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AUTHOR(S) B. F. Gibson

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Los Alamos, New Mexico 87545

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HYPERON AND HYPERNUCLEAR PHYSICS WITH INTENSE BEAMS

B. F. Gibson
Theoretical Division, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

A brief examination of progress in the study of hypernuclear physics and the hyperon-nucleon interaction is presented. The use of Λ-hypernuclei in the study of conventional (nonstrange) nuclei is explored. The status of the hyperon-nucleon force problem is reviewed. Anecdotal results are discussed for baryon numbers 4 and 13. Σ-hypernuclei are discussed. Production of $S = -2$ hypernuclei is mentioned.

One of the fundamental questions facing physicists today is that concerned with how we unify the basic forces of nature: gravitational, electromagnetic, strong nuclear, and weak nuclear. Although headway has been made toward an answer, the candidate "Grand Unified Theories" are so far just that, candidate theories. Along this path, nuclear physics has contributed to our overall knowledge of the strong force; it is in a position to contribute data on the weak force. Another fundamental question facing physicists today concerns our understanding of the structure of nuclei. These multibaryon systems comprise much of the mass and energy of our immediate surroundings. Synthesis of the elements is crucially based upon nuclear structure. Nuclei produce the energy of our solar system. Their interactions involve all the forces of nature. To comprehend our universe, we must understand the structure of nuclear systems. But there exist various levels of understanding. Just as one would not attempt to study liquid argon to learn about QED, one does not expect to extract significant knowedge about QCD from studying the binding of the neutron and proton to form deuterium. Likewise, one does not attempt to calculate the structure of complex crystals starting from first principles and QED; solid state is an interesting and viable field of physics independent of quantum electrodynamics.

Particle physics seeks to provide an understanding of elementary particle interactions at very high energies (ultra short distances). In contrast, nuclear physics strives to describe the nucleus at energies and interparticle distances corresponding to conditions which one might describe by two bags barely overlapping. Here, in a region that the particle physicist finds difficult to describe quantitatively with asymptotically free theories, the nuclear physicist finds simplification and order in terms of meson exchange models. It is the possibility of speculating about the transition from the remarkably successful picture of the nucleus as a composite system of interacting nucleons to one of a quark soup that intrigues many physicists. However, one must first define the limits of validity for describing nuclear phenomena in terms of physically observable baryons and mesons before evidence for quark degrees of freedom in nuclei can be critically evaluated. Recall two successes of nuclear physics in the last decade: 1) the perfection of model calculations based solely upon nucleon degrees of freedom to the point that comparison of results with experimental data revealed the inadequacies of the assumption and demonstrated the undeniable need to expand the model to include meson exchange currents - a new degree of freedom; 2) the perfection of realistic nucleon-nucleon potential model calculations to the extent that a comparison of results with well established experimental binding energies revealed discrepancies that could only be accounted for by the introduction of three-body forces. In each case detailed, precision calculations were required in comparison with numerous experimental data before it became possible to establish that these small but significant effects were genuine. Thus, nuclear physics seeks the appropriate degrees of freedom with which to describe nuclear systems and their interactions. The ultimate test of our intellect is whether we possess the capability to calculate all of the nuclear phenomena which we have the ability to measure.

In what follows, I will specialize the discussion to hypernuclear physics - those multibaryon systems in which one or more of the nucleons has been replaced by a hyperon (Λ, Σ, Ξ, Ω). Along the way, you will find mention of hypernuclear properties with possible relevance to quark model predictions - the Λ and Σ spin-orbit forces. You will see reference to the use of a nuclear target to search for the di-Λ (or "H" particle). These are the topics which may be most exciting to this audience. However, the primary purpose of this discourse is to impart some of the enthusiasm which nuclear physicists feel for this budding subfield - to survey the interesting directions of research which would be open if there were available an intense source of kaons.

Nuclear physicists strive to understand conventional nuclear matter; they also seek to create and study new forms of quasi-nuclear matter. The K and $\bar{K}$ mesons are useful for both purposes. Our knowledge of the stucture of conventional nuclei can be enhanced by utilizing the K^+ probe.[1] Because of its strangeness (S = +1), the low energy KN interaction is not resonant. There are no known S = +1 baryons or low-lying resonances. The heavy mass of this weakly interacting hadronic probe makes it an ideal high momentum transfer tool below meson production threshold. Because it interacts with the neutron as well as the proton, the K^+ should be useful in determining the neutron's role in collective excitations and the neutron components of particle-hole states. The (K^+,K^0) charge exchange reaction should be even better suited to structure studies than the standard (π^+,π^0) reaction; the kaon distortion in initial and final states is much less than that suffered by the pion. Of even more interest is the study of hypernuclei by means of the (K^-,π) reaction. One can explore the modifications of nuclei that occur when a distinguishable baryon is inserted. Hypernuclei offer an expedient means of looking beyond that found in nature, to investigate a new form of matter containing strange quarks. The study of such strange particle matter will add a third dimension to our microscopic picture of nuclear structure.

The study of hyperon behavior in nuclear matter and the fundamental properties of hypernuclei have been, since 1953, the driving interest in $\bar{K}$-nucleus physics. That interest should soar with the advent of intense kaon beams. The $\bar{K}$-meson (strangeness S = -1) interacts very strongly with nuclei. Like the pion, the $\bar{K}$ is strongly absorbed by the nucleus; its elastic channel wave function is localized primarily in the nuclear periphery. One can understand the resonance structure in the $\bar{K}N$ amplitude in terms of the conservation of strangeness, a basic symmetry of the nuclear strong force. At threshold the open inelastic channels are: $\bar{K}N \rightarrow \pi Y$ ($Y = \Lambda$ or Σ, baryons having S = -1). The $\bar{K}$ can fuse with the nucleon to form a variety of Y* resonances (S = -1) at laboratory momenta below 1.5 GeV/c just as the π coalesces with the nucleon to form the N*'s [the $\Delta(3,3)$, etc.]. Two of the more interesting Y* resonances are the $\Lambda(1405)$ and the $\Lambda(1520)$. The $\Lambda(1405)$ lies just below threshold in the K^--atom (zero energy) system and qualitatively alters the I = 0 $\bar{K}N$ amplitudes in the nuclear medium. The $\Lambda(1520)$, with its extremely narrow width ($\cong$ 16 MeV), is potentially useful in investigating the intriguing problem of the propagation of an isobar within the nucleus. Answers to questions of how the energy and lifetime are modified due to Fermi motion, Pauli blocking, and collision damping are fundamental to our understanding the mechanism of meson propagation and the role of mesonic degrees of freedom in nuclear matter.

The (K^-,π) strangeness exchange reaction can be exploited to investigate the S = -1 Λ-hypernuclei and Σ-hypernuclei as well as the generalized Y*-hypernuclei. The (K^-,K^+) double-strangeness-exchange reaction can be used to produce the S = -2 Ξ-hypernuclei and double-Λ- or double-Σ-hypernuclei. Only the (K^-,π^+) reaction forms a unique hypernucleus (the Σ^--hypernucleus) assuming a single-step strangeness-exchange reaction mechanism. Thus, knowledge of all final state channels is required for a complete picture of the strangeness exchange reactions, in particular the isospin structure. However, nuclear structure information can be extracted from binding energies, γ deexcitation energies, angular distributions or differential cross sections, etc., even in the absence of a complete knowledge of all reaction channels.

The use of the Λ as a probe of the properties of conventional (S = 0) nuclei is one of the strongest motivating factors in our study of hypernuclei.[2] Coupling a Λ to a nucleus will change the moment of inertia of a deformed nucleus and produce a corresponding effect upon the rotational band structure; it should produce an observable effect in the phonon spectrum of a vibrational nucleus; and it may alter the energy gap in a superfluid nucleus. Near the mass regions showing oblate-to-prolate phase transitions, the addition of a hyperon may alter the mass value A at which the transition occurs. An added Λ would certainly influence the fission process and most likely the properties of shape isomers. Giant resonance properties may be altered due to coupling of a Λ to the nucleus. Core polarization induced by a Λ would alter the moments of nuclei deduced from γ transitions. Compression due to the presence of a Λ will increase the Coulomb energy of the core nucleus. Finally, the addition of a Λ to a nucleus can raise the threshold for particle emission making low-lying continuum states stable against particle decay. The insertion of a tagged baryon into the nucleus permits us to perturb the nuclear core of the hypernucleus being investigated in a way not possible by means of standard isotope or isotone studies. Each of these perturbative alterations in the nuclear core provides a different test of our understanding of the underlying nuclear structure principles.

As an example, let us consider $^{7}_{\Lambda}$Li, where the observation of a hypernuclear γ ray has demonstrated that the low-lying continuum levels in ^{6}Li do become particle stable.[3] The ^{6}Li nuclear core is difficult to model. There are no bound ^{5}He or ^{5}Li nuclei from which it can be formed by addition of a nucleon; it is not well represented as a hole in ^{7}Li. Thus, isotope or isotone studies do not provide realistic tests of our nuclear models of ^{6}Li. The first excited state in the ^{6}Li spectrum (see Fig. 1) lies in the continuum, above the threshold for α+d decay. Because our methods of treating continuum states differ from bound state calculational methods and are not as reliable approximations, we have been limited to comparison with ground state properties of ^{6}Li for stringent tests of our mathematical models of that nucleus. However, the

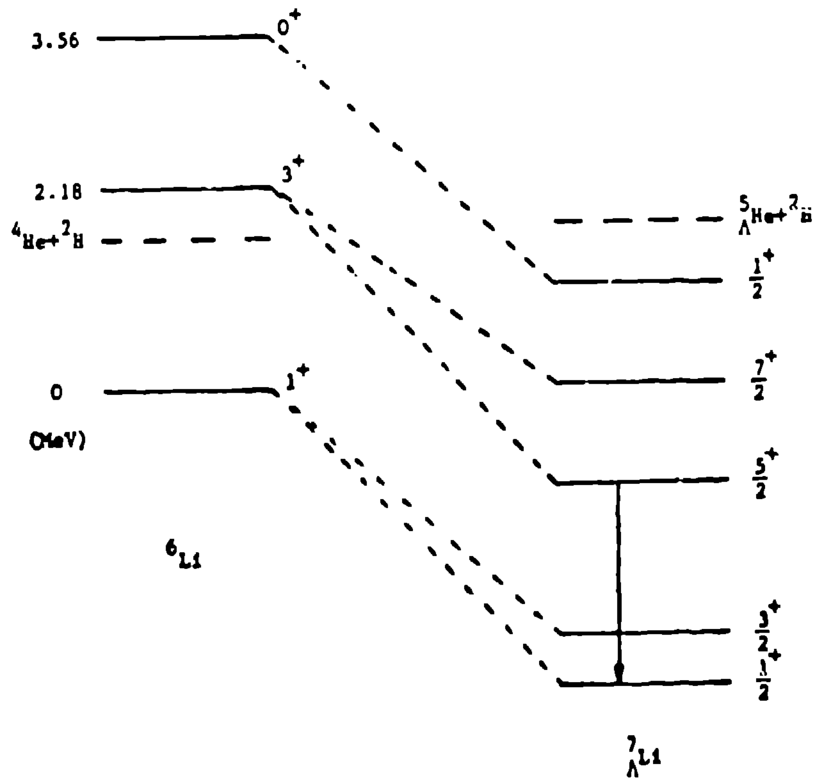

Fig. 1 Spectrum of ^{6}Li with possible corresponding particle stable levels in $^{7}_{\Lambda}$Li.

addition of a Λ to form ${}^{7}_{\Lambda}Li$ yields a hypernucleus which can be used to test our understanding of ^{6}Li. With the insertion of the relatively weakly interacting Λ, the ^{6}Li core remains intact while several continuum levels become particle stable. Our models can then be evaluated in terms of how well the dynamics of a system with several bound levels is reproduced. Our success in describing the spectrum of ${}^{7}_{\Lambda}Li$ depends crucially upon our correct modeling of ^{6}Li.

To understand and utilize Λ-hypernuclei, we must have a reasonable description of the ΛN interaction. The coupling of the ΛN-ΣN system in the $T = \frac{1}{2}$ channel is a complication not arising in low-energy nucleon-nucleon scattering. Experimental data on YN scattering are scarce. Because of the short lifetimes (of order 10^{-10} sec. or less) experiments are difficult, especially at low energy. Present fluxes of hyperons are not adequate to measure hyperon-nucleon cross sections. The limited low-energy YN data show a dominant s-wave character.[4] Only through the angular distributions for $\Sigma^{-}p \rightarrow \Lambda n$ inelastic scattering have nonnegligible p-wave contributions been established. At higher energies in the Λp system, near the $\Sigma^{+}n$ threshold, the data show evidence for the existence of at least one ΛN resonance ($M = 2919$ MeV) with a narrow (< 10 MeV) width. The lack of YN data has led to the construction of potential models very dependent upon sizeable theoretical input. More extensive data are clearly essential, not only to adequately treat hypernuclear structure but to verify the existence of bag model predictions of $S = -1$ dibaryon states and to explore such questions as whether the short range repulsion in the nucleon-nucleon force is the result of Pauli principle effects due to the quark structure of nucleons. (If the energetically most advantageous quark configurations are forbidden, then the presence of a strange quark in the YN interaction should reduce the repulsion compared to the NN interaction.)

Data on the A=4 Λ-hypernuclear isodoublet provide a good test of the low-energy characteristics of the fundamental hyperon-nucleon force as well as a unique opportunity to study the complications that arise in calculations of the properties of systems in which one baryon (here the Λ) couples strongly to another (the Σ) with a different isospin. In particular, when one represents the free YN interaction in terms of one-channel effective ΛN potentials, the resulting 0^{+} (ground) states and 1^{+} (excited) spin-flip states of the A=4 system are inversely ordered in terms of binding energies, the 1^{+} state being more bound. However, utilizing a coupled ΛN-ΣN separable potential model, we have been able to demonstrate that the spin-isospin suppression of the Λ-Σ conversion due to the composite nature of the ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ systems is sufficient to yield a 0^{+}-1^{+} binding energy difference in approximate agreement with the experimental measurement, when an exact four-body formalism is used as the basis for the numerical computation.[3] That is, the $T=\frac{1}{2}$ ^{3}H and ^{3}He nuclear cores do not interact with the Λ-Σ system in the same manner as do free $T=\frac{1}{2}$ protons and neutrons; the composite nature of the trinucleon bound states suppresses the Λ-Σ conversion process in a physically observable way.

To fully develop a picture of strange particle matter, we must understand the crucial aspects of hypernuclear structure. Of particular importance are the spin and parity of levels [using the (K^-,π) angular distribution], the isospin composition of levels [comparing (K^-,π^-) and (K^-,π^0) angular distributions], the nature and strength of the residual interaction experienced by the Λ (conventional analysis of hypernuclear spectroscopy), and the effects of charge symmetry breaking in the ΛN force (comparing levels in mirror hypernuclei). To progress beyond our present rudimentary knowledge, we require much better data (to deduce, for example, a reliable parameterization of the fundamental YN force from the anlysis of hyperon-nucleon scattering data). More intense beams and better resolution than presently available are needed in order to fully utilize these tagged baryon systems, to develop our knowledge of new forms of matter as well as conventional nuclear stucture.

What are our present experimental capabilities? The known momentum transfer characteristics of the (K^-,π) reaction are shown in Fig. 2. At the "magic momentum" of about 530 MeV/c for Λ production and 280 MeV/c for Σ production, the 0° momentum transfer vanishes in hyperon production at rest within the nucleus.[5] In this momentum transfer range the production of low-spin substitutional states, in which a nucleon is replaced by a hyperon in the same orbit, is emphasized. Higher spin states emerge at nonzero angles.

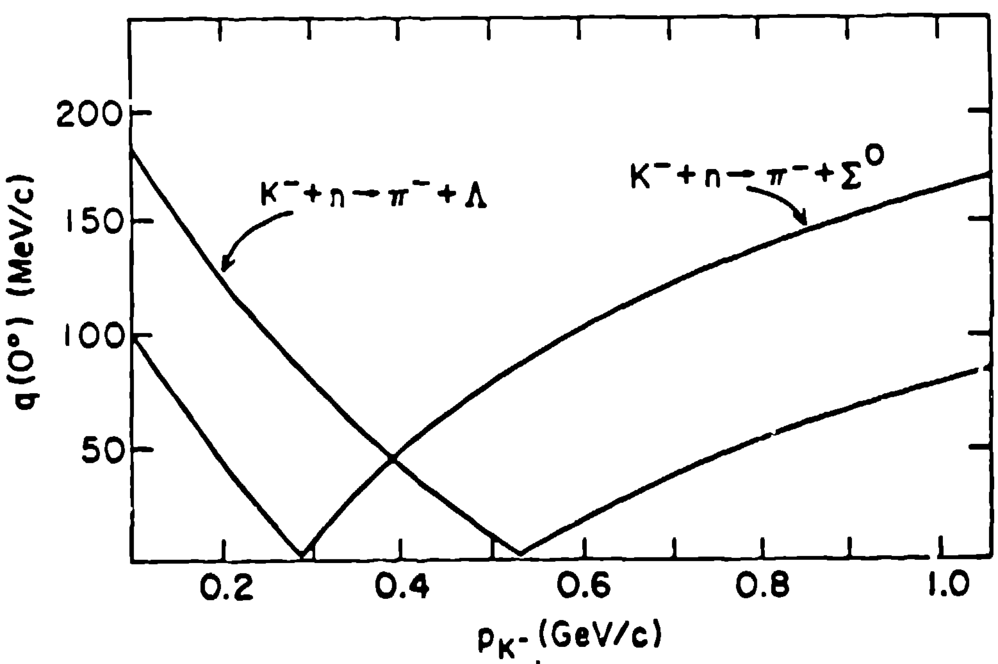

Fig. 2 Lab momentum transfer q at θ=0° as function of incident lab momentum for Λ and Σ production; large A is assumed and binding energy effects are neglected. [From C. B. Dover, L. Ludeking, and G. E. Walker, Phys. Rev. C 22, 2073 (1980).]

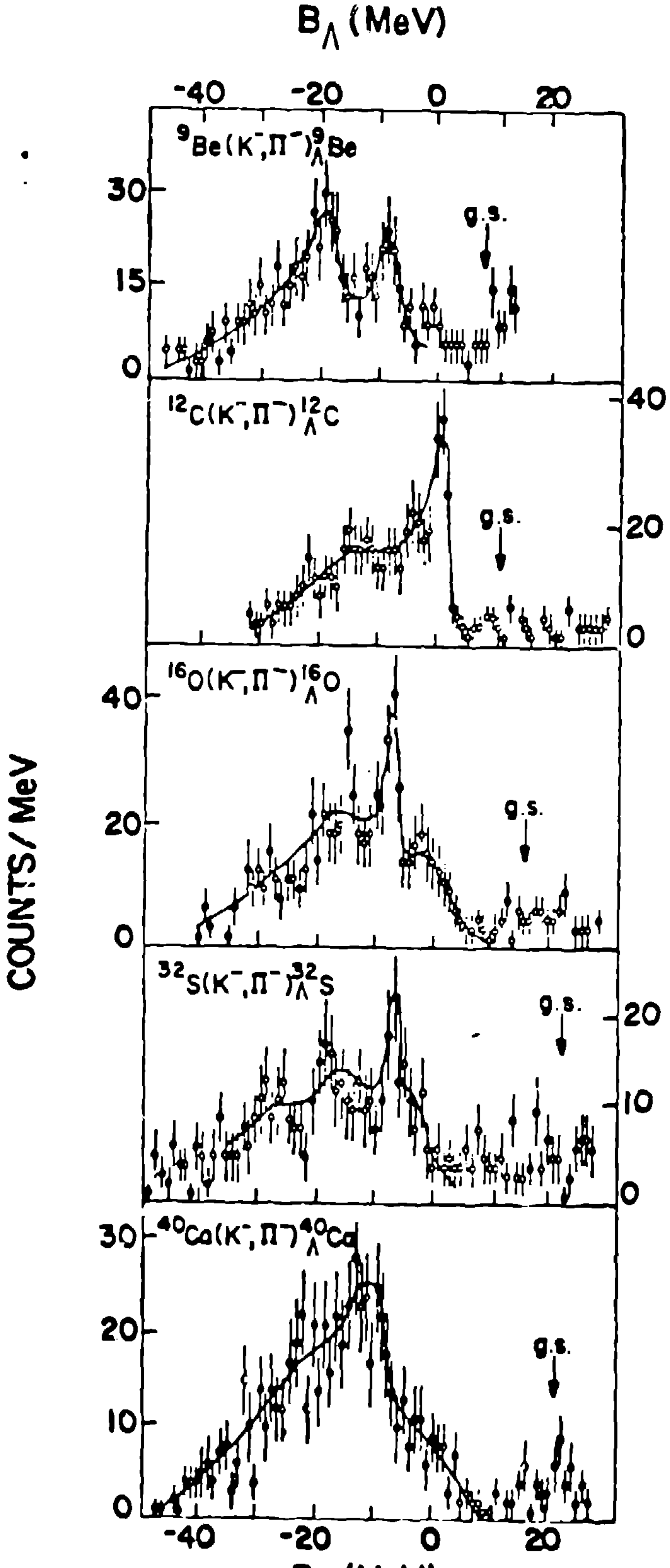

Fig. 3 Spectra for the (K^-,π^-) reaction as a function of the Λ binding energy. [From H. Brückner, et al., Phys. Lett. 62B, 481(1976).]

For example, in the (K^-,π^-) angular distribution from p-shell, spin-zero targets, the 0^+ hypernuclear states peak at 0°; the 1^- states, at about 10°, etc. As in other nuclear reactions, the shape of the angular distribution provides a clear signature for the spin of an isolated hypernuclear state. A sample from the results of the first (K^-,π^-) survey experiments is given in Fig. 3. The excitation functions are all for 0° (pion angle) and for an incident K^- momentum in the range from 700 to 800 MeV/c. The coarse energy resolution (3 to 5 MeV/c) precludes resolving the fine structure in the hypernuclear spectrum and is reminiscent of the early stage in nuclear structure physics with classical probes before high resolution spectrometers were available.[6]

More recently, angular distributions for the (K^-,π^-) reaction have been measured at BNL (see Fig. 4). The relative intensities of the peaks change with angle, and energy shifts occur that are directly related to the properties of the Λ-N interaction. Deviations from a weak coupling picture [coupling a Λ to the 0^+ (T=0) ^{12}C core ground state plus the 2^+(T=0), 1^+(T=0), 1^+(T=1), and 2^+(T=1) excited states of ^{12}C] provide information about the strength of the spin-orbit Λ splitting and the ΛN quadrupole-quadrupole potential.[7] High resolution data on a variety of p-shell targets are required before one can sort out the details of the spin-spin and spin-orbit parts of the ΛN force. However, a very exciting feature of the data is the indication that the spin-orbit force felt by the Λ in the nucleus is very small, a surprising contrast with the large spin-orbit force felt by nucleons. The large deviation of the ratio of the sizes of the dominant peaks from that predicted using neutron pick-up strengths confirms the tendency of hypernuclei to form states

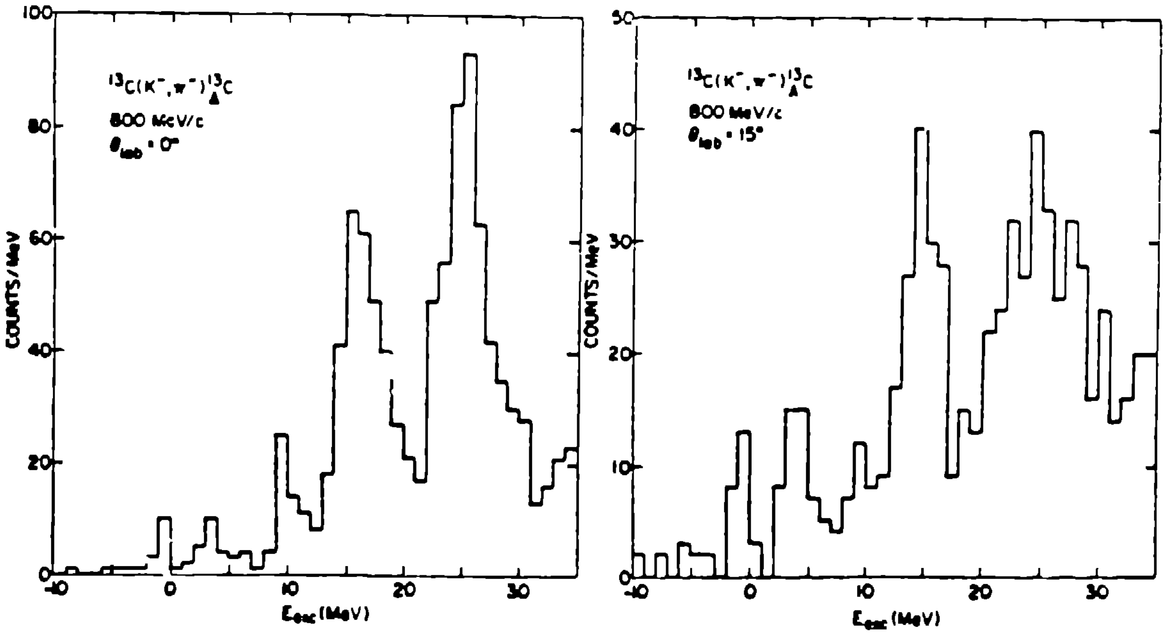

Fig. 4 Spectra for the reaction $^{13}C(K^-,\pi^-)^{13}_{\Lambda}C$ as a function of the excitation energy. [From M. May, et. al., Phys. Rev. Lett. 47, 1106 (1981).

with a higher degree of spatial symmetry than is possible in normal nuclei; if one uses as a basis the states with [54] and [441] symmetry, the [54] symmetry in $^{13}_{\Lambda}C$ is forbidden in a system of 13 nucleons by the Pauli principle.[7] Thus, evidence for a dynamical selection rule emerges. But the full exploitation of structure information available from the spectra of Λ-hypernuclei requires considerable improvement in energy resolution, which is possible only with more intense K^- beams.

Σ-hypernuclei studies lie at the forefront of current hypernuclear investigations.[3] Surprisingly narrow Σ states have been reported. (A large width due to strong Σ → Λ conversion had been anticipated.) Forward production of Σ's was studied in p-shell targets from Li to C using the (K^-,π^-) reactions at 720 MeV/c. The best evidence was for ^{9}Be (Fig. 5); data for the production of Λ-hypernuclei are shown for comparison. Narrow Σ states have been seen since at 400 and 450 MeV/c, presumably corresponding to coherent substitutional transitions leading to 0^+ final states. Interesting questions arise in the interpretation of these data. Why are some Σ states relatively narrow? What are the single-particle properties of a Σ in the nucleus (well depths, spin-orbit potentials, etc.)? Do Σ states have good isospin? The data are yet too crude to permit definitive answers. However, there are tantalizing hints that the Σ spin-orbit potential is larger than that of the

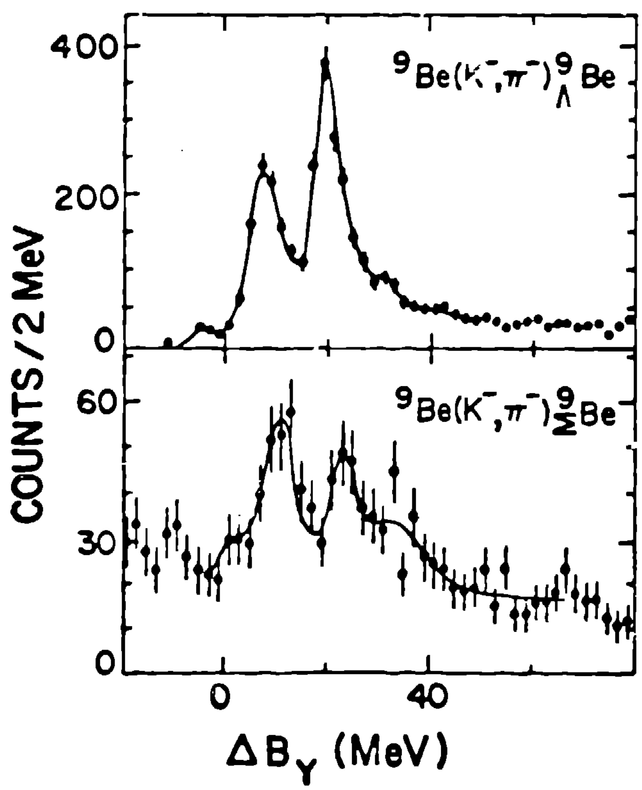

Fig. 5. Spectra for the (K^-,π^-) reaction on ^{9}Be leading to Λ-hypernuclei and Σ-hypernuclei. [From R. Bertini, et al., Phys. Lett. 90B, 375 (1980).]

nucleon; recall that for the Λ it appears to be almost zero. Angular distributions for both the (K^-,π^+) and (K^-,π^-) reactions are needed to answer these questions, as well as to obtain definite spin assignments. An intense, low momentum K^- beam would be of immense benefit in the study of Σ-hypernuclei.

Hypernuclear physics utilizing the double strangeness exchange reaction (K^-,K^+) lies in the future.[7] Cross sections for nuclear targets will be quite small (a few nb/sr to a μb/sr). Thus, the study of $S = -2$ hypernuclei would benefit enormously from the availability of an intense kaon beam in the 1- to 2- GeV/c momentum range. The spectroscopy of Ξ- and $\Lambda\Lambda$-hypernuclei represents a logical progression in the evolution of hypernuclear physics. The spectroscopy of such hypernuclei is rich, although only a restricted set of states (high spin with no spin-flip transitions) will be excited with measurable cross section using the high momentum transfer (K^-,K^+) reaction. Determining single particle properties of the Ξ is one goal; exploring the $\Lambda\Lambda$ interaction is another. The $\Xi^- p \rightarrow \Lambda\Lambda$ transition is not expected to broaden the levels significantly beyond what has been seen in Λ- and Σ-hypernuclei. The $\Lambda\Lambda$ pairing correlation effects should enhance states in $\Lambda\Lambda$-hypernuclei just as NN correlations do in $S = 0$ nuclei.

As remarked previously, the search for evidence of quark degrees of freedom in nuclear matter is a quest of current interest to many physicists. Let me remind you that we have already found them in the sense that one believes the quark description of N's and Δ's; i.e. $NN \rightarrow N\Delta$ excites a new quark degree of freedom. Likewise $\Sigma N \rightarrow \Lambda N$ involves a quark transition. However, there are two areas where hypernuclear physics offers some hope of providing credible evidence of a positive nature for the bag approach to quark models. First, the disparate sizes of the experimentally oberved mean-field Λ-nucleus spin-orbit force and Σ-nucleus spin-orbit force may differentiate between quark-model and meson-exchange model descriptions. Naive quark model descriptions of the Λ and Σ have led to ΛN and ΣN two-body spin-orbit potentials of very different magnitudes.[3] However, the step from two-body spin-orbit potential to one-body, mean-field force in a shell model is not a short one. Second, the search for the doubly strange "H" dibaryon, first proposed by Jaffe, is clearly of paramount importance. The $^3He(K^-,K^+n)$"H" reaction would appear to be the cleanest test of the existence of such a massive six quark object as is predicted by some quark models. Particle physics seeks at high energies the asymptotic, small r limit of particle phenomena, in contrast to nuclear physics where one goes to low energies to find asymptopia. As nuclear physics moves up in energy and momentum transfer to find new degrees of freedom and as particle physics moves down in energy to seek structure information beyond the r=0 limit, there is hope that these two once common fields will again come together.

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