Hypernuclei

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Dedicated to the Memory of Professors H. Bandō and J. Zofka,

Aggregates of hyperons and nucleons, both members of the baryon family, have proved invaluable in exploring nuclear structure models. Hypernuclear phenomena will in future be increasingly exploited in a new branch of nuclear physics that aims to investigate differences between free baryons and those embedded in nuclear matter.

Our understanding of nuclear matter represents nuclei as composite objects built up from two kinds of nucleons — the protons and neutrons — that are bound together in nuclei by forces due to the exchange of lighter particles, the mesons.

From particle physics we know that nucleons are simply two members of a larger family — the baryons — that includes nucleons and hyperons. All these particles are labelled by the quantum number strangeness. For nucleons the strangeness $S = 0$ and for hyperons $-3 \leq S \leq -1$. Strangeness is conserved in both the strong and electromagnetic interactions, but not in the weak interaction.

All these features suggest that the familiar description of the nucleon-nucleon interaction based on the exchange of mesons can be extended to the entire baryon family. The hyperon-nucleon and hyperon-hyperon interactions will involve the exchange of both strange and/or non-strange mesons. One can therefore consider the baryon-baryon interaction more generally, without distinguishing between the different members of the baryon family.

At this point it becomes natural to ask if the generalization can be extended to bound systems. In other words, can several systems be formed from aggregates of baryons, *i.e.* nucleons (N) and hyperons (Y), in much the same way as nuclear matter which is built up from nucleons.

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Baryon Aggregates

In order to discuss baryon aggregates, let us consider first the case of the Λ hyperon ($S = -1$). Its lifetime is short (2.6×10^{-10} s), being typical of a weak decay that does not conserve strangeness. However, in the time scale of the strong interaction (10^{-20} - 10^{-24} s), this lifetime is very long and Λ can therefore be considered as a stable particle. In nuclear matter, the Λ has a new decay channel through the $\Lambda N \rightarrow NN$ reaction. This is again a process which does not preserve strangeness and has a time scale of the order of 10^{-10} s. One could thus expect that the Λ hyperon lives long enough to combine with nucleons to form aggregates, provided, of course, the ΛN interaction is attractive.

Aggregates of Λ and nucleons were effectively observed for the first time in 1953 by Danysz and Pniewski in a emulsion experiment [1] and have been named hypernuclei. The discovery of Σ hypernuclei is more recent [2].

Experimental data for the lightest Λ-hypernuclear systems show that the Λ-N interaction has a quite different behaviour from that of the N-N interaction: the hypertriton $^3H_\Lambda$, the mass-3-system, is bound by 130 keV and has spin and parity $J = 1/2^+$. The mass-4-systems $^4H_\Lambda$ and $^4He_\Lambda$ have $J^\pi = 0^+$ and 1^+ for the ground state and the first excited state, respectively. These results indicate that the ΛN interaction is more attractive in the singlet spin state than in the triplet state by about 1 MeV, whereas just the opposite happens in the NN interaction.

Data on the YN interaction are quite scarce, particularly in the low momenta region where scattering data cannot be obtained owing to the short lifetime of the hyperon. The spectroscopy of hypernuclei can provide, in an indirect way, some information. It also allows for checking of the nuclear structure models. This is because the hyperon, being different by the quantum number S from the other nucleons, is able to occupy quantum states already filled up with nucleons. Another implication of this feature is that hypernuclei spectroscopy can be used at the same time to probe deeply bound states and highly excited states. Also of great interest is an understanding of the physical process leading to the spin-orbit part of the nuclear potential.

Applying Quark Models

Some of the quark models have been successful in outlining many features of the baryon spectrum, and it has been suggested that they could be even more appropriate for describing the short range region of the baryon-baryon interaction. They would provide an alternative description of nuclear matter: the nucleus being built up with quark bags which, because of confinement, behave like baryons at relatively large distances (> 1 fm) by interacting *via* boson exchange as in the conventional model. At shorter distances (< 1 fm), the bags overlap and fuse to form larger bags of six (or more quarks) where the interaction is carried out by quark and gluon exchange.

Understanding the relationship between this new approach and the traditional picture of nuclei, *i.e.*, how one can move from the quark description, valid for very short interaction distances, towards the meson exchange representation, adopted for longer interaction distances, is related to the problem of confinement. What is the size of the confinement volume? Is it the same when the interaction takes place between free baryons, or when the baryons are embedded in the nuclear matter as constituents of the nuclei?

An example of how persisting quark clusters deep inside nuclei can be tested with strange probes is shown in Fig. 1. The $^5He_\Lambda$ ground state can be described [3] in terms of the traditional picture, with all the nucleons plus the Λ occupying the $s_{1/2}$ state. But in the quark picture, while the s quark among

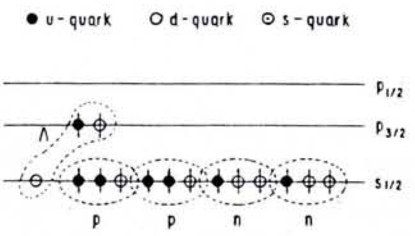
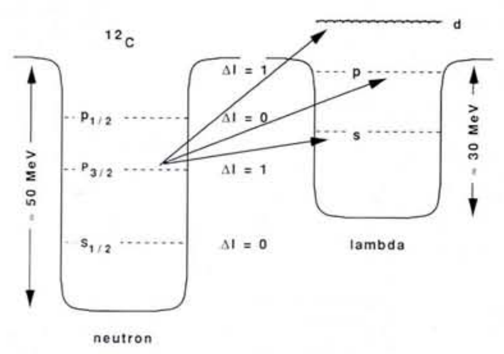


Fig. 1 — Quark structure of the $^5He_\Lambda$ hypernucleus.

Fig. 2 — Simplified scheme of the reaction mechanism leading to recoilless production (orbital angular momentum $\Delta L = 0$) and quasi-free production ($\Delta L = 1$).



the three quarks forming the Λ has the freedom to stay in the $s_{1/2}$ state, the u and d quarks, owing to the Pauli principle, do not have the same freedom and are raised into the $p_{3/2}$ shell. This effect may show up not only as a shallow potential in the most conservative approach, but also as anomalous phenomena which can be understood in terms of some deconfined character of the Λ and, by analogy, of the Σ in Σ hypernuclei.

Producing Hypernuclei

Hypernuclei can be produced using reactions involving one of two elementary processes namely, associated production and strangeness exchange. In associated production, a non-strange particle hits a nucleon and creates a hyperon (S = −1) and a meson K^+ (S= +1). An example of such a process is the reaction:

$$\pi^+ + n \rightarrow K^+ + \Lambda \qquad (1)$$

which has been used very efficiently at Brookhaven National Laboratory, USA, to produce Λ-hypernuclear states [4].

The largest amount of data has been produced so far, mainly at CERN, *via* the strangeness exchange process, which transfers the strangeness from a kaon K^- to a nucleon as follows:

$$K^- + N \rightarrow \Lambda + \pi^- \qquad (2)$$

$$K^- + N \rightarrow \Sigma + \pi \qquad (3)$$

The advantage of the exchange process is related to the peculiarities of the reaction mechanism as it leads to a simple interpretation of the hypernuclear states. The reaction kinematics are such that, when the pions are detected in the forward direction, the momentum transferred to the hyperon which is produced can be made very small by tuning the beam momentum. The hyperon which is selected maintains the spin and orbital wave function of the transformed nucleon (the orbital angular momentum change $\Delta L = 0$). A simplified scheme for the reaction mechanism leading to both the $\Delta L = 0$ production, by analogy with the Mössbauer effect also called recoilless production [5], and to the $\Delta L = 1$ production is shown in Fig. 2.

The kinematics of associated production (Reaction 1) that transfers to the hyperon are very different, when the kaons are detected at forward angles, as momenta larger than 250 MeV/c with high spin states arise.

Λ Hypernuclei

Examples of hypernuclear states obtained with Reaction 2 on ^{12}C and ^{16}O are given in Fig. 3 (the states are identified following the reaction scheme outlined in Fig. 2). Two peaks appear in the ^{12}C spectrum: the stronger one at the Λ binding energy $B_\Lambda = 0$ (lower scale) corresponds to the replacement of a neutron of the $p_{3/2}$ shell with a Λ; the second peak at $B_\Lambda = 11$ MeV is due to the replacement of a neutron of the $p_{3/2}$ shell with a Λ that drops into the $s_{1/2}$ shell. The energies required for these transformations are indicated in the upper scale and correspond to the mass difference M_{HY}-M_A between the hypernuclear state and the target nucleus. The energy difference between these two peaks is smaller than the corresponding energy gap between the s and p shells in ^{12}C, showing that the average potential felt by the Λ is much shallower (about 30 MeV) than that felt by a nucleon in ^{12}C (about 50 MeV). In ^{16}O, a neutron of either the $p_{3/2}$ or the $p_{1/2}$ shell can be transformed into a Λ and can then either stay in the same shell or move to the $s_{1/2}$ shell. This gives the four peaks shown in the figure.

It is important to note that the energy difference between the two peaks originating from a neutron in the $p_{3/2}$ shell is equal to that between the two peaks given by a neutron staying in the $p_{1/2}$

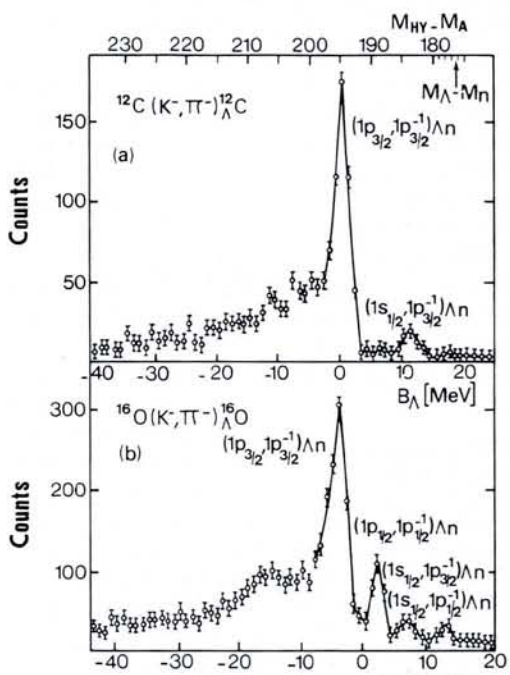


Fig. 3 — Λ-hypernuclear states obtained from the (K^-, π^-) reaction on ^{12}C (upper panel) and on ^{16}O (lower panel) plotted as function of the mass difference M_{HY}-M_A corresponding to the transformation energy. The Λ binding energy B_Λ is also given for each spectrum.

shell. This result implies that the spin orbit force felt by a Λ in the nuclear field is very small. In ordinary nuclei, this force, which is due to the coupling of the orbital angular momentum with the spin of the nucleon in the nuclear field, is quite strong. In ^{16}O it leads to an energy splitting between the $p_{1/2}$ shells of the order of 5 MeV. It is well established that the force acts over a short range even though its physical nature is not well understood. The measurement of the spin orbit energy splitting in hypernuclei thus provides additional constraints to theoretical models designed to describe the spin orbit force.

Free or bound

The study of the decay of hypernuclear states is related to the important question of whether the baryon has different properties when it is free or embedded in nuclear matter. The free Λ decays through the process $\Lambda \rightarrow N\pi$. Examining the decay of the ^{12}C state at B = 11 MeV, where the Λ is deeply embedded in the nuclear matter, has shown that the Λ decays almost exclusively through the process $\Lambda \rightarrow NN$, *i.e.*, mesonic decay is suppressed [6]. The lifetime of this state, however, is comparable to that of the free Λ.

Attempts to interprete these data have used three kinds of models, namely, classical meson exchange, a description in terms of quarks or a combination of the quark description for the short range part of the interaction with meson exchange for the long range part. All these approaches reproduce resonably well the lifetimes of the hypernuclear states, but not the branching ratios for the proton and neutron decays. Other data on the decay of deeply bound Λ-hypernuclear states of heavier hypernuclei are needed, together with more refined calculations, to see if the different decay behaviour of the Λ when it is embedded in the nuclear matter is in fact the signature of different behaviour for free and bound Λ, and is not simply related to some hindering of the mesonic decay due, more trivially, to phase space and/or Pauli blocking.

Associated production

The data [R.E. Chrien, private communication] shown in Fig. 4 were obtained using associated production of the Λ (Reaction 1). They illustrate perfectly that the Λ hyperon can occupy states already completely filled up with neutrons and protons. The most deeply bound states of the Λ hyperons would be ideal candidates to study the Λ decay properties discussed above. Another very important advantage of the (π^+, K^+) reaction is its high probability for producing polarized hypernuclei. Hence, an experimental programme at KEK in Tsukuba, Japan involves measuring the asymmetry of the non-mesonic decay of polarized Λ-hypernuclear states to protons.

Σ Hypernuclei

The experimental and theoretical aspects of Σ hypernuclei were the subjects of a recent review [7].

It has been fairly surprising to find that light Σ-hypernuclear states show up as fairly well defined peaks in the (K^-, π^-) reaction [2]. In fact, if Λ decay in nuclear matter proceeds through a weak interacting process, then the Σ can decay through the strong interacting process (ΔS = 0)

$$\Sigma + N \rightarrow \Lambda + N \quad (4)$$

The widths of the Σ-hypernuclear states are therefore expected to be a few tens of an MeV and not about 8 MeV as shown in Fig. 5. There are candidates for narrow Σ states with total baryon number A = 6, 7, 9, 12 and 16. Other experiments, however, have revealed no evidence for narrow Σ peaks in A = 7, 12 and 16 systems. A candidate for a bound Σ state for A = 4 has been reported recently [8].

The experimental situation remains controversial as combining results from all the current experiments has only generated data with low statistics owing to the weak intensities of low momentum kaon beams presently available. Mindful of a new generation of accelerators that could provide higher quality beams, it is useful to review the key questions related to the existence of Σ-hypernuclear states.

Assuming a potential model which accounts for the Σ-N scattering data, let us see if one can reliably predict the complex well depth (V_Σ-iW_Σ) where V_Σ and W_Σ are the real and imaginary components of the Σ-nucleus potential. The

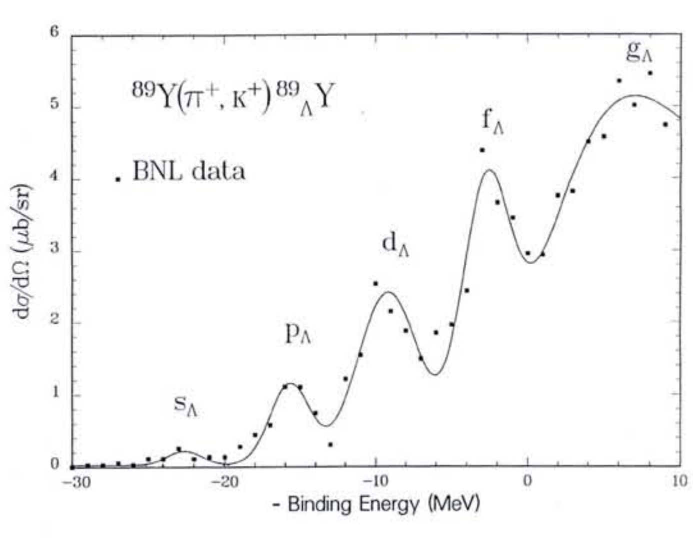


Fig. 4 — Hypernuclear states, obtained in the ^{89}Y $(\pi^+, K^+)^{89}Y_\Lambda$, reaction that is associated with the s, p, d, f, and g Λ-orbitals (the data for the differential cross sections were obtained at the Brookhaven National Laboratory, USA).

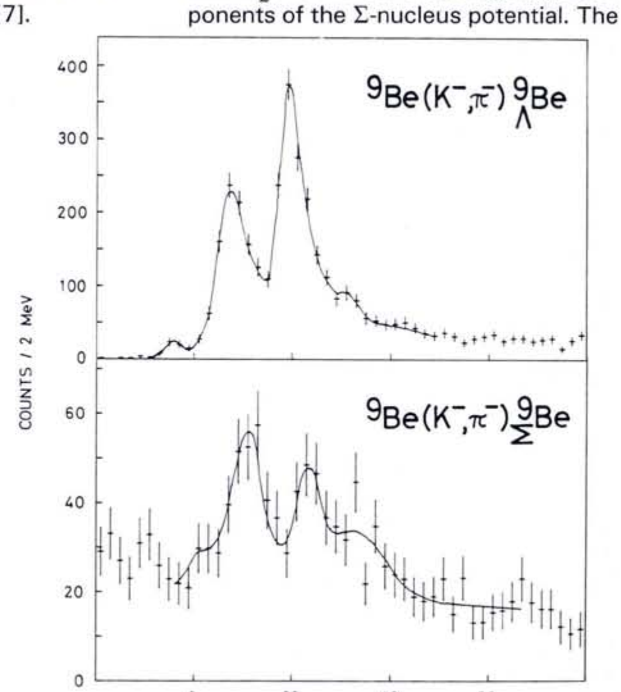


Fig. 5 — Λ- (upper panel) and Σ- (lower panel) hypernuclear states obtained in the reaction (K^-, π^-) on ^9Be [2]. $\Delta B_{nHyperon}$ is the difference between the binding energy of the hyperon in the nucleus and the binding energy of the nucleon in the target nucleus which has been transformed by a reaction in the hyperon.

key questions are: is V_Σ attractive and large enough to provide bound Σ states? And if so, is W_Σ small enough to lead to states which are relatively stable with respect to the $\Sigma N \rightarrow \Lambda N$ conversion?

Unfortunately, existing two-body ΣN data do not place strong constraints on the form of the ΣN potential $V_{\Sigma N}$ so even the sign of V_Σ cannot be reliably predicted. However, V_Σ can be assumed to be attractive if it is calculated using optical models fitted to Σ-atom level shifts and widths. With this assumption, V_Σ would be shallower than the corresponding Λ-nucleus potential and on the order of 20 MeV. The assumption would also imply agreement with the data shown in Fig. 5. However, a direct measurement of V_Σ is needed in order to resolve contradictory experimental data. This can be done in the same way as for Λ-hypernuclei with the (K^-, π^-) reaction, and for ordinary nuclei with the (e,e'p) reaction by analyzing the shape of the energy distribution of the Σ states produced in quasi-free scattering. But such an analysis requires data with good statistics and therefore high quality beams.

Another key point is to examine mechanisms which lead to the suppression of Σ decay widths, and thus to small values of W_Σ in finite nuclei. Pauli and dispersion effects have been considered, as well as the role of the spin dependence of the $\Sigma N \rightarrow \Lambda N$ conversion process [7]. In this case, the narrow Σ structures should show up best in the (K^-, π^-) reaction arising at a very low momentum transfer q because, as discussed for the Λ hypernuclei case, for large values of q, states with spin $J \neq 0$ are strongly excited and these states are expected to have a large energy width. The data of Fig. 5 measured at CERN, unlike other experiments, were obtained at low q.

Future Perspectives

In addition to Λ hypernuclei with a single Λ, two species of double-Λ hypernuclei have been observed [9] in emulsion experiments in the '60's, namely $^{10}Be_{\Lambda\Lambda}$ and $^{6}He_{\Lambda\Lambda}$. The binding energies $B_{\Lambda\Lambda}$ of these two hypernuclei have also been measured. However, the fact that all attempts to theoretically reproduce these findings have so far failed makes it important to check the original data using modern experiments. This could be done by studying, as suggested in a complete review on hypernuclear physics [9], the (K^-, K^+) reaction on nuclei. This process can produce either Ξ-hypernuclei ($S = -2$) or double-Λ hypernuclei. The latter are closely related to the existence and stability problem of the H particle, which was predicted some 20 years ago [10] as an exceptionally stable six quark bound state with a typical mass of 80 MeV below the threshold. Confirmation of the existence of double-$\Lambda\Lambda$ hypernuclei decaying through two successive weak decays $\Lambda \rightarrow \pi + p$ would provide strong evidence against the existence of the H particle with a very small mass (less than $2M_\Lambda$-$B_{\Lambda\Lambda}$), otherwise the H would be emitted much more rapidly than the weak decay instead of staying in the nucleus as $\Lambda\Lambda$.

Conclusions

The study of hypernuclear physics has proved to be essential in checking nuclear structure models, and for providing data describing the baryon-baryon interaction in the energy domain that cannot be probed by baryon-baryon scattering. The spin orbit force has been found to very small in Λ hypernuclei and there are indications that it could be much larger in Σ hypernuclei than in ordinary nuclei. However, the most attractive feature of hypernuclear physics is the possibility of investigating a new branch of nuclear physics that seeks to distinguish between different behaviours of the baryon, depending on whether it is free or embedded in the nuclear matter. Such differences would arise, for example, between the decays of the Λ, Σ and Ξ-hypernuclear states.

New experiments having a much higher statistical significance are needed to clarify some key points such as the Σ or double-$\Lambda\Lambda$ hypernuclei cases. European physicists have been very active, both in theoretical and experimental aspects, but since the shutdown of CERN's kaon beams, experiments now take place almost exclusively at Brookhaven in the USA and KEK in Japan.

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Material Processing under High Gravity

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A melt placed in a centrifuge is submitted to an "effective gravity field" which is more intense than the earth's field, and is also non-uniform. It is no surprise that crystal growth from such melts may have specific characteristics. Mass transport is affected: ionic crystals can be grown from centrifuged solutions hundreds times faster than is usual (P.J. Shlichta, W.R. Wilcox, USA, in the 1970's); light impurities may be expelled, which is important for proteins; structures obtained under constitutional supercooling conditions vary with the convection regime.

Studies of centrifuged eutectics are active in the USA, Hungary, China, Czecho-Slovakia and the USSR. New materials may even be found under high gravity. After the announcement by R. Parfeniev (FTI, Leningrad) and L. Regel (IKI, Moscow) of a magnetic moment of up to 130 K in BiSrCaCuO crystals remelted under high gravity, the centrifuge and ultracentrifuge machines existing in many biology and civil engineering laboratories may have to face a rush of new customers!

Gravity may stabilize or destabilize the convection currents in the melt. H. Wiedemeier (Rensselaer Polytechnic, NY, USA) and L. Regel found large differences in the growth from vapour when gravity is parallel or antiparallel to the growth direction. G. Müller (Erlangen University, Germany) showed in 1980 that the impurity striations found in InSb for destabilizing conditions could be removed if the melt was centrifuged, and explained it quantitatively in 1990 by the action of Coriolis acceleration. For Bridgman growth under stabilizing conditions of PbTe:Ag, H. Rodot (CNRS, France) and L. Regel found an inhibition of segregation for a well-defined value of the effective gravity.

Specialists of fluid dynamics are very active in improving their models. Some of them (W. Arnold, A. Chait and W.R. Wilcox, Clarkson University, NY, and NASA-Lewis, USA; G. Labrosse and A. Fikri, Orsay University, France) build rigorous descriptions of the convection regime in centrifuged melts. Others (H. Azuma, National Aerospace Laboratory, Japan; N. Baturin, IKI, Moscow, and J.C. Legros, Brussels University, Belgium) also try to describe, in simplified terms, the segregation effects. It is felt that these theories will soon generate the leading criteria for designing new experiments.

L. Regel, *Moscow, USSR;* **M. Rodot**, *Meudon, France;* **W.R. Wilcox**, *Potsdam, USA*