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HYPERON–NUCLEON INTERACTIONS: OPEN PROBLEMS AND KEY ISSUES

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ABSTRACT

We focus on open problems relating to hyperon–nucleon (YN) and hyperon–hyperon (YY) interactions in free space and in the nuclear medium. We include a discussion of meson exchange and quark/gluon descriptions of the two–body interaction, its spin dependence, the rôle of $\Lambda N \to \Sigma N$ and $\Lambda\Lambda \to \Xi N$ coupling, hyperon mean fields in nuclei, $YN \to NN$ and $YY \to YN$ weak decays, among other topics.

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We focus on open problems relating to hyperon–nucleon (YN) and hyperon–hyperon (YY) interactions in free space and in the nuclear medium. We include a discussion of meson exchange and quark/gluon descriptions of the two–body interaction, its spin dependence, the rôle of $\Lambda N \to \Sigma N$ and $\Lambda\Lambda \to \Xi N$ coupling, hyperon mean fields in nuclei, $YN \to NN$ and $YY \to YN$ weak decays, among other topics.

1. Introduction and Motivation

The nucleon–nucleon (NN) interaction has been extensively studied in precision experiments spanning the last four decades. The available NN data include differential and total cross sections and spin observables over a wide range of energy from threshold to 800 MeV (LAMPF) and above. The detailed knowledge of the energy and spin dependence of the NN force has permitted the extraction of scattering phase shifts in various partial waves $\{LSJI\}$, where $L =$ orbital angular momentum, $S =$ intrinsic spin, $J =$ total angular momentum and $I =$ isospin. The coupling of partial waves by tensor forces (for example, $^3\mathrm{S}_1 - {}^3\mathrm{D}_1$) is characterized by additional mixing coefficients ϵ_J. This wealth of information on NN strong interactions can then be confronted by theory, for instance one boson exchange (OBE) models[1,2] or the Paris potential[3].

The hyperon–nucleon (YN) interaction, the focal point of this Seminar, is much less well known than the NN force. Only a few cross section measurements[4] have been made, in a very limited momentum range, and virtually no spin information is available. The OBE description has been extended to the strangeness $S \neq 0$ sector[5–8], but strong dynamical assumptions, for instance SU(3) or SU(3) symmetry for coupling constants, are made in order to restrict the number of parameters. The limited YN data, particularly the absence of spin observables, do not afford a stringent test of these models, and more measurements are urgently needed.

In this talk, I will try to highlight some of the open problems and key issues regarding hyperon–nucleon interactions. More generally, these issues relate to the dynamics of strange quarks in low and medium energy strong interactions, i.e. in the regime of non–perturbative quantum chromodynamics (QCD).

The outline of the talk is as follows: In Section 2, the properties of the two–body YN and YY interactions in free space are discussed. We emphasize how a few key measurements could provide important constraints on the theoretical description. Implications of short range quark/gluon interactions and strange dibaryons are also mentioned. In Section 3, we review the available information on the nature of the effective two–body YN interaction in nuclei. Due to studies of hypernuclear spectroscopy[9,10], and particularly hypernuclear γ rays[11,12], more is known about the spin dependence of the effective YN interaction than the free space one. Here there are good prospects for further progress on the experimental front, at CEBAF, KEK and Brookhaven, by means of higher resolution experiments.

In Section 4, we comment on hyperon (Λ, Σ, Ξ) mean fields in the nucleus, and how these reflect averaged properties of the effective two–body interactions. We discuss prospects for finding a new spectroscopy of Ξ quasiparticle states in nuclei, and provide some estimates of their decay widths.

The hypernucleus provides a unique laboratory for the study of the strangeness changing ($\Delta S = 1$) $\Lambda N \rightarrow NN$ and $\Lambda\Lambda \rightarrow YN$ weak interactions. Some unsolved problems regarding the validity of meson exchange models and the $\Delta I = 1/2$ rule for such processes are emphasized in Section 5. Finally, the prospects for experimental and theoretical progress in our study of YN interactions are summarized in Section 6.

2. Two–Body Hyperon–Nucleon Interactions in Free Space

In this section, we first review the data, and then provide a discussion of the theoretical framework for describing YN scattering, focusing on meson exchange models. We also mention the quark/gluon calculations for the short range interaction and their possible implications for the existence of strange dibaryon resonances or bound states.

2.1. *The Data on YN Scattering*

For the nucleon–nucleon (NN) system, abundant scattering data are available, including the crucial spin observables (polarization, spin rotation, etc.) which enable us to unravel the spin dependent partial wave amplitudes from a phase shift analysis. In addition, the existence of a two–body np bound state, the deuteron, yields further constraints, particularly on the tensor (S_{12}) interaction. No corresponding ΛN or ΣN bound state has ever been seen. For hyperon–nucleon (YN) scattering, the data[4] are much more meager, consisting mainly of differential and total cross section measurements at low momenta for the $\Lambda p \rightarrow \Lambda p$, $\Sigma^0 p$, $\Sigma^+ p \rightarrow \Sigma^+ p$ and $\Sigma^- p \rightarrow \Sigma^- p$, $\Sigma^0 n$, Λn reactions. There is also some data on Λp total cross sections at very high energy[13], for instance from Fermilab. There is some meager data, with large error bars, on left–right asymmetry and polarization[14] in $\Sigma^- p \to \Lambda n$, but no other spin quantities have been obtained. At low momenta ($\leq$ 500 MeV/c), pion production ($YN \to YN\pi$) is not yet important, and the data can be interpreted in terms of a potential model with meson exchanges. We restrict our attention to this regime.

2.2. *One Boson Exchange Models*

The most detailed one boson exchange (OBE) models of the YN interaction have been constructed by the Nijmegen group, in both hard core[5] and soft core[6] versions, and more recently by the Bonn –Jülich group.[7,8] In the general form of the OBE model, the baryon–baryon potential is generated by the exchange of nonets of pseudoscalar (π, η, η', K), vector (ρ, ω, ϕ, K^*) and scalar mesons. An essential feature of scalar exchange is an effective σ(or ϵ), with a mass of order 500 MeV. This phenomenological object generates much of the spin–isospin independent medium range attraction in the potential, as well as an important component of the spin–orbit interaction. Sometimes a Pomeron exchange is included[6], which is thought to encompass a class of non–perturbative multi–gluon processes.

In the NN sector, the most important exchanges are the $\{\pi,\ \rho,\ \omega\}$, which are quark–antiquark ($Q\overline{Q}$) systems containing non–strange quarks (u, d) and antiquarks ($\bar{u}, \bar{d}$), plus the effective σ, whose quark composition is unclear. Mesons containing strange quarks (K, K^*, ϕ) play essentially no rôle in NN scattering, but are activated in YN and YY processes. For instance, K exchange generates the longest range part of the $\Lambda N \to N\Lambda$ potential, whereas π exchange is absent in first order. In $S = -2$ interactions ($\Lambda\Lambda$, ΞN for example), strange mesons are expected to play an even more important rôle[15] than for $S = -1$.

If the couplings of strange mesons to hyperons are left as free parameters, one would encounter no difficulties in fitting the limited YN data, but very little would be learned. A more reasonable strategy is to limit the choice of parameters by imposing SU(3) symmetry on the coupling constants. The breaking of SU(3) then occurs through the use of the observed masses for the baryons and exchanged mesons. For example, the SU(3) relations for the coupling constants g_{BBM} of the $1/2^+$ baryon octet (N, Λ, Σ, Ξ) to the 0^- meson octet (π, η_8, K, $\overline{K}$) assume the form (units of $g_{NN\pi}$)

$$g_{\Lambda NK} = -\frac{(1+2\alpha)}{\sqrt{3}}, \quad g_{\Sigma NK} = 1 - 2\alpha, \quad g_{\Sigma\Sigma\pi} = 2\alpha,$$

$$g_{NN\eta_8} = (4\alpha - 1)/\sqrt{3}, \quad g_{\Sigma\Lambda\pi} = g_{\Sigma\Sigma\eta_8} = -g_{\Lambda\Lambda\eta_8} = 2(1-\alpha)/\sqrt{3} \qquad (1)$$

where α is the pseudoscalar F/D ratio. In the Nijmegen models,[5,6] α is adjusted phenomenologically to achieve a best fit to the data ($\alpha = 0.485$ for Model D Ref. 5, $\alpha = 0.355$ for the soft core version Ref. 6), whereas one version of the Bonn model[7,8] imposes the stronger constraint of SU(6) symmetry, for which $\alpha = 2/5$. Values of α for the magnetic (f) and electric (g) couplings of vector mesons must also be chosen, as well as the SU(3) character of the σ. These SU(3) parameters are not uniquely determined by the limited YN data, since changes in the α's can be accommodated by modifications in the short range cutoffs, in order to achieve a comparable fit to the data. A sizable number of parameters are hidden in the short range parametrization of the OBE potentials, so one is unable to draw a firm conclusion as to whether SU(3) symmetry is in fact satisfied for coupling constants. One can assert, however, that this assumption is at least consistent with the data.

We know that SU(3) symmetry must be broken, since the differing exchanged meson masses lead to potentials of significantly different range ($1/\mu_\pi \simeq 1.4$ fm, $1/\mu_K = 0.4$ fm for π and K exchange, for instance). It remains an interesting question as to whether some remnants of SU(3) symmetry survive in the scattering cross sections. In the SU(3) limit, one obtains the following relations[16] for the s–wave ($L = 0$) cross sections $\sigma_{0,1}$ corresponding to singlet (σ_0) and triplet (σ_1) spin states:

$$\begin{aligned}
&\sigma_0\left(\Sigma^+p \to \Sigma^+p\right) = \sigma_0\left(np \to np\right)\\
&\sigma_0\left(\Sigma^-p \to \Lambda n\right) = \frac{1}{3}\sigma_0\left(\Sigma^-p \to \Sigma^0 n\right)\\
&\sigma_0\left(\Lambda p \to \Lambda p\right) = \frac{1}{6}\left[5\sigma_0\left(\Sigma^+p \to \Sigma^+p\right) + \sigma_0\left(\Sigma^-p \to \Sigma^-p\right) - \frac{5}{3}\sigma_0\left(\Sigma^-p \to \Sigma^0 n\right)\right]\\
&\sigma_1\left(\Lambda p \to \Lambda p\right) = \frac{1}{2}\left[3\sigma_1\left(\Sigma^-p \to \Sigma^-p\right) + 3\sigma_1\left(\Sigma^-p \to \Sigma^0 n\right) - \sigma_1\left(\Sigma^+p \to \Sigma^+p\right)\right]\\
&\sigma_0\left(\Xi^-p \to \Xi^0 n\right) : \sigma_0\left(\Xi^-p \to \Sigma^0\Lambda\right) : \sigma_0\left(\Xi^-p \to \Lambda\Lambda\right) = 1 : 3 : \frac{9}{2} \qquad (2)
\end{aligned}$$

In Nijmegen Model D, these relations are found to be satisfied[16] at the 30% level, after suitable phase space factors are removed. Experimental tests of Eq. (2) would require knowledge of spin–separated cross sections $\sigma_{0,1}$ at very low momentum where s–wave scattering is dominant. No such data are currently available.

We now discuss some of the striking differences in the predictions of various OBE models for observables which have so far not been measured. In particular, these models produce about the same spin–averaged total cross sections, but quite different spin observables. Even at the level of differential cross sections, significant differences already appear. For example, in Nijmegen Model F, $d\sigma/d(\cos\theta)$ for the $\Sigma^-p \to \Lambda n$ reaction at 160 MeV/c decreases monotonically from about 100 mb at $\theta = 0°$ to 45 mb at $\theta = 180°$. In contrast, in Bonn Models A and B, $d\sigma/d(\cos\theta)$ is nearly isotropic, at the level of 70 mb. The integrated σ's are about the same. Similar behavior is observed for $\Sigma^\pm p \to \Sigma^\pm p$ elastic scattering: $d\sigma/d(\cos\theta)$ exhibits a dramatic forward peak for Model F, while Bonn Models A,B lead to only a modest peak at $\theta = 0°$. The data appear to show some forward peaking, but the error bars are very large, and one cannot clearly choose between the models. Thus there is a strong motivation to measure the angular distributions for YN scattering with increased precision, in order to further constrain the OBE models.

The source of the anisotropy in the Nijmegen models is the relatively strong p–wave amplitudes at low momentum, compared to those in the Bonn model. This difference also shows up strongly in numerous spin observables, for instance the polarization P, the depolarization D, and the spin rotation parameters $\{R, A, R', A'\}$. Comparisons of these quantities for Bonn A,B *vs.* the Nijmegen soft core (NSC) model have been given by Reuber *et al.*[8] The differences are large, and measurements of $P(\theta)$ to ± 0.1 near $\theta = 90°$ for low momentum $\Lambda p \to \Lambda p$ elastic scattering would be sufficient to distinguish between the models. (NSC predicts $P(\theta) \simeq 0.6$ at 90°, Bonn B gives 0.3, and Bonn A about 0.15.) The predicted spin transfer parameter D_{NN} for 100 MeV Λp scattering also displays dramatic model dependence: NSC gives $D_{NN} \geq 0.65$ for all θ, whereas Bonn A yields $D_{NN} \leq 0$, with maximum differences near $\theta = 90°$. Any experimental information on spin observables would be most welcome, as a means of constraining potential models. It is unlikely that any of the current parametrizations on the market will yield correct predictions for spin observables. However, the framework of the OBE model is likely to be sufficiently flexible, through its multi–parameter short range part, to handle any influx of new data. A weakness of the OBE models is that the short range part is treated in a purely phenomenological way, and one can absorb many ills by parameter fitting. For example, the flexibility in the short range cutoffs impede the extraction of unique values for the F/D ratios α, which are the quantities of interest in an SU(3) picture.

At about 650 MeV/c, one reaches the thresholds for the $\Lambda p \to \Sigma^+ n$, $\Sigma^0 p$ reactions. Near these thresholds, a cusp should appear in the $\Lambda p \to \Lambda p$ total cross section. In Nijmegen Model F, there is a strong cusp, corresponding to a jump in σ by about a factor of two. The magnitude of the cusp effect is sensitive to the $\Lambda N \to \Sigma N$ coupling potential. Existing data are too poor to even establish the presence of the cusp, much less its size. Further measurements of the $\Lambda p \to \Lambda p$ cross section in the region between 500–700 MeV/c are indicated, with rather fine momentum intervals.

2.3. *Quark/Gluon Exchange and Short Range Hyperon Interactions*

In the OBE model, one introduces phenomenological cutoffs to temper the short range behavior of the meson exchange potentials. This is clearly not a satisfactory procedure, and one would like to replace it by a more fundamental description in terms of quarks and gluons, the underlying constituents of QCD. At short distances, the baryons overlap, and the notion of a meson exchange potential loses its validity: quark degrees of freedom must come into play. The operative question is how to implement this idea in the non–perturbative regime of QCD which characterizes low energy baryon–baryon interactions. This remains a crucial unsolved problems, although some promising work in this direction has been initiated by the Tokyo[17–19] and Tübingen[20–21] groups. The idea is to use the Resonating Group Method[22] with a properly antisymmetrized six quark wave function to describe the BB interaction at short distances. A color magnetic one gluon exchange (OGE) interaction is introduced between quarks, of an adjustable strength α_c. The effect of quark antisymmetry and the OGE interaction is to produce a zero in the BB radial wave function, the position of which depends on the channel quantum numbers $\{LSJI\}$. This mimics the effect of the "hard core" in OBE models, for instance Nijmegen D and F.

By itself, the OGE interaction produces phase shifts which resemble hard sphere scattering. To achieve fits to data, the OGE mechanism, which generates an interaction reminiscent of vector meson exchange (ρ, ω), must be supplemented by medium and long range attraction (π and σ, at least). Such "hybrid" models have been somewhat successful. However, the medium range potential must be adjusted phenomenologically to achieve a fit. An attempt to describe NN scattering by grafting a theoretically calculated long and medium range interaction (the Paris potential[3]) onto a OGE term was not successful[23]. This may indicate that deficiencies of the OGE description can be absorbed by phenomenologically readjusting this meson exchange potential, and hence one does not really test the validity of the OGE mechanism. The fact that α_c is found to be of order unity, and not small, also makes us somewhat suspicious.

A reason to pursue the quark calculations more vigorously is provided by the observation, from the binding energies of double Λ hypernuclei,[24–26] of a strongly attractive $\Lambda\Lambda$ interaction in the relative s–state ($^1\mathrm{S}_0$). One finds an increase in binding energy due to the $\Lambda\Lambda$ interaction of

$$\Lambda B_{\Lambda\Lambda} = -\langle V_{\Lambda\Lambda}(r)\rangle \simeq 4 - 5 \text{ MeV} \tag{3}$$

This is to be compared to the equivalent matrix elements which characterize the $^1\mathrm{S}_0$ NN and ΛN interactions[10,27] in the p–shell, namely

$$-\langle V_{NN}(r)\rangle \approx 6 - 7 \text{ MeV} \tag{4a}$$

$$-\langle V_{\Lambda N}(r)\rangle \approx 2 - 3 \text{ MeV} \tag{4b}$$

In a meson exchange model, one might expect a hierarchy of interaction strengths such that $|V_{\Lambda\Lambda}| < |V_{\Lambda N}| < |V_{NN}|$. This is true in Model D, for instance, for the medium and longer range parts of the potential. Why is $\langle V_{\Lambda\Lambda}(r)\rangle$ stronger than $\langle V_{\Lambda N}(r)\rangle$? The answer could be in the differing short range behavior. For instance, the effect of quark antisymmetry, i.e., the effective hard core radius, is dependent on strangeness as well as $\{LSJI\}$. The repulsion generated through antisymmetry can be reduced in certain channels when strange quarks are added to the system. For example, for the six quark *ssuudd* system in an SU(3) singlet configuration, the effective hard core vanishes. Thus the substantial value of $\langle V_{\Lambda\Lambda}(r)\rangle$ is likely to be due to diminished short range repulsion at the quark level rather than some enhancement in the medium range attraction generated by meson exchange.

2.4. *Strange Dibaryons?*

Thus far, except for the deuteron, no stable dibaryon state is known. From emulsion experiments[28] which have led to the identification of ${}^{3}_{\Lambda}$H and heavier hypernuclear species, it appears that no two–body Λp bound state exists. Also, a study[29] of the reaction $K^{-}d \to \pi^{+}(\Sigma^{-}n)$ failed to yield any candidates for a $\Sigma^{-}n$ bound state. Occasionally, the existence of narrow strange dibaryon structures has been claimed,[30,31] but these have not been confirmed. Nevertheless, intriguing possibilities remain. For instance, one might ask whether the attractive $\Lambda\Lambda$ interaction, given in Eq. (3), is sufficient to form a two–body ${}^{1}\mathrm{S}_0$ bound state. We know that the nn ${}^{1}\mathrm{S}_0$ state is unbound, and $\langle V_{NN}(r)\rangle$ is stronger than $\langle V_{\Lambda\Lambda}(r)\rangle$, so we might expect that the $\Lambda\Lambda$ system is unbound. However, the diminished kinetic energy for $\Lambda\Lambda$ *vs.* nn favors binding, so the answer is unclear. If a weakly bound $(\Lambda\Lambda)_b$ state exists, it could be copiously produced in relativistic heavy ion collisions. Baltz *et al.*[32] estimate a production rate for $(\Lambda\Lambda)_b$ of order 0.07 per central Au+Au collision at Brookhaven AGS energies (11.7 GeV/c momentum per particle). If $(\Lambda\Lambda)_b$ lies near threshold, the branching ratio for the weak decay $(\Lambda\Lambda)_b \to p\pi^{-} + p\pi^{-}$ remains substantial, and this mode furnishes a nice experimental signature for $(\Lambda\Lambda)_b$ production.

There is also the possibility of a deeply bound $S = -2$ dibaryon, the H, with the same quantum numbers as $(\Lambda\Lambda)_b$. Such an object, proposed by Jaffe[33], would be a $(uuddss)$ six quark SU(3) singlet state. Unlike $(\Lambda\Lambda)_b$, which can be viewed as a quasi–molecular state like the deuteron, the deeply bound H has only a small parentage of $\Lambda\Lambda$ in the hadron basis. Searches are underway[34,35] at the Brookhaven AGS to find the H in the reactions

$$\Xi^{-} + d \to H + n \tag{5a}$$

$$K^{-} + {}^{3}\mathrm{He} \to K^{+} + H + n \tag{5b}$$

The processes (5a,b) are favorable if the H has an appreciable ΞN component in its wave function[36]; they are much less suited to the formation of a $(\Lambda\Lambda)_b$ quasi–molecular state, which would have only a small (ΞN) wave function admixture. From KEK experiments, there are also limits on H production in (K^{-}, K^{+}) reactions on nuclear targets.[37] Experiments on double hypernuclear formation should also be actively pursued, since the observation of weak decays of $\Lambda\Lambda$ hypernuclear systems can be used to place limits on the binding energy of the putative H. For instance, consider two possible decays of ${}^{6}_{\Lambda\Lambda}$He:

$${}^{6}_{\Lambda\Lambda}\mathrm{He} \to \pi^{-} + p + {}^{5}_{\Lambda}\mathrm{He} \tag{6a}$$

$${}^{6}_{\Lambda\Lambda}\mathrm{He} \to H + {}^{4}\mathrm{He} \tag{6b}$$

If the weak decay (6a) is seen, then we know that the strong decay (6b) did not occur, which places a constraint on the H mass. Essentially, if weak decays of $\Lambda\Lambda$ hypernuclei are seen, the H must hide close to the $\Lambda\Lambda$ threshold, in which case it would correspond to $(\Lambda\Lambda)_b$ rather than the six quark SU(3) singlet.

3. Effective YN Interactions in the Nucleus

As discussed earlier, we have very little direct knowledge of the spin dependence of the ΛN interaction in free space, since only spin–averaged cross sections have been measured. More information is available concerning the spin dependence of the effective interaction $V^{\text{eff}}_{\Lambda N}$ in the nucleus, from analyses of Λ hyprnuclear spectra[10] and γ ray energies.[11,12] $V^{\text{eff}}_{\Lambda N}$ may be written in the form

$$V^{\text{eff}}_{\Lambda N} = V_0 + V_\sigma \vec{\sigma}_N \cdot \vec{\sigma}_\Lambda + V_\Lambda \vec{\ell}_{N\Lambda} \cdot \vec{\sigma}_\Lambda + V_N \vec{\ell}_{N\Lambda} \cdot \vec{\sigma}_N + V_T S_{12} \tag{7}$$

where $\vec{\ell}_{N\Lambda}$ is the relative orbital angular momentum of the ΛN pair and S_{12} is the usual tensor force operator. Note that there are two independent spin–orbit terms for the ΛN system, since the Λ and N are distinguishable particles. The five potentials $V_i(r)$ in Eq. (7) give rise to matrix elements $\overline{V}$, Δ, S_Λ, S_N and T, respectively. Energy splittings ΔE of hypernuclear levels are proportional to linear combinations of these matrix elements. For example, for ${}^{7}_{\Lambda}$Li states obtained by coupling an $s_{1/2}$ Λ to the 1^+ ground state of ^{6}Li$(1/2^+, 3/2^+)$ or the 3^+ excited state at 2.18 MeV $(5/2^+)$, we obtain[38]

$$\begin{aligned} \Delta E\,(5/2^+ \rightarrow 1/2^+) &= 2.18 + 0.07\Delta - 1.0S_\Lambda + 0.95S_N + 0.22T \\ \Delta E\,(3/2^+ \rightarrow 1/2^+) &= 1.35\Delta + 0.15S_\Lambda - 0.06S_N - 1.29T \end{aligned} \tag{8}$$

Based on a construction of $V^{\Lambda N}_{\text{eff}}$ obtained from Nijmegen Model D, Millener *et al.*[38] predicted a set of standard values for use in the hypernuclear p–shell:

$$\Delta = 0.5, \quad S_\Lambda = -0.04, \quad S_N = -0.08, \quad T = 0.04 \quad \text{(in MeV)} \tag{9}$$

On the basis of this interaction, which was consistent with the γ ray data then available, Millener *et al.*[38] predicted a value $\Delta E \simeq 170$ keV for the $2^- \rightarrow 1^-$ γ ray transition between the members of the ground state doublet in ${}^{10}_{\Lambda}$B. Unfortunately, this transition was not observed by Chrien *et al.*[39], who obtained a limit $\Delta E < 80$ keV, indicating a spin splitting even smaller than the feeble spin dependence for the ΛN interaction predicted by Eq. (9). Fetisov *et al.*[40] incorporated this limit in a revised analysis, and obtained values

$$\Delta = 0.3, \quad S_\Lambda = -0.02, \quad S_N = \begin{cases} -0.35\,({}^7\text{Li}) \\ -0.1\ \ (A > 7) \end{cases}, \quad T = 0.02 \text{ (in MeV)} \tag{10}$$

The very weak spin dependence for the ΛN interaction required by the data is qualitatively consistent with the expectations of meson exchange models[38], although the hope of finding a universal set of matrix elements for the p–shell is not borne out by Eq. (9). In particular, the strength of the one–body Λ–nucleus spin–orbit potential[41] is found to be very small, at least an order of magnitude smaller than the corresponding N–nucleus spin–orbit potential. A small Λ spin–orbit splitting is explained[42] naturally in the meson exchange picture, although a precise experimental determination of this quantity is still highly desirable.

4. Mean Fields for Hyperons in the Nucleus

The Λ well depth U_Λ, i.e., the mean field experienced by the Λ in the center of a nucleus, is rather well determined from analyses of (π^+, K^+) and (K^-, π^-) cross sections on nuclear targets[43]:

$$U_\Lambda \approx 28 \text{ MeV}. \tag{11}$$

This value is about 1/2 of that for a nucleon. In nuclear matter, U_Λ can be calculated, by standard techniques, as a function of the nucleon Fermi momentum k_F. For $k_F = 270$ MeV/c, we should obtain the value of Eq. (11), and this serves as a constraint on the validity of a given meson exchange model. The standard models are all relatively successful in this regard: Model D gives $U_\Lambda \approx 35 - 45$ MeV, the NSC model yields $U_\Lambda \approx 23$ MeV, while Bonn A and B produce $U_\Lambda \approx 30$ and 31 MeV, respectively.

The mean fields for Σ and Ξ hyperons[42] in nuclei are also expected to be attractive, and comparable in magnitude to that for the Λ. Some old emulsion events have been used to extract a well depth of $U_\Xi \approx 24 \pm 4$ MeV for the Ξ hyperon[44]. Data on Σ^-–atoms suggest a depth $U_\Sigma \approx 15 - 20$ MeV, and quasi–stable Σ states in the continuum have a long and controversial history[45].

The attractive Σ and Ξ mean fields will support a spectrum of single particle bound states. Unlike the Λ, these configurations are generally unstable with respect to strong decay processes $\Sigma N \to \Lambda N$ or $\Xi N \to \Lambda\Lambda$. Under special circumstance, multi–strange systems containing a Ξ can be stabilized against strong decay[15], for instance ${}_{\Xi^0\Lambda\Lambda}^{\quad\;\, 7}\text{He}$ (${}^4\text{He} + 2\Lambda + \Xi^0$), due to Pauli blocking and binding effects. It is very difficult to stabilize a Σ against strong decay by such mechanisms, since the large energy release $Q \approx 75$ MeV in free space $\Sigma N \to \Lambda N$ decay cannot be compensated by the modest well depth U_Σ. On the other hand, the strong decay widths of single Σ's or Ξ's bound to a non–strange nuclear core could be reduced to a level where such states are observable as quasiparticle excitatios. There is some evidence[46] for the ground state of ${}^4_\Sigma\text{He}$, i.e, a $s_{1/2}$ Σ bound to an $A = 3$ nuclear core. The widths of Ξ single particle states are expected to be less than those for Σ states, because of the lower Q values for $\Xi N \to \Lambda\Lambda$ (23.2 MeV for $\Xi^0 n \to \Lambda\Lambda$, 28.3 MeV for $\Xi^- p \to \Lambda\Lambda$ in free space). In nuclear matter, the semi–classical estimate of the Ξ decay width yields the result

$$\Gamma_\Xi \approx (v\sigma)_{\Xi^- p \to \Lambda\Lambda} \quad (\rho^0/2) \approx 13 \text{ MeV} \tag{12}$$

where v is the relative velocity and $\rho^0/2 \approx 0.08$ fm^{-3} is the proton density. At KEK, a preliminary cross section value $\sigma_{\Xi^- p \to \Lambda\Lambda} \approx 19$ mb has been obtained[47] at 600 MeV/c; this was used to arrive at Eq. (12), assuming that $v\sigma$ is approximately independent of v at low momentum.

In a finite nucleus, Γ_Ξ can be considerably suppressed[48] due to binding effects and diminished wave function overlaps. For ${}^5_\Xi\text{H}$ ($\Xi^- + {}^4\text{He}$), a width of order $\Gamma_\Xi \approx 200$ keV is predicted[48], in agreement with estimates obtained by Akaishi and Myint[49]. For the ${}^{15}_{\Xi}\mathrm{B}$ ($\Xi^- + {}^{14}\mathrm{C}$) system, the width of the Ξ^- $1s$ state is predicted[48] to be in the range

$$\Gamma_\Xi \approx 1.5 - 6 \text{ MeV} \tag{13}$$

The lower value is obtained if a potential based on Model D is used for the $\Xi^- p \to \Lambda\Lambda$ transition, while the upper limit ensues if one fits a zero range interaction in Born approximation to the measured[47] value $\sigma_{\Xi^- p \to \Lambda\Lambda} = 19$ mb. The $1p$ Ξ state is found to be a bit narrower; the increased phase space available for its decay is more than compensated by the fact that the $1p$ state is more surface localized than the $1s$ Ξ, thereby impeding the $\Xi N \to \Lambda\Lambda$ transition.

If widths of the order of Eq. (13) indeed prevail, a fully developed spectrosocopy of Ξ states should be observable, at least in light nuclei. For a well depth of $U_\Xi \simeq 24$ MeV, the $1s$ and $1p$ Ξ states bound to a nuclear p–shell core are predicted[44] to be separated by about 7–8 MeV. These states can be produced via the (K^-, K^+) or (K^-, K^0) reactions on nuclear targets. An energy resolution of order 5 MeV should be sufficient to resolve the $1s$ and $1p$ Ξ states.

The Ξ single particle excitations are of interest in their own right, but also as "doorway states" for the production of discrete $\Lambda\Lambda$ hypernuclear states. Due to binding effects, the ${}_\Xi\mathrm{A}$ configurations are often stable with respect to the emission of two Λ's into the continuum. The dominant branching ratios for Ξ hypernuclear decay are then $n + {}_{\Lambda\Lambda}\mathrm{A}$ and $\Lambda + {}_\Lambda\mathrm{A}$, leading to various bound hypernuclear states. For the case of ${}^{15}_{\Xi}\mathrm{B}$, the neutron emission branch was estimated[48] to comprise about 70% of the total decay rate, leading to several excited states of ${}^{14}_{\Lambda\Lambda}\mathrm{B}$. Coincidence experiments involving the (K^-, K^+n) reaction on p–shell targets thus represent a very promising method for forming $\Lambda\Lambda$ hypernuclei.

For the estimates of the decay width of Ξ single particle states, it is crucial to know the $\Xi^- p \to \Lambda\Lambda$ conversion cross section at low momentum. Experiments to measure this quantity should be strongly pursued.

5. Hyperon–Nucleon Weak Decays

In all but the lightest hypernuclei, the non–mesonic weak decay $\Lambda N \to NN$ takes precedence over the free space $\Lambda \to N\pi$ process, which is Pauli–blocked. Schumacher[50] discussed the measurements and interpretation of non–mesonic Λ decay at this conference, so I will be brief.

There are a number of fascinating and unsolved problems involving the $\Lambda N \to NN$ process in nuclei[51]. Since the c.m. momentum release is of order 400 MeV/c, it is expected that short range effects will be important. Indeed, the simplest model of the $\Lambda N \to NN$ reaction, which takes into account only the longest range process, weak pion exchange, fails to account for the data. Weak π exchange is dominated by the ${}^3\mathrm{S}_1 \to {}^3\mathrm{D}_1$ transition ($\Delta L = 2$) induced by the tensor (S_{12}) component, which achieves the best kinematical matching of initial and final states. However, this implies the dominance of $\Lambda p \to np$ over $\Lambda n \to nn$ transitons, and this is not seen in the data. In a meson exchange picture, K and other shorter range forces become important, and the calculation of these is quite model dependent[52].

In weak processes, the $\Delta I = 1/2$ rule is generally observed, for reasons that are not well understood. For instance, for $\Lambda \to N\pi$, this rule predicts $\Gamma(\Lambda \to p\pi^-) = 2\Gamma(\Lambda \to n\pi^0)$, which is close to the truth. In the $\Lambda N \to NN$ process, we are offered another independent test of the validity of the $\Delta I = 1/2$ rule. The data are not yet good enough to permit a precise test, but Schumacher[50] has presented an analysis which suggests that the rule may not hold. If this conclusion holds up, it could be of considerable importance for the theory of weak interactions. At this conference, Oka[53] presented a first attempt to calculate $\Lambda N \to NN$ decays in the quark model. This approach seems to imply violation of the $\Delta I = 1/2$ rule. Another possibility is that three–body $\Lambda NN \to NNN$ weak processes enter the picture, and imitate $\Delta I = 1/2$ rule violations at the two–body level.

In $\Lambda\Lambda$ hypernuclei, there exists a novel possibility for non–mesonic weak decay, namely

$$\Lambda\Lambda \to \Sigma^- p,\ \Sigma^0 n,\ \Lambda n \qquad (14)$$

The $\Sigma^- p$ mode should be observable as a “vee”, with a kink in the Σ^- track due to the subsequent weak decay $\Sigma^- \to n\pi^-$. This would furnish a distinct signature for the weak decay of a $\Lambda\Lambda$ hypernucleus in its ground state. The branching ratio for the decay ${}^{6}_{\Lambda\Lambda}\mathrm{He} \to \Sigma^- + p + {}^4\mathrm{He}$ has been roughly estimated[54] to lie in the range 3–6%, which may be experimentally accessible. The hypernucleus ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ can be produced in the reaction

$$\Xi^- + {}^6\mathrm{Li} \to n + {}^{6}_{\Lambda\Lambda}\mathrm{He} \qquad (15)$$

starting from Ξ^- atomic states. The branching ratio for (15) is estimated[55] to be of the order of 3%.

6. Outlook

There is an extensive array of basic questions regarding YN and YY strong and weak interactions which remain unresolved. Some of these issues could be addressed in future experiments at Brookhaven and KEK, using tagged hyperon beams from the $\pi N \to K^+ Y$, $K^- N \to \pi Y$ and $K^- p \to K^+ \Xi^-$ reactions. By studying secondary interactions of the Λ, Σ and Ξ hyperons in a hydrogen target, key measurements of the YN differential and total cross sections could be performed. It is important to determine the energy dependence and angular shape of the cross sections in order to obtain more constraints on dynamical models. For instance the anisotropy of $d\sigma/d\Omega$ at low momentum is sensitive to the balance of s and p wave scattering, while the strength of the cusp in the Λp total cross section near the ΣN thresholds reveals information on the $\Lambda N \to \Sigma N$ coupling potential. A measurement of the $\Xi^- p \to \Lambda\Lambda$ conversion cross section is crucial in assessing the stability of Ξ quasiparticle states in the nucleus. Since Λ decay is self–analyzing, it may also be possible to measure spin observables in Λp scattering. For instance, knowledge of the polarization $P(\theta)$ would enable us to extract information on the two–body spin–orbit potential, and study its relation to the one–body Λ–nucleus spin–orbit potential, which is known to be weak. The measurement of spin–separated cross sections $\sigma_{0,1}$ and other spin observables would offer much stronger constraints on meson exchange models than one obtains from an analysis of spin–averaged cross sections alone. The available versions of the Nijmegen and Bonn YN potentials predict strikingly different patterns for some spin quantities. Even a modest amount of data on differential cross sections and polarization, for example, would probably enable us to discard the existing parametrizations of the OBE models. In view of the considerable degree of flexibility in parametrizing the (largely) theoretically uncontrolled short range part of the YN potentials, the OBE description can always be refitted to accommodate new data. Nevertheless, one may hope that additional YN measurements will lead to a somewhat sharper statement regarding the validity of SU(3) symmetry for meson–baryon coupling constants.

In addition to exploring free space YN scattering processes, it is also worthwhile to investigate hyperon interactions in the nuclear medium, and try to relate these theoretically to the free space ones. This can be accomplished by various means. For instance, measurements of hypernuclear γ rays provide energy splittings ΔE of hypernuclear levels with high precision, and enable us to constrain the spin dependence of the effective ΛN interaction $V_{\text{eff}}^{\Lambda N}$. If higher resolution ($\leq 1$ MeV) (K^-, π) or (π^+, K^+) experiments could be performed, we could start to disentangle the fine structure of the Λ hypernuclear spectrum, which again reflects the spin dependence of $V_{\Lambda N}^{\text{eff}}$. Experiments at Brookhaven with the (π^+, K^+) reaction have so far only achieved an energy resolution of 3 MeV or so. This proved very useful in probing the spin–averaged Λ single particle states and obtaining a detailed picture of the density dependence of the Λ–nucleus mean field, but was insufficient to shed light on the question of fine structure. The advent of higher resolution (π^+, K^+), (K^-, π^-), (K^-, π^0) and (γ, K^+) experiments (the latter at CEBAF) is eagerly awaited.

The strangeness $S = -2$ sector offers some particularly intriguing areas for research, which could shed a special light on the rôle of strange quarks in baryon–baryon strong interactions. A fundamental issue is the existence of a stable six quark H dibaryon, or possibly a weakly bound quasi–molecular state $(\Lambda\Lambda)_b$. A key question is how to make the transition from a meson exchange picture at long and medium range to quark/gluon dynamics at short distances. In the SU(3) singlet H channel, this difficulty seems particularly acute, since pseudoscalar and vector meson exchange forces are repulsive, while the color magnetic one gluon exchange forces generate a strong attraction at short distances. It remains unclear how to merge these two pictures in a consistent way. The meson and quark/gluon exchange mechanism also compete in the weak sector, in the $\Lambda N \rightarrow NN$ and $\Lambda\Lambda \rightarrow \Lambda N$, ΣN processes. In the meson exchange picture, one usually imposes the $\Delta I = 1/2$ rule by hand. The violation of this rule, if confirmed, would signal the need to treat the dynamics at the more fundamental level of quarks.

In summary, the study of hyperon–nucleon interactions both in free space and in nuclei is a most worthwhile enterprise, offering new insights into the dynamics of strange quarks in weak and strong baryon–baryon interactions. It should be vigorously pursued on both the theoretical and experimental fronts.

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