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THE OUTLOOK IN HYPERNUCLEAR PHYSICS

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A reasonable classification of the information obtained in the study of hypernuclei may be made according to its bearing on the following three areas of physical problems:

- (i) the properties of the nuclear interactions of the hyperons,
- (ii) the weak interactions of the Λ hyperon,
- (iii) the properties of nuclei.

Here we shall survey briefly some of the questions of current or future interest in these areas, as well as some of the experiments which appear feasible in the near future and which will bear directly on these questions.

1. The Nuclear Interactions of the Hyperons.

From the study of binding energies of Λ -hypernuclei, we have already learned a great deal about the qualitative properties of the Λ -N interaction in the 1S_0 and 3S_1 states,

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and this information has been given an interpretation by de Swart and Iddings¹ in terms of the properties of the pion-hyperon couplings $\Sigma\Lambda\pi$ and $\Sigma\Sigma\pi$. However there are still many questions of detail about the Λ -N forces, about which we know little:

(i) the exchange character of the Λ -N interaction.

The exchange of a K or K^* meson between Λ and N will give rise to an exchange term in the Λ -N potential. There are theoretical reasons to believe that this will not be a significantly large term but this needs to be checked directly,

(ii) the tensor potential contribution to the Λ -N interaction. Meson-theoretical calculations suggest that there is no reason to expect this to be a large term for the Λ -N system, in contrast with the N-N situation.

(iii) the nature of the hard core interaction in the Λ -N interaction. This information would be enlightening on the origin of the hard core in baryon-baryon interactions. At present, the most attractive hypothesis is that this hard core repulsion arises primarily from a universal and very strong coupling of the baryon with a neutral vector meson field. ^(possibly the ω meson) This hypothesis would require the Λ -N hard core to have radius comparable with that for the N-N system, apart from small modifications due to the exchange of other vector mesons such as the ρ , K^* and φ , which appear to be more weakly coupled to baryons and which have different couplings for different baryon multiplets.

(iv) the spin-orbit coupling for the Λ -N system. The most natural origin for strong spin-orbit forces in a baryon-

baryon system is the exchange of vector mesons, so that this question may have quite direct relationship with (iii). In this view, it is natural to expect a strong spin-orbit interaction in the Λ -N system, just as is known for the N-N system, and it will be very informative to learn about its sign and strength.

Probably it will be quite difficult to learn about these questions from Λ -hypernuclei. In p-shell hypernuclei, the s-wave Λ particle interacts with p-shell nucleons and so the magnitudes of the exchange component and especially of the spin-orbit interaction are relevant to the B_Λ value and the pattern of excited levels in these nuclei. More accurate and reliable B_Λ values for a wide range of Λ -hypernuclei are very desirable to allow a more detailed study of their systematics in this region. Another parameter directly relevant to these questions is the well depth D_Λ of nuclear matter for a Λ particle; D_Λ depends quite strongly on the properties of the p-wave Λ -N interaction.

Experiments on Λ p scattering would naturally give much more direct information about the Λ -N interaction, but these are generally rather difficult experiments, in view of the short lifetime of the Λ particle. One possibility is the use of Λ particles from the reaction $K^- + p \rightarrow \Lambda + \pi^0$ for K^- coming to rest in liquid hydrogen; this provides a copious source of Λ particles of 32 MeV kinetic energy (there are also lower energy Λ particles from the $\Sigma^0 \pi^0$, $\Sigma^0 \rightarrow \Lambda + \gamma$ sequence) and a search for the rare Λ p scattering events near these K^- stops can be carried out rather quickly

and efficiently. In this way it should be possible to obtain a good value for $\sigma_{\text{tot}}(\Lambda p)$ for a Λp c.m. energy in the s-wave region, which should provide an interesting check on the Λ -N potentials deduced from hypernuclear B_{Λ} values. These Λ particles are necessarily unpolarized; a source of strongly polarized Λ particles would allow much more informative experiments. For π^{-} momenta in the range 1000-1500 MeV/c at least, the reaction $\pi^{-} + p \rightarrow \Lambda + K^0$ leads to strongly polarized Λ particles with an angular distribution strongly peaked in the backward direction, thus giving quite strong production of relatively slow Λ particles with strong polarization. In due course, it may be possible to make use of these particles to study some polarization properties of Λp scattering; already a number of Λp scattering events have been observed in this way^{2,3} and used to estimate $\sigma_{\text{tot}}(\Lambda p)$. The simplest polarization property to measure is the mean depolarization of the Λ particles due to Λp scattering; this parameter is directly related to the relative strengths of the singlet and the triplet ΛN scattering. Possibly experiments of this kind will prove possible with spark chambers, using a hydrogen target inside the chamber; this would allow the collection of events at a much more reasonable rate. Similar studies of $\Sigma^{-}p$ and $\Sigma^{+}p$ cross sections, using hydrogen chambers or spark chamber methods, would also be of great value in providing new parameters to relate to the primary mechanisms giving rise to hyperon-nucleon forces.

The study of hyperfragment production rates in specific hyperon reactions should also prove quite informative on the de-

tailed character of the primary hyperon-nucleon interactions. For example, whereas $\Lambda^4\text{H}$ and $\Lambda^4\text{He}$ are produced in about 20% of $\text{K}^- - \text{He}^4$ reactions which lead to a primary Λ particle (identified by the characteristic momentum of the associated π^- meson), not more than one example of $\Lambda^4\text{H}$ has been observed in 300 examples of $\Sigma^- + \text{He}^4$ capture at rest. This low rate of $\Lambda^4\text{H}$ formation (which involves about the same momentum transfer as occurs in the $\text{K}^- + \text{He}^4 \rightarrow \Lambda^4\text{He} + \pi^-$ reaction) is probably related with the detailed spin character of the interaction $\Sigma^- + p \rightarrow \Lambda + n$.

The recent and remarkable observation of a $\Lambda\Lambda$ -hypernucleus by the Warsaw group⁵ has opened up a large new field of research. When suitable methods are developed to increase the yield of slow Ξ^- mesons which can be stopped in emulsion, the study of the $\Lambda\Lambda$ -hypernuclei formed will quickly lead to a rather accurate value for the Λ - Λ interaction in the $^1\text{S}_0$ state. For this determination, observations on the system $\Lambda\Lambda\text{He}^6$ will be of particular interest, since this is the system for which the most reliable calculations can be made at present. From the study of the heavier systems, we may expect to learn further about the spin-dependent term in the Λ -nucleus interaction (about which we have some indications from Λ -hypernuclear B_Λ values) and about the distortion of the core nuclei by the presence of several Λ particles. The study of specific capture reactions of particular simplicity will also be important; to illustrate this, we may mention the reaction $\Xi^- + \text{Li}^7 \rightarrow \Lambda^4\text{H} + \Lambda^4\text{H}$, whose interest (as pointed out by D. Wilkinson⁶) lies in the fact that the final state consists of two identical spinless Λ particles.

It will also be of interest to study the angular correlations between the two successive Λ decays of the $\Lambda\Lambda$ -hypernuclei, for example in the sequence $\Lambda\Lambda\text{He}^8 \rightarrow \pi^- + \Lambda\text{Li}^8 \rightarrow \pi^- + \text{Be}^{8*}(J = 2+)$, which provide a direct check on the spin value for ΛLi^8 . Probably studies of this kind should not be made in emulsion, since the atomic fields probably suffice to destroy the alignment of the ΛLi^8 during the relatively long time ($\sim 10^{-10}$ sec.) it remains at rest, awaiting the second Λ decay. The study of the branching ratios for the various decay modes of $\Lambda\Lambda$ -hypernuclei would also provide a check on many of our present beliefs about the decay of bound Λ -particles. To provide an example, we may consider $\Lambda\Lambda\text{H}^4$ and its two-body decay mode $\Lambda\Lambda\text{H}^4 \rightarrow \pi^- + \Lambda\text{He}^4$. With $J = 1$ expected for $\Lambda\Lambda\text{H}^4$, and $J = 0$ for ΛHe^4 , this decay requires $\ell = 1$ for the pion and can therefore occur only through the relatively weak p-interaction for Λ decay: hence the two-body decay modes for $\Lambda\Lambda\text{H}^4$ may be expected to be relatively rare, in contrast with the situation for ΛH^4 .

Now that an example of the $\Lambda\Lambda$ -hypernucleus has been established, it appears reasonable to mention the possibility of forming hypernuclei containing three Λ -particles. The systematics of the $p_{3/2}$ meson-baryon resonances, the $N_{3/2}^*$ (1238 MeV), the Y_1^* (1385 MeV) and the $\Xi_{1/2}^*$ (1530 MeV), strongly suggest the existence of a further state, the Ω^- -baryon with mass about 1680 MeV.^{7,8} This object has not yet been established, although there was an event reported by Eisenberg⁹ in 1954 which may have been an example of Ω^- -decay. The point is that this Ω^- -baryon is predicted to be long-lived, with

decay modes $\pi + \Xi^-$, $K^- + \Lambda$ and $\bar{K} + \Sigma$ due to the weak interactions, and to have strangeness $s = -3$. When the Ω^- particle comes to rest in emulsion and interacts with a nucleus, the following one- and two-nucleon capture processes are possible:

In case (1), if the Ξ^- hyperon undergoes a second interaction in the same nucleus, or in case (2), the effect of the capture process would be to release three Λ -particles within the nucleus. Even though the net energy release is quite high (~ 110 MeV for reaction (2)), there is a finite probability that all three Λ -particles may be trapped to form a $\Lambda\Lambda\Lambda$ -hypernucleus. In such a system, the lowest state available to third Λ particle is a p-state, in consequence of the Pauli principle. This condition will forbid the binding of the three Λ particles to the lightest nuclei, since the p-level of the Λ -nucleus interaction is bound only for sufficiently large core nuclei. The simplest estimates would suggest that $\Lambda\Lambda\Lambda\text{Be}^{11}$ should be stable; this system could be formed in reactions such as

2. The Weak Interactions of the Λ -hyperon.

The study of the beta-decay processes for hypernuclei could usefully complement studies of the properties of Λ beta-decay carried

out for free Λ particles. Processes of particular interest which may be studied in a helium bubble chamber are

With $J = 0$ for ΛH^4 , these processes represent zero-zero transitions^{which} are allowed only through the Fermi part of the Λ_e and Λ_μ interactions, so that a knowledge of their rate would allow a direct separation between the Fermi and Gamow-Teller terms in these interactions. This information may also be obtained from studies of the beta-decay of free polarized Λ particles. The greatest difficulty in the study of processes (4) will be the problem of low statistics; the branching ratio for these processes in ΛH^4 is expected to be of order 10^{-3} , so that there is no advantage in this respect over the study of free Λ -decay.

The lifetimes of the light hypernuclei form a subject of great interest, especially in view of the short lifetimes which have recently been found for ΛH^3 by two different investigations.^{10,11} This result is very much of a surprise, in view of the light binding in ΛH^3 ; it is difficult to obtain a lifetime much shorter than 1.8×10^{-10} sec from the theoretical calculations which have given a good account of the branching ratios observed for ΛH^3 and other light hypernuclei. Until this short lifetime is understood, there is reason for some skepticism about our progress in the quantitative understanding of the weak interaction processes in hypernuclei, so that it is of importance to confirm this result and to establish

more accurate lifetimes for the other light hypernuclei $\Lambda^4\text{H}$, $\Lambda^4\text{He}$ and $\Lambda^5\text{He}$.

Observations on hypernuclei offer the only means available for the study of the weak interaction

giving rise to non-mesic de-excitation of the Λ particle. There has already been a great clarification in our knowledge of the charge and spin dependence of this interaction, due to the data available on $\Lambda^4\text{He}$ studies in the helium chamber.¹⁰ Direct studies of the non-mesic rates for $\Lambda^4\text{H}$ and $\Lambda^5\text{He}$ (and also for $\Lambda^3\text{H}$, although here the rate expected is quite small, due to the low Λ binding) would be very valuable at this point, both of the total rates and of the $(\Lambda p)/(\Lambda n)$ ratio. Data on the rates (or branching ratios) for specific modes of decay, such as

would also provide valuable information. The decay rates for specific modes would also allow further tests of the $\Delta I = \frac{1}{2}$ rule for this interaction (5); at present, the only test available involves the inequality $\Gamma_{\text{nm}}(\Lambda^4\text{H}) \leq 2 \Gamma_{\text{nm}}(\Lambda^4\text{He})$, which appears to be just satisfied. The comparison of the absolute rates for the modes (6a), (6b) and for

provide another inequality, $R(n\text{He}^3) + R(p\text{H}^3) \geq \frac{1}{2}R(n\text{H}^3)$, which can give a further test of the $\Delta I = \frac{1}{2}$ rule in this process (5).

The spin-dependence of the interaction (5) may be investigated to some extent by comparing the ΛH^4 , ΛHe^4 and ΛHe^5 rates, especially the rates for the individual two-body modes. However there will be both parity-conserving and parity-reversing terms in this interaction and these can be separated only by polarization studies. These require observations on the angular distribution of non-mesic decay, relative to the polarization direction for the initial hypernucleus, for example for ΛHe^5 decay, or on the longitudinal polarization of the high energy nucleons emitted from each of the light hypernuclei. The study of polarization correlations between the two fast nucleons emerging from non-mesic decay will also be necessary before a complete analysis of the spin-dependence of the non-mesic interactions can be made.

There is the possibility that multinucleon contributions to the non-mesic Λ -decay rate may complicate the situation. It appears difficult to separate these processes from the process (5) on a purely empirical basis, since there can always be final state interactions which involve further nucleons. In light hypernuclei, complicated final states, involving the emission of a fast deuteron or a roughly equal sharing of the energy between three final particles, can occur even without invoking secondary interactions, as has been shown for the case of $\pi^- + \text{He}^4$ capture by the calculations of S. Eckstein.¹² The identification of multinucleon terms will require the observation of detailed deviations from the results of

calculation based on the two-body interaction (5). Probably, the proper procedure is to assume that the de-excitation process is dominantly of the type (5), until data turns up which cannot be reconciled with this hypothesis.

The absolute strength of the interaction (5) is of particular interest. One parameter directly relevant to this is the lifetime for a large hypernucleus (say $A \sim 100-200$). This lifetime could probably be measured by electronic techniques, by studying the occurrence of large energy releases following K^- capture in heavy nuclei with delay times of order 10^{-10} sec. The present data suggests that this interaction (5) is intrinsically weaker than that of the nuclear beta-decay interaction by about an order of magnitude; however, it is difficult to make this comparison ^{meaningful} until more is known about the form of the interaction (5).

3. Nuclear Physics and Hypernuclei.

(i) Nuclei away from the stability valley. Very little is known about the properties of many nuclear species with excess neutrons or protons relative to the normal species, such as H^5 , He^7 , He^8 , C^9 , etc. In most cases, it is not even known empirically whether these systems have particle-stable ground states. These systems are generally quite difficult to form in the kind of nuclear reactions which have been most convenient for experiment in the past, since they usually involve the transfer of at least two neutrons or

two protons to (or from) the stable target nucleus. When these systems are formed (at a low rate), it is often difficult to establish their identity conclusively with the usual techniques. For example, the emulsion technique is very convenient for the detailed study of individual rare events; there have been reported in the literature several events following high energy nuclear disintegrations,¹³ which may represent $C^9 \xrightarrow{\beta^+} B^9 \xrightarrow{\beta^+} Be^{9*} \rightarrow n + 2\alpha$, but even with this striking sequence of phenomena, it has been difficult to establish conclusively even the existence of bound C^9 . Similarly, there have recently been reports¹⁴ of the observation of the beta-decay of H^5 , following $\gamma + Li^7$ reactions at high energy, but here again, the arguments are sufficiently indirect as to allow question concerning this interpretation of the observations.

Any of these "exotic nuclei" which are particle-stable will certainly form a Λ -hypernucleus, and this will even be the case for many nuclear systems for which there is no stable ground state, since a bound Λ -particle generally adds at least an additional MeV to the stability of the system with respect to removal of the least strongly-bound nucleon.¹⁵ ΛBe^7 provides a well-known example of this situation, for there is no bound state Be^6 ; from an accurate knowledge of B_Λ for ΛBe^7 , it would be possible to deduce (after some necessary corrections) the position of the lowest level of Be^{6*} . In these "exotic hypernuclei," it is the last nucleon which has the least binding; in ΛBe^7 , the last proton has binding $B_p = 0.4 \pm 0.5$ MeV, compared with $B_\Lambda = 3.5$ MeV (relative to $He^4 + 2p$). The formation rate for these lightly-bound hypernuclei may be

expected to be quite appreciable; $\Lambda^3\text{H}$, with $B_\Lambda = 0.2$ MeV, is a well-known system, and the formation rate for $\Lambda^7\text{Be}$ must also be quite appreciable (since the two identified events represent only the (strongly suppressed) π^- mode). Then, in the $\Lambda \rightarrow p + \pi^-$ decay for the bound Λ particle, the relatively large energy release gives rise to fragments whose tracks are frequently long enough to allow identification and accurate measurement; the interpretation of the hypernucleus may be checked by the requirements that the momenta balance and that the B_Λ value obtained agrees with the known pattern of B_Λ values for neighboring hypernuclei. For example, the systems $\Lambda^6\text{H}$, $\Lambda^8\text{He}$, $\Lambda^9\text{He}$, $\Lambda^{10}\text{Li}$, $\Lambda^{10}\text{C}$, etc. are all to be expected, and perhaps even neutral systems such as $\Lambda^5\text{n}$ (following a recent report¹⁶ that n^4 may have a bound state at -4 MeV) may be observed in work with propane chambers.

Little is known about the existence and properties of light nuclei with high isospin, $I \geq \frac{3}{2}$, and it is quite possible that observations on "exotic Λ -hypernuclei" may allow some more convenient and conclusive evidence to be obtained concerning such nuclei. We should emphasize that the process of K^- capture with π^+ emission, or of Σ^- capture with proton emission can readily lead to the charge changes necessary to reach the neutron-rich systems; the proton-rich systems may be less readily accessible, although it is relatively easy to emit several neutrons in these formation reactions, in view of the large kinetic energy released.

(ii) Excited States of Hypernuclei. Λ -hypernuclei will generally possess excited states, some of which may be particle-

stable. Some of these states may even be metastable, i.e. they may undergo Λ -decay preferentially, rather than γ -decay. For example, Danysz and Pniewski¹⁷ have suggested that the first excited state of ΛHe^{7*} (which will have $J = \frac{3}{2}+$) may be metastable, a possibility which may account for unusual spread in the B_Λ values reported for ΛHe^7 events; Pniewski¹⁷ has also pointed out that Λ^0 ^{17*} ($\frac{1}{2}+$) at 6 MeV would also be metastable, at least that the Λ -decay and (e^+e^-) decay modes would be competitive for this system. However, generally, these excited states will decay by γ -emission; for example, the second excited state of ΛHe^{7*} (which will have $J = \frac{5}{2}+$) may be expected to decay by an M1 transition to the $J = \frac{3}{2}+$ excited state of ΛHe^{7*} .

Questions of interest in connection with these γ -transitions are

(a) the energies of the excited states. It is conceivable that these may be observed from the study of production reactions, in favorable cases where the levels are widely spaced. For example, the first level of ΛC^{13*} may be expected at an excitation energy of about 4 MeV, and its formation might be distinguished from ground state formation in the reaction

On the other hand, it may be feasible to observe the γ -rays directly (which would generally be a more satisfactory procedure) with the use of counter techniques. Mesic X-rays have been observed at Berkeley for K^- stopping in various light materials,¹⁸ and the possi-

bility of observing the γ -rays emitted from the resulting Λ -hypernuclei has been considered by Ashmore and Falla in a communication to this conference. Observations on the locations of these excited states would give additional evidence on the spin-dependence of the Λ -nucleon interaction; for example, the attachment of a Λ -particle to Li^6 forms two levels, the ground level with spin $\frac{1}{2}+$ and an excited level with spin $\frac{3}{2}+$, their splitting being due directly to the spin-dependent term in the Λ -N potential. Also, such information could frequently give an informative test of current theories of nuclear structure. For example, in ΛBe^{9*} , the $J = 2+$ level Be^{8*} at 3 MeV gives rise to two excited levels, with spins $\frac{3}{2}+$ and $\frac{5}{2}+$. If L-S coupling holds, or if the alpha particle model were valid for Be^{8*} , the splitting between these levels would vanish, whereas their splitting is quite large for nuclear j-j coupling; the magnitude of this splitting actually gives a measure of the degree of intermediate coupling appropriate to Be^{8*} .

(b) (γ, γ) and (γ, π) angular correlation studies can be made between the hypernuclear γ -rays and with the final decay pion. These could provide direct tests of the spin values predicted for these excited states.

(c) the measurement of γ -lifetimes for selected transitions. These lifetimes will provide tests of theoretical calculations of the structure of the hypernuclear wavefunctions in selected cases; for M1 transitions, they will depend on the Λ magnetic moment (which will probably have been determined by experiments on the free Λ particle, by the time hypernuclear γ -lifetimes can be

determined).

(iii) Branching Ratios for Mesic Decay of Hypernuclei.

For the transitions

$$(\Lambda Z^A) \longrightarrow \pi^- + (Z+1)^{A*}, \quad (9)$$

the relative transition rates to various final states will provide tests of the structure of the wavefunctions for the hypernucleus ΛZ^A and for the nuclear states $(Z+1)^{A*}$. For example, the rate for the decay mode $\Lambda \text{Li}^8 \longrightarrow \pi^- + \text{Be}^{8*}$ ($J=2+$, $I=1$) depends quite strongly on the nuclear coupling scheme, being forbidden through the s-interaction of Λ -decay for L-S coupling (since the transition is then $^1P_1 \longrightarrow ^3P_2$, which required spin-flip) and being quite strong for j-j coupling.

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