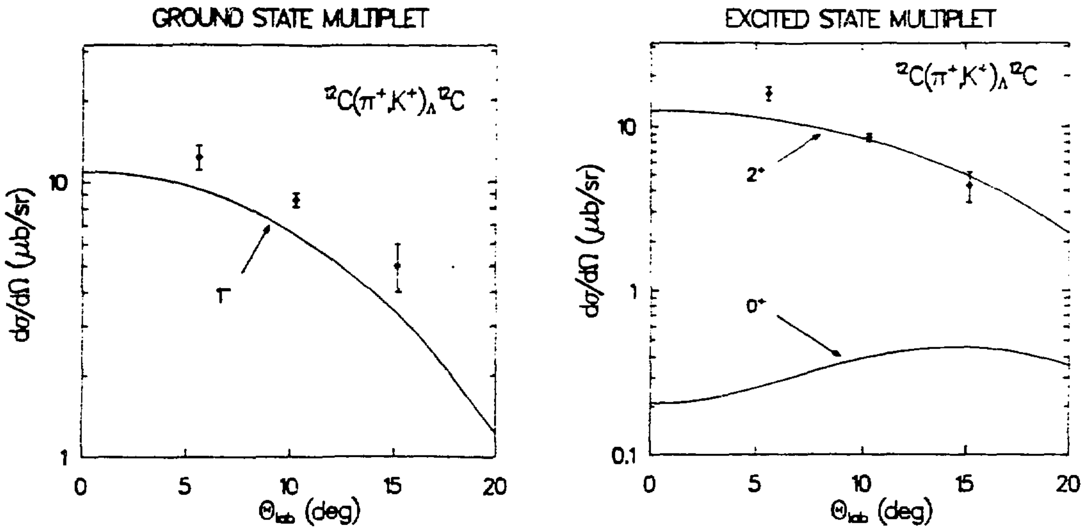

Fig. 10. DWBA predictions for the (π^+,K^+) reaction on ^{12}C.

The Lifetime of the Λ Hypernucleus

In the absence of nuclear matter, a Λ hyperon decays to a nucleon with a mean life of 263 ps, via the emission of a pion. The presence of nuclear matter introduces a competitive decay mode, the non-mesonic decay mode.

The non-mesonic decay mode is of special interest because it affords the opportunity to study the weak component of the baryon-baryon interactions, or the four fermion weak interaction. This issue is closely related to the parity-violating processes in ordinary nuclei. Calculations of the decay rates have been carried out in the framework of mesonic exchange by McKellar and Gibson[15], and in terms of a two-baryon, 6 quark model, by Heddle and Kisslinger[16]. These calculations have offered a range of lifetimes between τ=1/3 and τ=3 τ_{free}. Lifetime measurements from nuclear emulsion have been limited to light hypernuclei, and are too crude to shed much light on the four fermion weak interaction.

At BNL, the group led by scientists from Carnegie-Mellon University have demonstrated the feasibility of a direct measurement of the decay of the hypernucleus $_\Lambda{}^{12}C$.[17]

The decay protons have been detected in a scintillation hodoscope situated near the ${}^{12}C$ target. A digital wire chamber forms part of the detector package and allows the proton trajectory to be reconstructed so that an accurate flight-time correction can be made (Fig. 11).

The ${}_{\Lambda}^{12}C$ missing mass spectrum is shown in Fig. 12. Decay protons were observed from three broad regions of this spectrum:

1) The region of the ground states.
2) The region of the p substitutional peak.
3) The region of the s substitutional state.

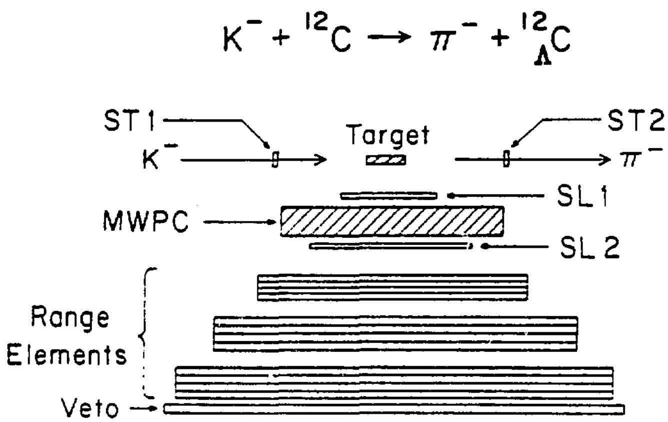

Fig. 11. Experimental apparatus for the lifetime measurement on ${}^{12}C$.

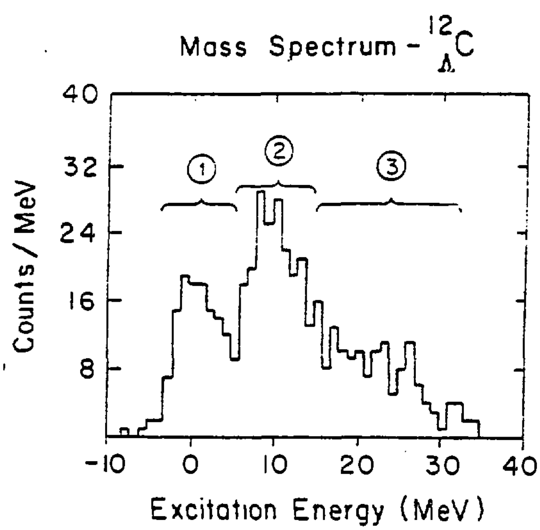

Fig. 12. The missing mass spectrum of ${}^{12}C$.

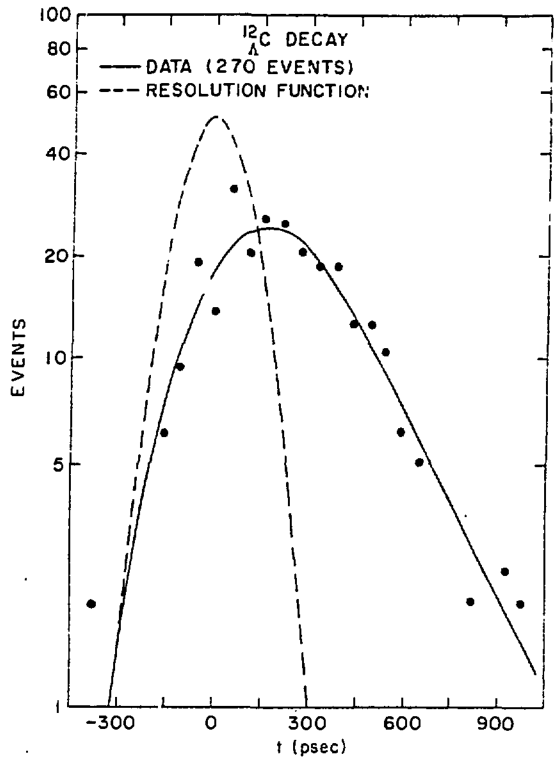

Fig. 13. A timing curve for decay protons from ^{12}C.

Energetic decay protons from all three regions were observed, indicating stable hypernuclear formation. Only region (1) corresponds to $_{\Lambda}{}^{12}C$ decay; for this region a decay rate, expressed as a ratio to free decay, of 1.25 ± 0.18 is observed. State 2, being proton unbound, corresponds to ^{11}B decay, and a ratio 1.37 ± 0.16 was obtained. In region 3 it is not possible to identify the hypernucleus produced; in this region a ratio 1.31 ± 0.2 was obtained. Figure 13 shows a timing curve generated for region 2.

These observations are in agreement with the expected non-mesonic decay rates for infinite matter obtained by McKellar et al. ($\Gamma_{nm}/\Gamma_{\Lambda}$ = 0.5 to 2.0).

Future Directions for Research

It is apparent that we have made only a modest beginning on extracting the wealth of information potentially available from hypernuclei. Research possibilities may be divided into several categories: a) extension of present measurements to more nuclear targets for Λ hypernuclear studies; b) more detailed studies of Σ states through (K^-,π^-) and (K^-,π^+) reactions and their intercomparison; c) production of S=-2 hypernuclei including double Λ and cascade hypernuclei; d) an exploitation of the $(\ ^+,K^+)$ reaction for studies of states with high momentum components, e) studies of excited states of hyperons, such as the Y^* resonances and their decay modes; and f) the study of S=-1 and S=-2 dibaryon resonances and their relation to the exciting and challenging aspects of the role of quarks in nuclear models and the testing of various quark bag model calculations. Because of thresholds, cross sections, and reaction kinematics, a complete program of research on strange systems requires several different momentum ranges. Perhaps the most exciting area lies in the momentum region above 1.0 GeV/c.[6]

Hypernuclear physics has so far been devoted to strange nuclei with S=-1. At momenta above about 1.1 GeV, strangeness changing reactions such as (K^-,K^+) which can produce nuclei with S=-2 become feasible. Such nuclei might contain a cascade particle (Ξ) or two Λ's. There is meager evidence for both of these from nuclear emulsion experiments. There is much theoretical interest in dibaryon resonances and their relationship with quark-bag models. Dibaryon resonances with various strangeness quantum numbers have been predicted; perhaps the most interesting, however, is the H-particle proposed by Jaffe[18], which contains 6 quarks in an SU(3) flavor singlet. The H has S=-2 and might, for example, be produced in a (K^-,K^+) reaction on ^{3}He. Aerts and Dover[19] have suggested such an experiment in which the (K^-,K^+) reaction on a proton produces a cascade particle Ξ^-, which subsequently fuses with a second proton to form the H. The H could also be formed from a atomic state, for instance, in the process $\Xi^- + d \rightarrow H + n$, as proposed by the Carnegie-Mellon group (Fig. 14)[20].

These experiments with S=-2 nuclei require a beam line with a higher momentum than is currently available. The cross section for Ξ^- production on the free proton lies above 1 GeV/c; hence a line covering the range from 1-2 GeV would be optimal for exploitation of the (K^-,K^+) reaction. At the same time, such a line would be suitable as a source of pions for the (π^+,K^+) and $(\pi^+,K^+\gamma)$ studies.

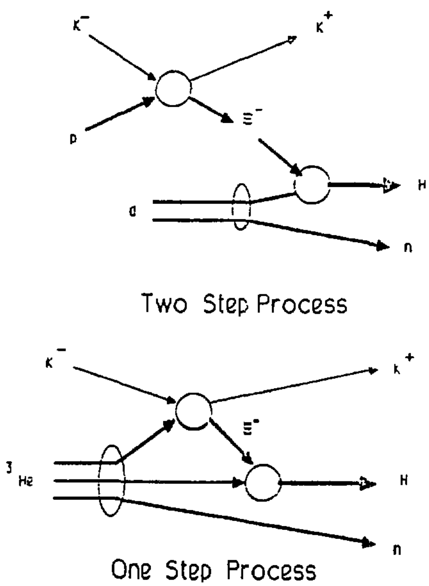

Fig. 14. Two methods for forming the suggested "H" particle.

In view of the existence of LESB-1, and the opportunities offered at KEK, it is our feeling that best way to improve hypernuclear research facilities at the AGS is to construct a line offering separated kaons and pions in the 1.0 to 2.0 GeV/c region. This would complement existing facilities and help to offer a full range of options to the experimenter. It would play a decisive role in continuing hypernuclear research until the time when a next generation kaon factory is available.

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