LA-UR 87-782

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LA-UR--87-782

DE87 007477

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SUBMITTED TO Proceedings of the Eighth Summer School of Nuclear and Particle Physics Group of the Australian Institute of Physics, Launceston, Tasmania, February 2-6, 1987

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HYPERNUCLEAR PHYSICS

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ABSTRACT

A brief overview of progress made in the study of hypernuclear physics is presented. The use of Λ-hypernuclei to study properties of conventional (nonstrange) nuclei is explored. Our knowledge of the hyperon-nucleon force is reviewed. Anecdotal examples of interesting hypernuclear phenomena are discussed. The status of Σ-hypernuclei is considered along with a search for the "H" dibaryon.

1. INTRODUCTION

High energy 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 internucleon distances which correspond to conditions that some would describe by two bags barely overlapping. Here, in the nonperturbative QCD region that is difficult to describe quantitatively with asymptotically free theories, the nuclear

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physicist has found some simplification and order in terms of "elementary" baryons and meson exchange potential 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. It is at this interface between nuclear physics and QCD that one seeks experimental signatures of quark excitation modes in nuclei. 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 our description of nuclei can be critically evaluated. A major success in nuclear physics was the perfection of model calculations based solely upon nucleon degrees of freedom to the point that comaprison 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. 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. Nuclear physicists continue to seek to discern the appropriate degrees of freedom with which to describe nuclear systems and their interactions.

In what follows I will limit the discussion to hypernuclei - 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 hear mentioned properties of hypernuclei with possible relevance to quark model predictions - hyperon spin-orbit interactions and anomalous binding of Λ-hypernuclei. You will find reference to the use of a nuclear target to search for the di-Λ or "H" particle. These are topics which may be currently the most eye catching. However, the primary purpose of this discussion is to impart some of the enthusiasm which nuclear physicists feel for this budding sub-field - to survey the interesting directions for research that would be opened if there were available an intense source of kaons of sufficient energy to permit systematic investigation of hypernuclear physics.

2. KAON-NUCLEUS INTERACTIONS

As nuclear physicists strive to understand conventional nuclear matter, they also seek to create and investigate new forms of quasi nuclear matter. Both K and $\bar{K}$ mesons are useful for these purposes. Our knowledge of the structure of conventional nuclei could be enhanced by the utilization of the K^+ as a probe.[1] Because of its strangeness (S = +1), the low-energy K^+N interaction is not resonant. That is, the $u\bar{s}$ K^+ quark configuration implies an absence of the normal $q\bar{q}$ resonances that occur in meson interactions with nucleons. There are no known S = +1 baryons or low-lying resonances. The heavy mass of this feebly interacting hadronic probe makes it an ideal high-momentum transfer tool below the threshold for meson production. Because it interacts with the neutron as well as the proton, the K^+ would 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 $(\pi^{\pm},\pi^0)$ reactions. The kaon suffers much less distortion in the initial and final states than does the pion. Of even more interest is the study of hypernuclei by means of the (K^-,π) reaction. Here one can explore the modifications of nuclei which occur when a distinguishable baryon is inserted. Furthermore, hypernuclei offer an expedient means of looking beyond that matter found in nature, to investigate a new form containing strange quarks. The study of such strange particle matter will add a third dimension to our microscopic picture of nuclear systems comprised of neutrons and protons.

The study of hyperon behavior in nuclear matter and the fundamental properties of hypernuclei have been, since 1953, the driving interst in $\bar{K}$-nucleus physics. That interest will grow with the advent of intense kaon beams. The $\bar{K}$ meson (strangeness S = -1) interacts very strongly with nucleons. Like the pion, the K^- is strongly absorbed by the nucleus. Its elastic channel wave function is localized in the nuclear periphery. One can easily comprehend the resonant structure of 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: $\bar{K}N \to \pi Y$ (where $Y = \Lambda$ or Σ, baryons also having $S = -1$). The $\bar{K}$ can fuse with the nucleon to form a variety of Y^* ($S = -1$) resonances 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 ($\approx$ 16 MeV), is potentially useful in the investigation of the intriguing problem of the propogation of an isobar within the nucleus. Answers to questions of how the energy and lifetime of this resonance are modified due to Fermi motion, Pauli blocking, and collision damping are fundamental to our understanding the mechanism of meson propogation and the role of mesonic degrees of freedom in nuclear matter.

3. Λ-HYPERNUCLEI

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 utilized 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. Knowledge of all final state channels is required in order to obtain 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 of differential cross sections, etc., even in the absence of complete knowledge of all reaction channels.

3.1 The Λ as a Probe

Use of the Λ as a probe of the properties of conventional (S=0) nuclei is a strong motivating factor in our study of hypernuclei.[2] The insertion of a tagged baryon into the nucleus permits us to perturb the nuclear core of the resulting hypernucleus in a manner not possible by means of traditional isotope or isotone studies. 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 generate an observable effect in the phonon spectrum of a vibrational nucleus; it should alter the energy gap in a superlfuid nucleus. Near the mass values showing oblate to prolate phase transitions in deformed nuclei, the addition of a hyperon may alter the mass at which the transition occurs. An added Λ will certainly influence the general fission process and most likely the properties of shape isomers. Giant resonance properties will be altered by coupling a Λ to the nucleus. Core polarization induced by a Λ will alter the moments of nuclei deduced from γ transitions. Compression due to the presence of the 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. Each of these perturbative alterations of 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 hupernuclear 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 with the addition of a single nucleon. It is not well represented as a hole in ^{7}Li. Thus, neither isotope nor isotone studies provide realistic tests of our nuclear models of ^{6}Li. The first excited state in the ^{6}Li spectrum lies in the continuum (see Fig. 1), above the threshold for α+d decay. Because our methods of modeling continuum states differ from bound-state calculational methods and are not as reliable approximations, stringent tests of our mathematical description of ^{6}Li have been limited to comparison with

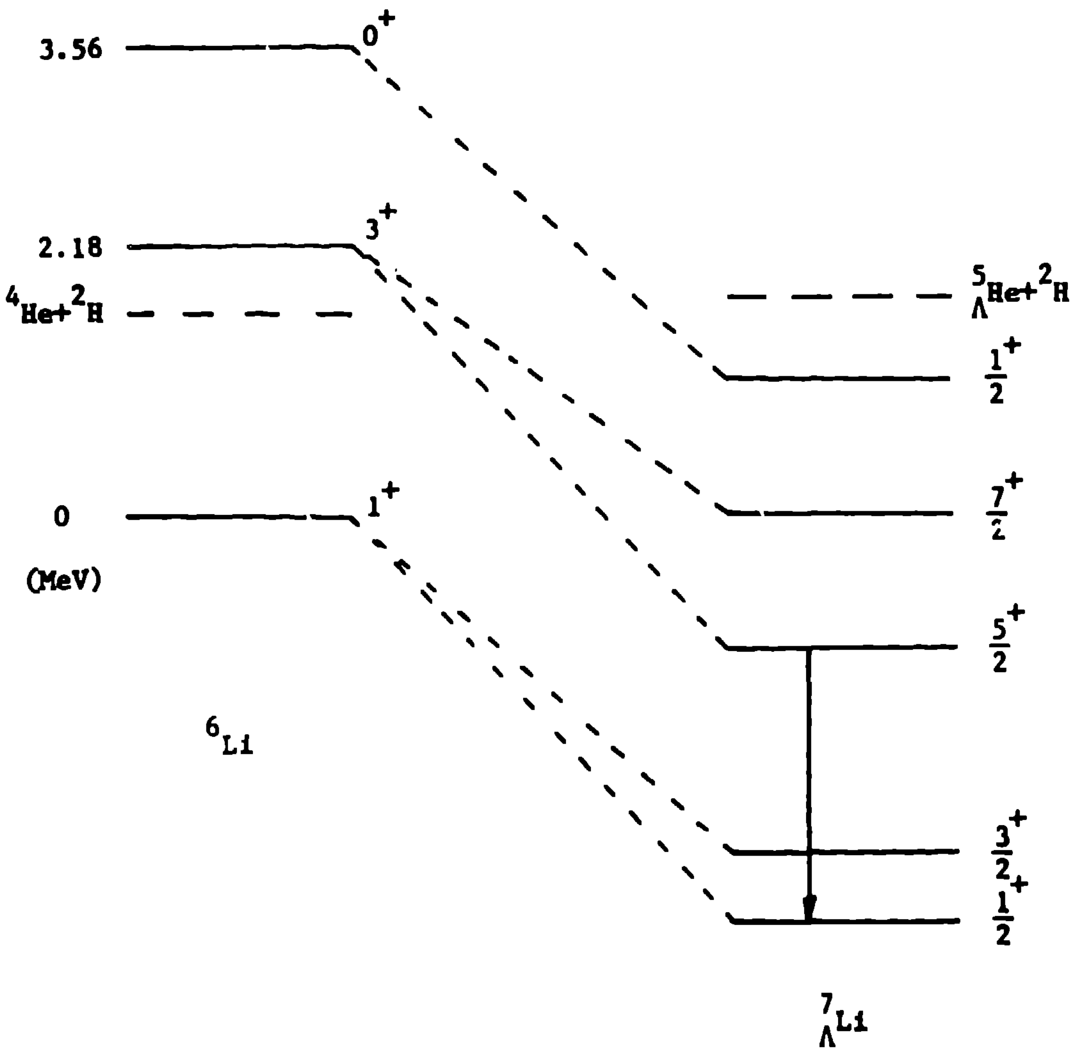

Fig. 1 Comparison of the spectrum from ^6Li with the expected particle stable levels of $^7_\Lambda Li$.

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

3.2 The Hyperon-Nucleon Force

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 $T = 1/2$ channel is a complication not arising in low-energy nucleon-nucleon scattering. Experimental data on hyperon-nucleon scattering are very sparse, which severely restricts our understanding of the character of the basic free YN interactions. Elucidation of the nature of the YN interactions would bear not only upon hypernuclear physics but on the question of the roles of quark and meson degrees of freedom in baryon-baryon systems. Increasing strangeness implies a lessening importance of pion exchange effects, which should expose the intrinsically short-range quark and/or heavy meson exchange contributions. Because of the short lifetimes (of order 10^{-10} sec), 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 exhibit a dominant s-wave character.[4] Only through the angular distributions for $\Sigma^- p \to \Lambda n$ 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 ($M = 2191$ MeV) with a narrow (< 10 MeV) width. The lack of YN data makes a full phase shift analysis impractical and has led to the construction of potential models which are very dependent upon the sizeable theoretical input. For example, one boson exchange models of the $S = -1$ baryon-baryon sector have been constrained by combining the analysis with that of the ($S=0$) nucleon-nucleon sector and using SU(3) to relate couplings. Even so, the existing data inadequately constrain the model. More extensive data are essential, not only to adequately treat hypernuclear structure, but to verify the existence of quark model predictions of $S = -1$ dibrayon states. Furthermore, we we wish to explore such questions as: 1) whether the short-range repulsion in the nucleon-nucleon force is the result of Pauli principle effects involving the quark structure of nucleons. (That is, 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.); and 2) whether the $^3S_1$ domination of the $\Lambda N \to \Sigma N$ transition confirms the negligible quark induced conversion predicted for this process.

Data on the A=4 Λ-hypernuclear isodoublet provide a test of the low-energy characteristics of our models of the hyperon-nucleon force as well as the opportunity to explore 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, if one represents the free YN interaction in terms of one-channel effective ΛN potentials, the resulting 0^+ (ground) state and 1^+ (excited) spin-flip state of the A=4 system (see Fig. 2) are inversely ordered in terms of binding energies, the 1^+ state being more bound. However, utilizing a coupled ΛN-ΣN separable potential

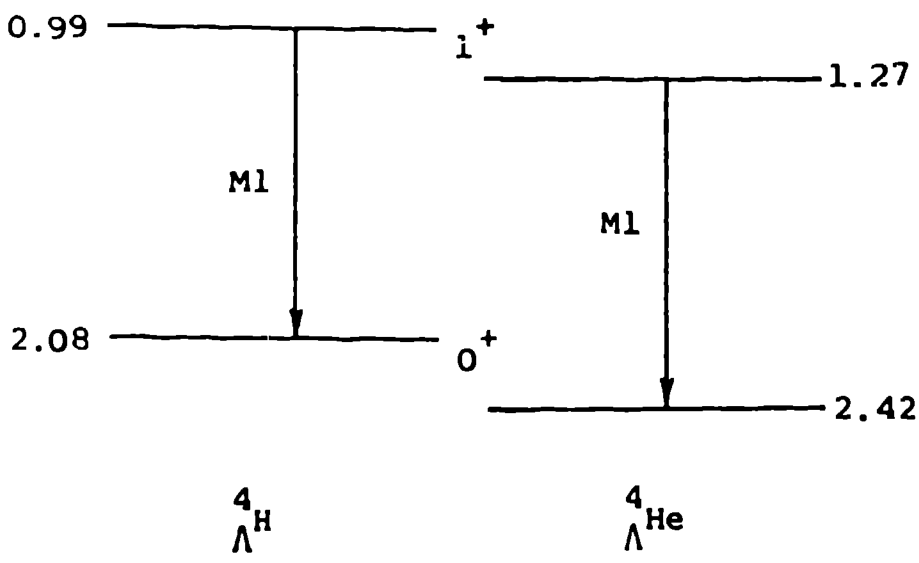

Fig. 2 Particle stable levels in the A=4 hypernuclear isodoublet.

model, we have been able to demonstrate that the spin-isospin suppression of the Λ-Σ conversion (due to the composite nature of the nuclear cores of the $^4_\Lambda$H and $^4_\Lambda$He hypernuclei) may be 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 computations.[5] That is, the $T = 1/2$ ^3H and ^3He nuclear cores do not interact with the Λ-Σ system in the same manner as do free $T=1/2$ neutrons and protons; the composite nature of the trinucleon bound states can suppress the ΛN-ΣN conversion process (transition) in a physically observable manner. More complete calculations utilizing realistic tensor force models are required to complete the analysis.

3.3 Anomalous Binding

Bag model practitioners argue forcefully that some 5% of the nucleon-nucleon wave function (probability) within a nucleus (that corresponding to center-to-center separations of less than 1 fm) must be described by a 6-quark bag structure. A similar estimate must hold for the hyperon-nucleon interaction. Modifications of the structure of nuclear bound states due to a 6-quark bag character of the short-range part of the baryon-baryon interaction should be especially visible in hypernuclei, where one has a "tagged" quark or baryon with which to work. Percolation of the identifiable s quark through nuclear matter should lead to model predictions which differ measureably from those in which the Λ is a distinguishable, elementary baryon. There are several suggestive puzzles in the existing hypernuclear data. Charge symmetry breaking in the mirror nuclei, for which an explanation in terms of the u and d mass difference has been offered,[6] is magnified in Λ-hypernuclei: $\Delta B_{CSB}(^3H-^3He) \approx 120$ keV compared to $\Delta B_{CSB}(^4_\Lambda He-^4_\Lambda H) \approx 360$ keV. The binding energy of $^5_\Lambda He$ is anomalously small compared to estimates of simple model calculations based upon ΛN potentials parameterized to account for the low-energy scattering data: such models overbind the $A=5$ ground state by 2-3 MeV.[7] Quark model explanations have been suggested[8] as have conventional baryon model explanations such as the suppression of ΛN-ΣN coupling and/or tensor force effects.[9] Choosing among the alternatives is difficult because of the paucity of data. Systematic studies as a function of mass are needed to rule out models tailored to a single datum. Only a thorough, systematic investigation can test such ideas as whether the Λ in heavy hypernuclei is a distinguishable, elementary baryon that slides into a 1s shell orbital or whether the s quark of the Λ is spread over many orbitals or even forced to surface by the Pauli exclusion principle. Is quark confinement absolute?

3.4 Nonmesonic Weak Λ Decay

There has been renewed interest in the weak decays of Λ-hypernuclei because of new experiments which can provide accurate data on various partial decay widths and because the EMC effect has led to the realization that nucleon properties may be altered in the nuclear medium and that hypernuclear decays offer a probe of this possibility. The weak interaction is of very short range. Thus, one expects to be able to explore the quark nature of the baryon-baryon interaction through an investigation of the weak decay of the Λ in nuclear matter. Indeed, Pauli blocking in a heavy system inhibits the $\Lambda \to N\pi$ free-space decay mechanism. The dominant decay mode of such hypernuclei becomes that of the nonmesonic four-Fermion $\Lambda N \to NN$ transition. Meson exchange model calculations confirm that the nonmesonic decay rate Γ_{nm} is sensitive to the short-range ΛN coupling. Thus, QCD effects can be important in the decay process. Calculations of $\Gamma_{nm}/\Gamma_{free}$ in nuclear matter exist for both meson exchange and quark models. (see Fig. 3.) A value for $\Gamma_{nm}/\Gamma_{free}$ of approximately 1 from the meson exchange models[10] is some 3-5 times smaller than the quark model predictions.[11] A recent BNL experiment involving ${}^{12}_{\Lambda}C$ gives a measured value of $\Gamma_{nm}/\Gamma_{free} \approx 1.3 \pm 0.2$,[12] which differs significantly from the only other measurement (A=16) that yielded 3 ± 1.[13] Clearly there is much experimental and theoretical work to be done in this area, if we are to understand the weak decay process and possible implications of QCD effects in nuclei. McKellar summarized the situation recently by asking:[14] 1) Does the $\Delta I = 1/2$ rule apply to nonmesonic decays of hypernuclei? 2) Can we understand the various partial decay rates? 3) Can we calculate the absolute decay rates?

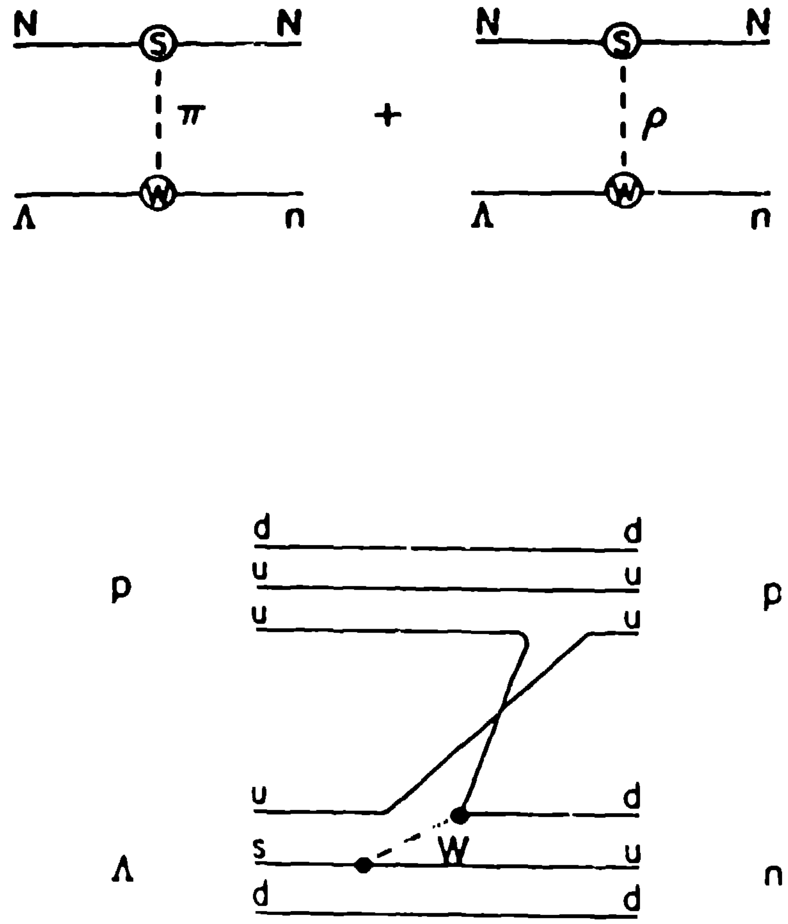

Fig. 3 Representative one-boson-exchange and quark interchange diagrams contributing to the nonmesonic $\Lambda N \to NN$ weak decay of the Λ in nuclear matter.

3.5 Hypernuclear Structure

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 need much better data.

What are our present experimental capabilities? The known momentum transfer characteristics of the forward (K^-,π) reaction are shown in Fig. 4. At the "magic momentum" of about 530 MeV/c for Λ

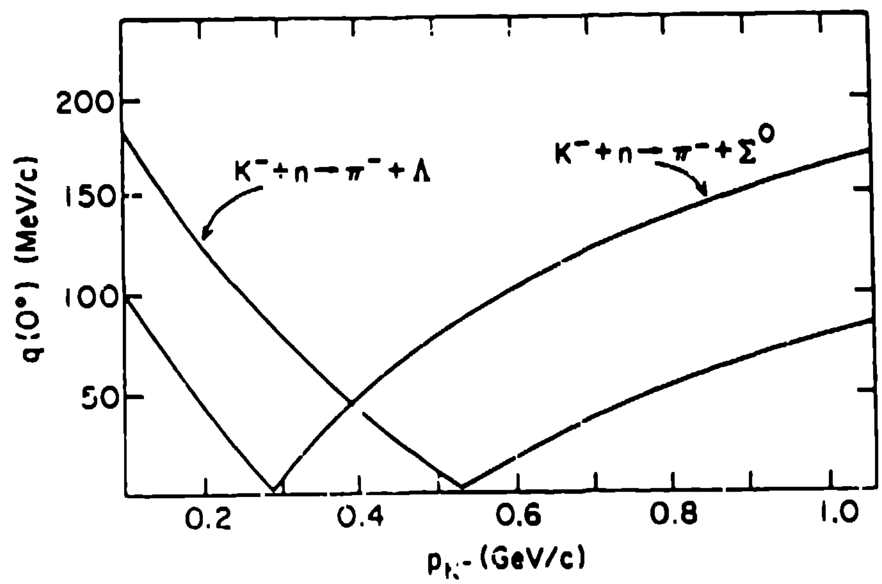

Fig. 4 Laboratory momentum transfer q at $\theta = 0^0$ as a function of incident momentum for Λ and Σ production under the assumption of large A and negligible binding energy effects.

production (280 MeV/c for Σ production), the 0^0 momentum transfer vanishes.[15] By selecting the right momentum, one can keep the momentum of the hyperon below the nucleon Fermi momentum and favor $\Delta\ell = 0$ transitions. (This is referred to as "recoilless production".) 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. For example, in the (K^-,π^-) angular distributions 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[16] is shown in Fig. 5. The excitation functions are all for 0° (pion angle)

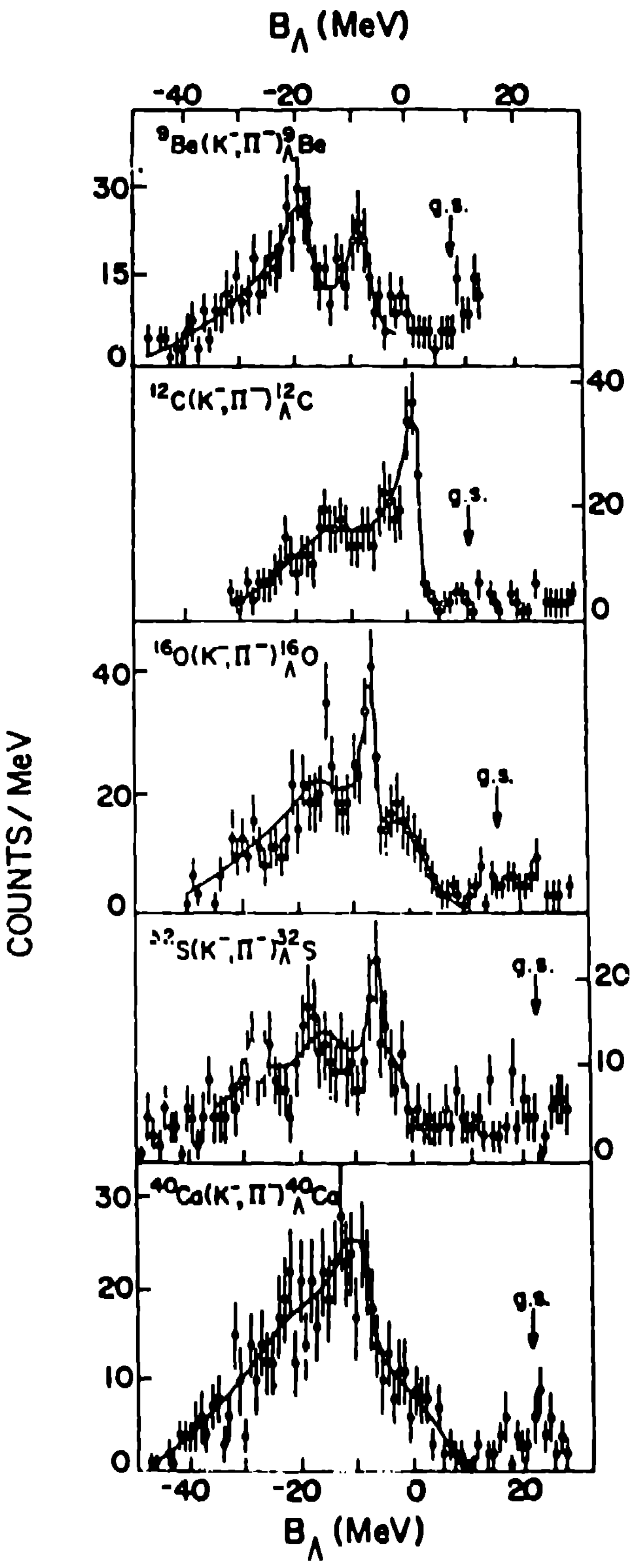

Fig. 5 Spectra for the (K^-,π^-) reaction as a function of the Λ binding energy.

and for incident K^- momenta in the range from 700 to 800 MeV/c. The coarse energy resolution (3-5 MeV/c) precluded resolving the fine structure in the spectra and is reminiscent of the early stage in nuclear structure physics using classical probes before high resolution spectrometers were available.

More recently, angular distributions for the (K^-,π^-) reaction have been measured.[17] (see Fig. 6). The relative intensities of the peaks change with angle, and energy shifts occur that are directly related to the properties of the ΛN interaction. Deviations from a

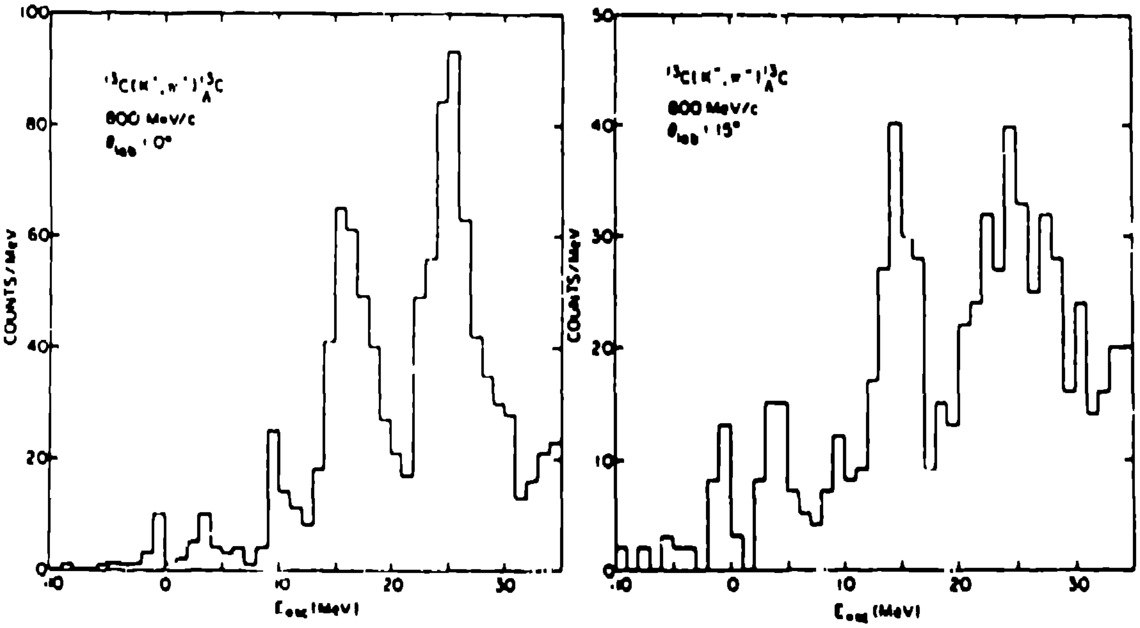

Fig. 6 Spectra for the (K^-,π^-) reaction on ^{13}C as a function of the excitation energy.

weak coupling picture [coupling of 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 Λ-nucleus spin-orbit splitting and the ΛN quadrupole-quadrupole potential.[1] 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, the large deviation of the ratio of the sizes of the dominant peaks from that predicted using neutron pickup strengths confirms the tendency of hypernuclei to form states 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 by the Pauli principle in a system of 13 nucleons.[18] Thus, evidence for a dynamical selection rule emerges. But 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.

4. Σ-HYPERNUCLEI

The observation of unexpected narrow structure in the $(K^-,\pi^{\pm})$ excitation spectra at energies corresponding to Σ-hypernuclei has thrust this area of hypernuclear physics to the forefront of the field.[19] Forward production of Σ's was studied in p-shell targets from ^{7}Li to ^{12}C at 720 MeV/c incident kaon momentum. The best evidence was for ^{9}Be; see Fig. 7, where data for the Λ-hypernuclei excitation spectrum is shown for comparison. Narrow structure has also been seen at 400 and 450 MeV/c, presumably corresponding to coherent substitutional transitions leading to 0^+ final states. More recently, stopped K^- capture in ^{12}C has been exploited to produce Σ-hypernuclear states.[20] In this case, the states produced are presumed to not include the ground state because of the momentum tr involved (see Fig. 4). By using π^0 tagging, it was insured that the states decay by $\Sigma^- p \rightarrow \Lambda n$ conversion (followed by weak $\Lambda \rightarrow n\pi^0$ decay) and not by quasi free $\Sigma^- \rightarrow n\pi^-$. Hungerford has also reported results for Σ^- states using a ^{6}Li target.[21] Several interesting questions arise concerning the interpretation of these data. Why are there narrow Σ states? What are the single particle properties of a Σ in a nucleus: well depth, spin-orbit potential, etc.? Do Σ-hypernuclear states have good isospin? The data are yet too crude to permit definitive answers, but theoretical analysis offers some interesting possibilities.

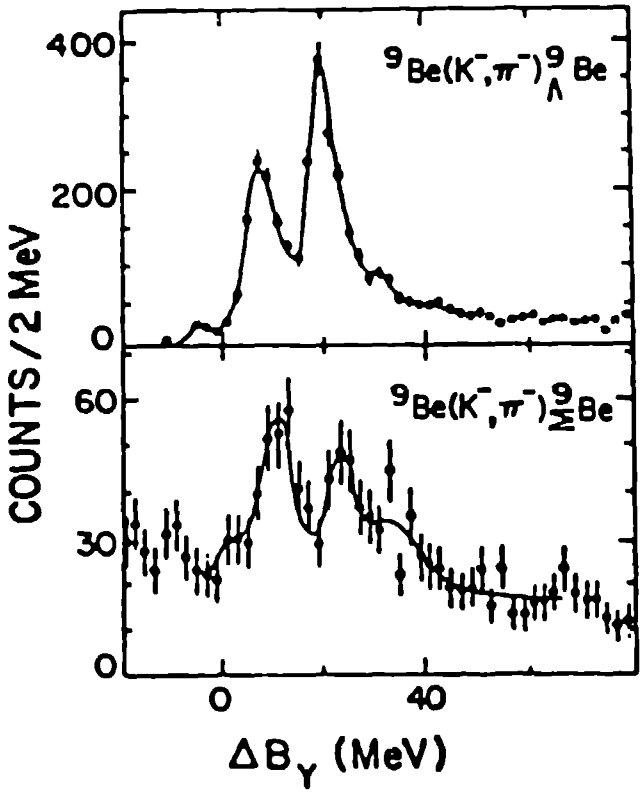

Fig. 7 Spectra for the (K^-,π^-) reaction on ^9Be leading to Λ-hypernuclei and Σ-hypernuclei.

4.1 Narrow Structure or Widths

The mean free path of a Σ^- in nuclear matter is

$$\lambda = [\sigma(\Sigma^- p \to \Lambda n)\rho_p]^{-1}$$

where σ is the conversion cross section and ρ_p is the proton density. The associated decay time is $\tau = \lambda/v$, where v is $\Sigma^- p$ velocity, and the corresponding width is

$$\Gamma_{nm} = h/\tau$$

$$= \langle v\,\sigma(\Sigma^- p \to \Lambda n)\rangle\rho_p ,$$

where $\langle\ \rangle$ signifies an average that incorporates medium corrections such as Fermi averaging. Gal and Dover[22] estimated from the experimental $\Sigma N \to \Lambda N$ cross section that

$$\Gamma_{1S} \approx 15\text{-}20 \text{ MeV},$$

which gives the scale to be expected. Several alternative explanations of why there should exist Σ-hypernuclear continuum excitations with narrower structure ($\Gamma < 5$ MeV) have been proposed. It has been argued that the $\Sigma N \to \Lambda N$ conversion width is partially cancelled by the Σ escape width when the Σ orbit places it in the surface of the nucleus. Conversely, it has been argued that, because the $\Sigma N \to \Lambda N$ conversion is dominated by the $T=1/2$, ${}^3S_1$ ΣN channel, it may depend upon spin-isospin factors. The range of the $\Sigma N \to \Lambda N$ conversion interaction has been offered as another possible explanation.

Let us examine the isospin suggestion in more detail in the light of data from the recent ${}^6Li(K^-,\pi^+){}^6_\Sigma H$ experiment[21] shown in Fig. 8. The narrow structure near 20 MeV is identified with $p(K^-,\pi^+)\Sigma^-$ production on the ${}^4He$ core of ${}^6Li$, a recoilless substitution. (The proton-separation energy from ${}^4He$ is 20 MeV, and the Σ binding energy should be no more than the 2 MeV Λ-separation energy in ${}^4_\Lambda He$ if the Σ is bound at all.) Because the two protons of ${}^4He$ are coupled to spin-0, the Σ^-p pair formed by the substitution reaction are left in a spin-0 state. ($\Sigma^-n \to \Lambda N$ conversion is, of course, forbidden by charge conservation.) Experimentally, $\Sigma^-p \to \Lambda n$ conversion occurs primarily through the spin-1 channel, because the tensor component of the one-pion-exchange mechanism dominates. Thus, the ${}^1S_0$ $\Sigma^-p \to \Lambda n$ conversion that can follow the $p(K^-,\pi^+)\Sigma^-$ reaction on the ${}^4He$ core of ${}^6Li$ is suppressed, leading to the narrowness of the 20 MeV structure seen. Conversely, the interaction of a Σ^- outside the ${}^4He$ core with the two protons in the ${}^4He$ core would be a mixture of ${}^1S_0$ and ${}^3S_1$, and the spin-1 transition would not be suppressed. This argument leads one to the conclusion that the width of the lower energy structure in the figure should not be strongly quenched. Because nuclear cores of most hypernuclei are not spin saturated, quenching of the $\Sigma N \to \Lambda N$ transition leading to narrow Σ-states would be very A dependent. This suppression would be most pronounced in the s-shell and p-shell hypernuclei, where spin-isospin saturated cores do not account for such a large fraction of the nucleons. The narrowest Σ width would occur in the lightest Σ-hypernuclei, in particular for those with maximum spin.

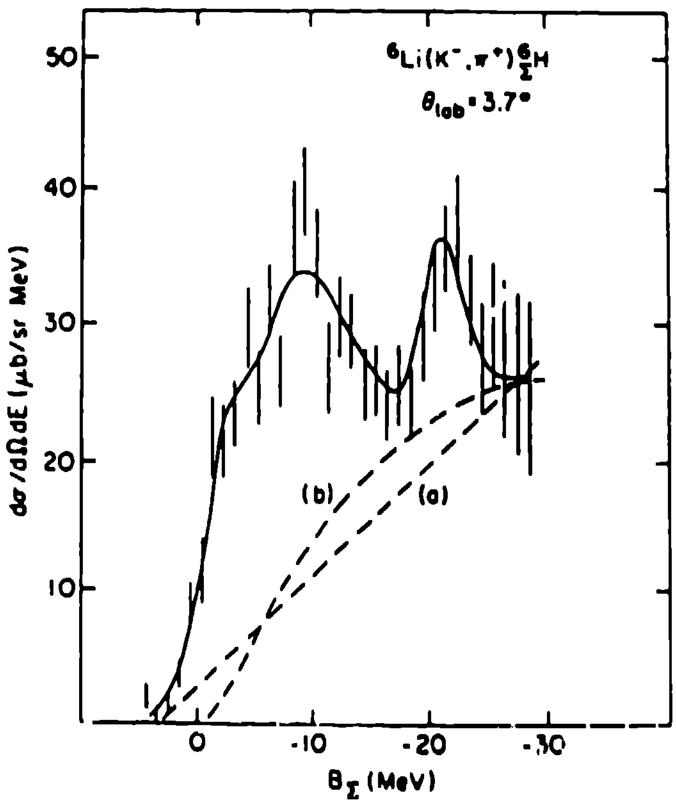

Fig. 8 The $^6Li(K^-,\pi^+)^6_\Sigma H$ spectrum at 713 MeV/c; curves (a) and (b) represent different possibilities for quasi free formation.

The quark-gluon picture provides a different scenario. The s quark of the Σ must exchange with the appropriate u or d quark of the nucleon in the $\Sigma N \to \Lambda N$ transition in order to couple properly into a Λ configuration. Direct interchange of a single quark cannot lead to such a conversion; a quark rearrangement is required. Thus, short-range $\Sigma N \to \Lambda N$ conversion due to quark exchange is strongly quenched. The $\Sigma N \to \Lambda N$ conversion seen in the free interaction is the result of a long-range pion exchange process. Accordingly, $\Sigma N \rightarrow \Lambda N$ conversion is suppressed in the confines of a nucleus, where long-range interactions are less effective (c.f., the NN tensor force is much less effective in binding the compact alpha particle than the deuteron). This quenching of the Σ width would imply that a rich Σ-hypernucleus spectroscopy awaits our search.

4.2 Spin-Orbit Interaction

An exciting feature of the (K^-,π^-) reaction studies leading to p-shell Λ-hypernucl was the discovery that the mean-field spin-orbit interaction of a Λ in the nucleus is very small, being less than 2 MeV compared to 6 MeV for a nucleon.[23] A simple quark-gluon interchange model (Fig. 9) in which the Λ and N can exchange only light quarks predicts the ΛN spin-orbit force to be identically zero.[24] Unfortunately, it is also the case that the one-boson-exchange potential model (Fig. 10) and the meson mean-field approach to baryon-baryon scattering yield a small (nonzero) value for the ΛN spin-orbit interaction in comparison with that of the NN system.[1] Nonetheless, because of the strong spin-spin nature of the QCD quark-quark interaction and because the NN spin-orbit interaction is of shorter range than either the central or tensor components, the hypernuclear spin-orbit force is still viewed as a possible means of investigating quark-gluon degrees of freedom in nuclei. Detailed quark cluster model calculations for the spin-orbit strengths of the NN, ΛN, ΣN, and ΞN two-body systems yield ratios of[25]

$$V^{NN} : V^{\Lambda N} : V^{\Sigma N} : V^{\Xi N} = 1 : 0.2 : 1.5 : \ldots$$

where V^{NN} has been normalized to a value of 1. Comparing with single quark-gluon interchange model predictions of

$$1 : 0 : \frac{4}{3} : -1/3 \ ,$$

we see that the details of the model may not be so important. However, both of these model predictions for the free-space spin-orbit

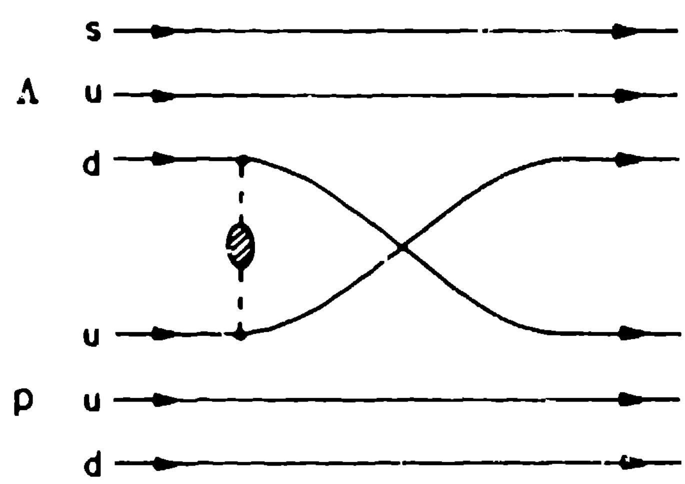

Fig. 9 Quark-gluon exchange diagram in the quark interchange model of the Λ-p interaction.

interactions are significantly different from the one-boson-exchange model predictions of[1)]

$$1 : 0.2 : 0.4 : 0.15 .$$

The alternative mean-field approach (which in certain limits can be made to yield results identical to the additive quark interchange model) predicts a similar ratio of strengths;[23)]

$$1 : 0.2 : 0.5 : 0.05 .$$

Thus, the quark model predictions for the ΣN and ΞN spin-orbit interaction strengths differ qualitatively from those of the more traditional approach to nuclear physics in terms of baryon-baryon interactions.

Because we can extract information from bound systems much more easily than we can make definitive hyperon-nucleon scattering measurements, systematic studies of Σ-hypernuclei and Ξ-hypernuclei offer the best means of attempting to check these intriguing spin-

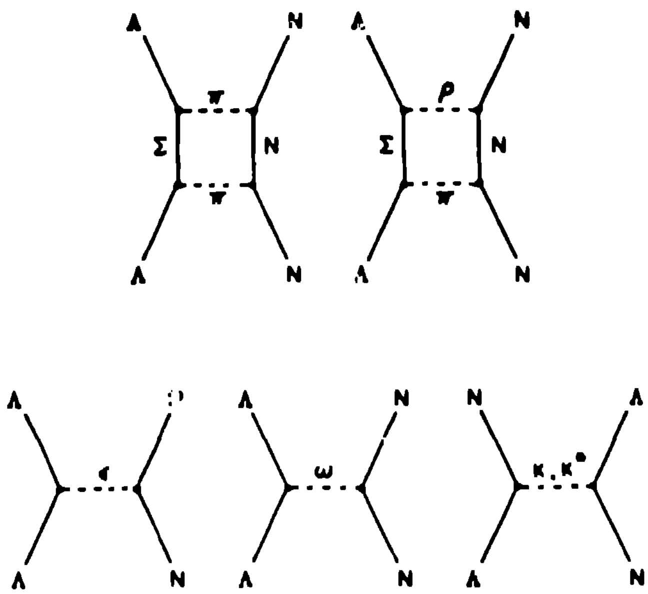

Fig. 10 Meson exchange contributions to the ΛN interaction in the one-boson-exchange model of the ΛN interaction.

orbit interaction predictions. It was just such a study which first showed the Λ-nucleus spin-orbit interaction to be small. However, the hypernuclear spectra provide information about the mean-field strength felt by the hyperon in the nuclear medium, so that care must be exercised in the interpretation of such data. As an example of the difference between projectile-nucleus spin-orbit size and the two-body interaction spin-orbit strength, we note the baryon-nucleus spin-orbit strength ratios for the quark cluster model[25)]

$$U^N : U^\Lambda : U^\Sigma \approx 1 : 0.2 : 0.6$$

show that U^Σ is considerably reduced in comparison to the $V^{\Sigma N}$ value quoted above for the same quark cluster model. Interpretation of hyperon-nucleus spin-orbit effects is not trivial. However, a systematic investigation of Σ-hypernuclei and Ξ-hypernuclei should shed real light on the correct picture of hadron interactions.

5. STRANGENESS -2

Hypernuclear physics utilizing the double strangeness exchange reaction (K^-,K^+) lies in the future. Cross sections for nuclear targets will be quite small, a few nb/sr to a μb/sr.[1] Thus, the study of S = -2 hypernuclei needs a new intense kaon beam, one in the 1 GeV/c to 2 GeV/c momentum range. The spectroscopy of Ξ-hypernuclei and $\Lambda\Lambda$-hypernuclei represents a logical progression in the evolution of hypernuclear phsyics, although only a restricted set of states (high spin with no spin-flip transitions) are likely to be excited with measureable cross section by the high momentum transfer (K^-,K^+) reaction. Study of $\Lambda\Lambda$-hypernuclei will provide our only window through which we can explore the $\Lambda\Lambda$ interaction. The $\Xi^- p \rightarrow \Lambda\Lambda$ transition should not broaden the levels of Ξ-hypernuclei significantly beyond what has been found in the S = -1 hypernuclei. In $\Lambda\Lambda$-hypernuclei we will test whether $\Lambda\Lambda$ pairing correlations enhance states as NN correlations do in S=0 nuclei.

As I remarked previously, the search for evidence of quark degrees of freedom in nuclear matter is a quest of current interest to many physicists. In the sense that one believes the valence quark description of N's and Δ's, we have found them: NN $\rightarrow$ NΔ excites a new quark degree of freedom. However, in addition to the investigation of the hyperon-nucleon spin-orbit interaction, there is another area in which hypernuclear physics offers some hope of yielding the type of positive evidence that is sought that quark degrees of freedom must be taken into account in the energy range corresponding to nonperturbative QCD: the search for the doubly strange (S = -2) "H" dibaryon. The H, as first proposed by Jaffe[27] in a simple Bag model calculation, is a spatially symmetric uuddss six-quark object which would be stable against strong decay into two Λ's by some 60 MeV. A variety of theoretical paths have reached similar conclusions.[28] On the other hand, there also exists evidence for S = -2 $\Lambda\Lambda$-hypernuclei.[29] The existence of ${}^{6}_{\Lambda\Lambda}He$ argues against the stability of the H six-quark dibaryon, because the $\Lambda\Lambda$ pair should have decayed rapidly to the H (unless, perhaps, the H lies very close to the $\Lambda\Lambda$ threshold). The search for the H dibaryon is of paramount importance. The reaction

$^3He(K^-,K^+n)$"H" would appear to offer the cleanest test for the existence of such a massive six-quark object. A two-step reaction

$$K^- + p \rightarrow K^+ + \Xi^-$$
$$\Xi^- + d \rightarrow \text{"H"} + n$$

has been proposed for the Brookhaven AGS,[30] but an enhanced kaon intensity would certainly improve the feasibility of such a search.

6. CLOSING REMARKS

Particle physics seeks at high energies the asymptotic, small distance (r) limit of particle phenomena. Nuclear physics must go to very low energies, the large distance limit to find asymptopia. As nuclear physics moves to higher energies and momentum transfer to find new degrees of freedom and as particle physics looks down in energy to seek structure information beyond the r=o limit, there is hopefully an interface where these two once common fields will again come together.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy. The author gratefully acknowledges many valuable discussions with P.D. Barnes, G.E. Brown, C.B. Dover, J.L. Friar, A. Gal, E.M. Henley, D.R. Lehman, B. Povh, H.A. Thiessen, and J.D. Walecka. Finally, the author wishes to thank Mrs. E. Smart for her technical assistance in the preparation of the manuscript.

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