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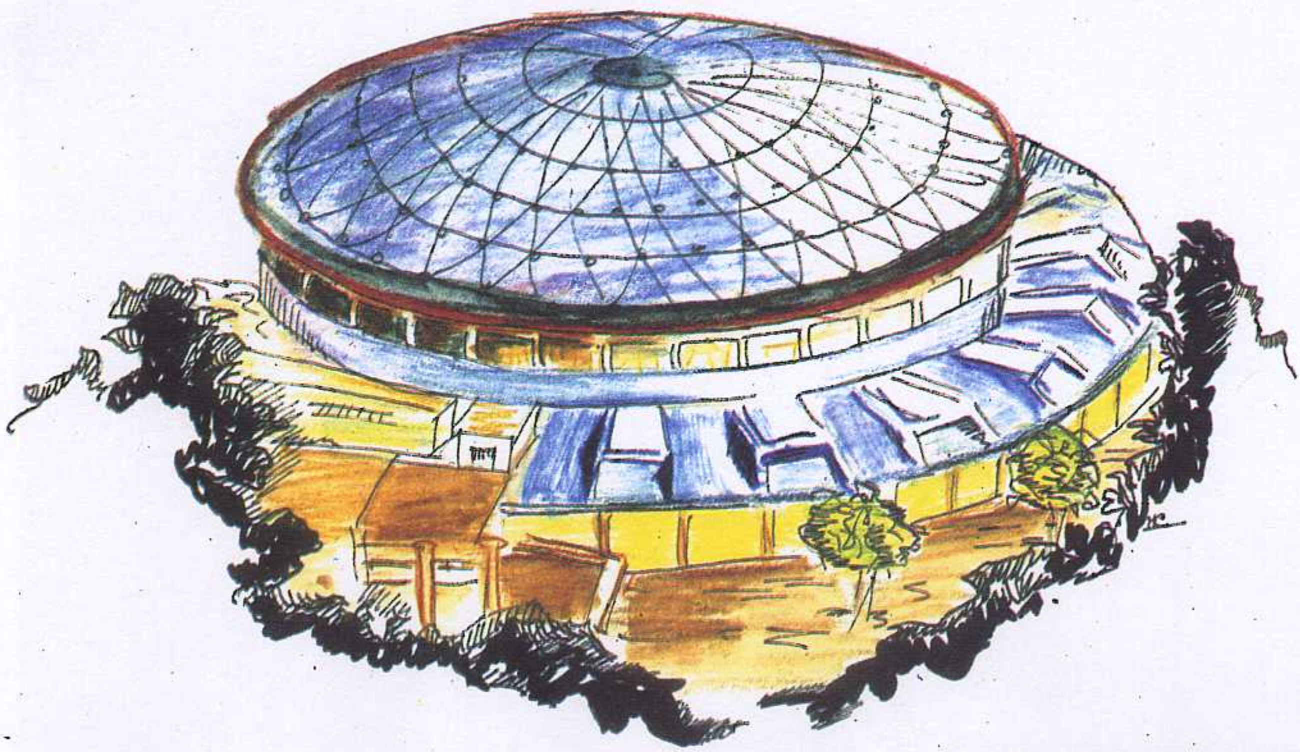
HYPERNUCLEAR PHYSICS

Contribution to the DAΦNE Physics Handbook



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HYPERNUCLEAR PHYSICS

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1. Introduction

Λ-hypernuclei are probably the first example of a subject of investigation which is today a well recognized field of physics, the intermediate energy physics. Since their discovery in 1953 by Danysz and Pniewski[1] in an emulsion experiment, their properties have focussed the interest of both particle and nuclear physicists.

From the particle physics side, Λ-hypernuclei are interesting since they may allow to obtain, in an indirect way, information on the Λ-*N* interaction in the low momentum region, where direct scattering experiments cannot be done owing to the short lifetime ($2.6\ 10^{-10}$ s) of the Λ-hyperon. Furthermore, and perhaps more interesting, a Λ-hyperon embedded in nuclear matter exhibits a new kind of weak interaction, forbidden to a free Λ decaying into $N+\pi$, the four baryon reaction $\Lambda+N \rightarrow N+N$. After nearly forty years, no precise and reliable data exist on this very interesting process, due to the difficulties both of producing copiously Λ-hypernuclei in well-defined states and of detecting the (n,p) and (n,n) pairs from their non-mesonic decay. A recent analysis on this subject can be found in Ref.[2].

From the nuclear physics point of view, it is worth re-emphasing that Λ-hypernuclei provide the best example of the validity of the single particle model without the difficulties linked to the Pauli exclusion principle and to the pairing interactions, as in ordinary nuclei. Fig.1 shows an excitation spectrum in ${}^{89}_{\Lambda}Y$ obtained with the (π^+,K^+) reaction at AGS, showing s, p, d, f, and g Λ-orbitals. It demonstrates in a striking way the validity of the concept of shell model orbitals, not just in the valence region, but deep within the nuclear interior. In nonstrange nuclei, the single-particle strength is broadly fragmented with excitation energy, and a deeply bound hole-state is so fragmented as to be essentially unobservable. In a Λ-hypernucleus, the distinguishable Λ may occupy any orbital and its rather weak core interaction leads to a well-defined, sharp set of states.

More interesting is the unique possibility offered by Λ-hypernuclei of testing a new approach to the description of nuclear matter. Following the success of some of the quark models in outlining many features of the baryon spectrum, it has been suggested that they could be even more appropriate for describing the short range region of the baryon-baryon interaction. Following this approach, the nucleus has to be represented as built up with quark bags. Due to confinement, the bags behave like baryons at relatively large distances (> 1 fm)

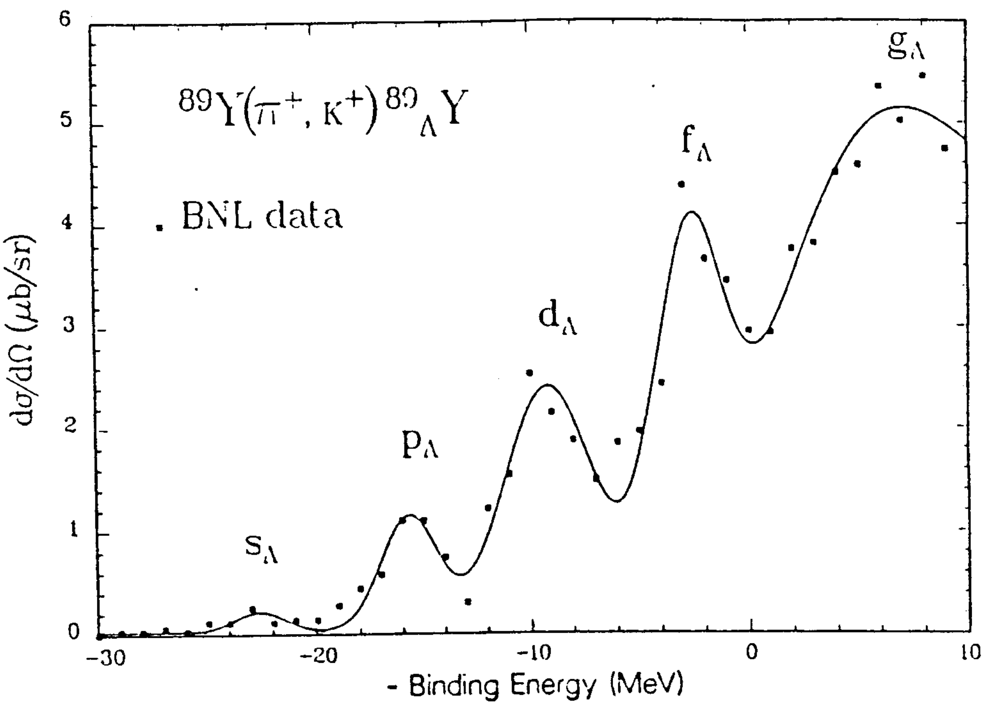

Fig.1 Hypernuclear states obtained in the ^{89}Y (π^+,K^+) $^{89}_{\Lambda}Y$ reaction, showing the Λ in the s, p, d, f and g orbitals, as measured at AGS.

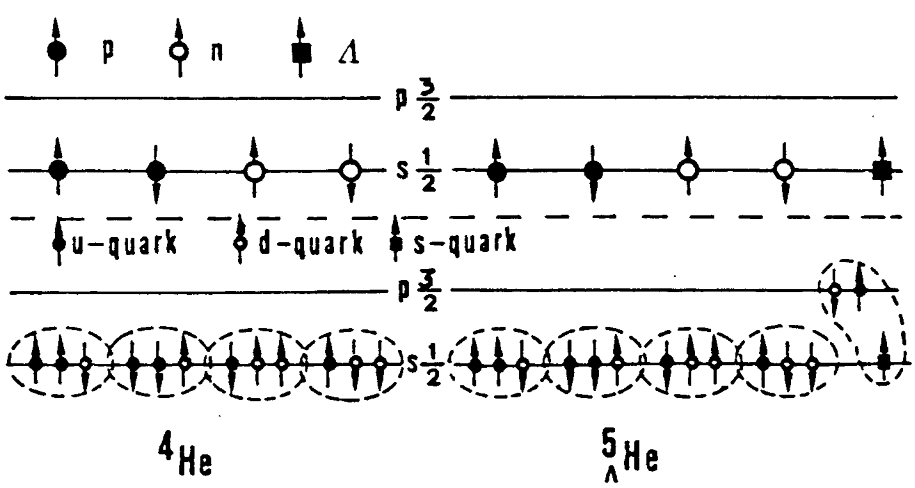

Fig.2 Baryon (upper row) and quark (lower row) configurations for the ^4He and $^5_{\Lambda}He$ systems.

and interact through boson exchange as in the conventional model. At shorter distances (< 1 fm), the bags may overlap and fuse to form larger bags of six (or nine) quarks, where the interaction is carried out by quark and gluon exchange.

An example of how hypernucler physics may give unique answers to this fundamental problem is shown by Fig.2. In the first row the baryon configuration for ^{4}He and $^5_\Lambda$He are reported. The baryons are assumed to be distinguishable, with the component quarks fully confined. In the second row the opposite hypothesis is assumed, i.e. that the quarks are fully deconfined, so that they occupy quark shell orbitals. For ^{4}He there is no substantial difference between the nucleon and quark description. For $^5_\Lambda$He , on the contrary, one can notice that the u- and d-quarks of the Λ cannot stay in the $s_{1/2}$ orbital, but in the $p_{3/2}$ one, whereas the s-quark may occupy the lowest energy state. In the baryon picture, all the 5 elementary constituents may occupy the $s_{1/2}$ orbital. Then, if there is a partial deconfinement of the quarks in nuclei, this effect could manifest itself more clearly in hypernuclei. As a matter of fact, the binding energy of $^5_\Lambda$He in the ground state is slightly smaller than that expected with the baryon picture, but more data on many hypernuclei are necessary before drawing any conclusion.

Finally, the puzzling situation concerning the existence of Σ-hypernuclei has to be clarified. In fact, the discovery of narrow peaks in production reactions, interpreted as due to defined Σ-hypernuclear states, was quite surprising. In fact, though the Σ-hyperon for many aspects is similar to the Λ-one, it was believed that its behaviour in nuclear matter was completely different. In fact, if Λ decay in nuclear matter proceeds through a weak interacting process ($\Delta S = 1$), then the Σ can decay through the strong interacting process ($\Delta S = 0$) $\Sigma + N \rightarrow \Lambda + N$. The width of the Σ-hypernuclear states are therefore expected to be a few tens of MeV. Following the first experiments at CERN and AGS which claimed the unexpected presence of narrow Σ-hypernuclear states, further detailed studies at KEK did not show evidence for the existence of Σ-hypernuclei, apart, perhaps the $^4_\Sigma$He. A clear-cut answer to this intriguing puzzle is urgently needed. A recent review on the theoretical and experimental aspects of Σ-hypernuclei can be found in Ref.[3]

2. Production of hypernuclei

Neglecting for simplicity the hypernuclei production processes induced by antiprotons and relativistic ions, there are essentially two ways for producing and studying the hypernuclear spectra, with K^- beams and with π^+ beams.The larger amount of data has been produced so far by means of the strangeness exchange reaction:

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

on a neutron of a nucleus, which transfers the strangeness from the K^- to the struck neutron, transforming it into a Λ. The reaction kinematics of (1) (Feshbach-Kerman kinematics) has the specific feature that, with the π^- detected at 0°, there is in the laboratory frame a "magic" value of the K^- momentum for which the Λ-hyperon is produced at rest, and the π^- carries all the momentum. The momentum transfer is then very small, 0 at the magic momentum (505 MeV/c), and can be varied in a controlled way by changing the beam momentum and/or the π^- emission angle. Hypernuclear final states for which the Λ has the same spin and orbital wave function of the transformed neutron are the most copiously ones produced by (1).The cross-sections may reach values of the order of the mb/sr.

Recently, the associated production reaction :

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

always on a neutron of a nucleus, was proved to be very efficient for producing Λ-hypernuclei at AGS. The kinematics of (2) is such that a relatively large momentum (~ 250 MeV/c) is transferred to the Λ-hyperon, always for forward detection of the K^+. The cross-sections are then lower by at least two orders of magnitude than those for (1), but this drawback is overcompensated by the larger intensities of the π^+ beams. The hypernuclear final states produced by (2) are different than for (1); mainly high spin hypernuclear states are observed.

A way of combining the advantages of (1) and (2): high production rate and a large spectrum of hypernuclear final states, is that of using reaction (1) but with K^- at rest. The momentum transferred to the produced Λ-hyperon is of the same order of magnitude (250 MeV/c) than (2) and the production rates for defined hypernuclear final states are still quite high: 10^{-3}/ stopped K^-. This technique was used very efficiently at KEK, and can be exploited at best at DAΦNE.

The arguments so far reported for Λ-hypernuclei are valid also for Σ-hypernuclei, mutatis mutandis in the kinematics due to the different mass of the Σ-hyperon. But the main problem is whether the Σ-hypernuclei exist at all !

More details on hypernuclear physics can be found in Ref.[4].

3. Experiments on hypernuclei at DAΦNE and conclusions.

DAΦNE is an approved project: operation at $L = 10^{32}$ cm^{-2} s^{-1} is expected in 1995, at $L = 10^{33}$ cm^{-2} s^{-1} two years later. At moment, hypernuclear physics is carried out at KEK (both with stopped K^- and with π^+ in flight) and at AGS (with π^+ in flight). Two major projects exist for the year 2000. KAON at Vancouver will provide K^- beams with fluxes reaching ~ 10^6 K^-/s, and PILAC at LAMPF will provide π^+ beams with fluxes of ~ 10^9 π^+/s. The first project is in good shape for approval, the second one is starting the procedure. Both projects have put hypernuclear physics at the top of their scientific priorities. CEBAF has too a program of hypernuclear physics, but it must be noticed that the production of hypernuclei by electromagnetic probes, though studied from many years from the theoretical point of view, was never attempted experimentally. Unforeseen backgrounds may deserve bad surprises !

Provided that a 2π magnetic spectrometer with good energy resolution (200 KeV) is installed at DAΦNE, matching the excellent features of the produced K^- (15 MeV, tagged, background free), the production rates for a single hypernuclear state with K^- at rest, with this resolution, will be an order of magnitude better at DAΦNE at $L = 10^{32}$ cm^{-2} s^{-1} than those presently achieved at KEK and AGS. At $L = 10^{33}$ cm^{-2} s^{-1} they will be comparable with those foreseen at KAON and PILAC (if approved, and in any case not before 2000).

However, the production rate of a single hypernuclear state is not the unique parameter of interest and judgement. For spectroscopy studies the characterization of a state (spin, parity) is the main interest, and experiments using K^- or π^+ in flight, able to measure an angular distribution, are better suited than an experiment with K^- at rest, for which only the production rate of a defined hypernuclear state can be measured. On the other side, the 2π spectrometer under study at DAΦNE can be very efficiently used also for the detection of the particles (π, p, n) emitted following the decay of a particular hypernuclear state. Measurements of the mesonic / non-mesonic disintegration channels, of particular importance for the study of the $\Lambda N \rightarrow N N$ weak interaction, can be performed in the best way at DAΦNE , and this could be the specific characterization of this facility.

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