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DOUBLE HYPERNUCLEI OR H PARTICLES?

Morgan May
Physics Department, Brookhaven National Laboratory, Upton, NY 11973

Existing data and current experiments on $\Lambda\Lambda$ and Ξ hypernuclei are reviewed. The relationship between hypernuclei containing two strange quarks, the H particle and related objects is discussed.

1 Introduction

We will begin with the H particle, stranglets and strange matter since these proposed objects are a strong motivation for studying hypernuclei containing two strange quarks. The data on $\Lambda\Lambda$ and Ξ hypernuclei will then be reviewed, as well as experiments in progress or scheduled. Many have contributed to the work that will be discussed, which took place primarily at KEK and BNL. At this time of transition, and anticipation of new experimental results and facilities, we take time to remember Carl Dover and Hiro Bando who contributed so much to this field.

2 H Particle and Related Objects

The H particle was proposed by Jaffe[1] in 1977 as a 6 quark bound state ($uuddss$) qualitatively different from the known mesons ($q\bar{q}$) and baryons (q^3). The H is a spin and isopin singlet state of two up, two down and two strange quarks. Jaffe presented simple and compelling reasons that the H would be deeply bound based on symmetry and the color magnetic interaction of the quarks. Arguments were later put forth by Chin and Kerman[2], Witten[3], Farhi and Jaffe[4] and others making plausible the existence of multiquark states q^n with $n \gg 3$. These proposed states are characterized by large strangeness fraction S/A, and a correspondingly anomalous charge to mass ratio q/A.

Strange hadronic matter which is composed of normal baryons but which can have similar S/A and q/A to strangelets may exist under certain circumstances and will be briefly discussed latter. Whether or not the conditions for its existence prevail can be discovered by a study of Ξ hypernuclei.

It has long been recognized[5] that at high density such as is found in the cores of neutron stars, hyperon will appear in increasing number as the density increases and will be stable due to the Pauli principle. In 1984 Witten[3] proposed that strange quark matter might be the ground state of QCD; his paper led to speculation that the cores of neutron star are strange quark matter, or that there are no neutron stars, only strange stars[6].

The H particle is the lightest member of the family of objects that includes strangelets and strange matter. $\Lambda\Lambda$ hypernuclei have a direct relationship to the H particle and thus may be a cornerstone for understanding the subject. Two Λ particles in the ground state of a $\Lambda\Lambda$ hypernucleus have the same quantum numbers as the H particle and will convert to an H if energetically allowed. If $m_H < 2m_\Lambda$, the H will decay by the weak interaction; for larger masses the H may exist only as a broad resonance. There is a window of H masses such that 2 free Λ are above the mass of the H, but 2 Λ in a nucleus cannot convert to the H when binding energies are taken into account. In this approximately 30 MeV window (depends on species) the H particle and $\Lambda\Lambda$ hypernuclei can both exist. However if $\Lambda\Lambda$ hypernuclei exist, a more deeply bound H particle would be ruled out.

Many attempts have been made to refine the calculation of the mass of the H particle. There is a wide variation in the masses predicted by different calculations[7], with a majority giving results below the $2m_\Lambda$. Present calculations are unable to predict convincingly whether the H exists or not. For example, lattice gauge calculation today are at the level of 15% systematic error for normal hadrons limited by the size of the box in which the calculation is performed and by the lattice spacing; 15% of m_H is 300 MeV. Putting 6 quarks in a box of the same size is an tighter squeeze, so the error would likely be greater. The new Columbia lattice machine together with its sister machine to be built at the Riken Institute at Brookhaven may reduce[8] these errors by a factor of 2.

The difficulty in finding or ruling out the H by experiment is due to the large range of lifetimes, masses and decay modes needed to be explored. Fig. 1 shows the regions of sensitivity of several AGS experimental searches for the H particle in the H lifetime $\times$ H mass plane. The curve is the calculation of Donoghue et al.[9], which is the only published relationship between lifetime and mass for the H; the relationship depends critically on the wavefunction of the H particle so that the H may lie far from the curve. So far the H has not been found or ruled out by experiment.

3 $\Lambda\Lambda$ Hypernuclei Experiments

In the 1960's there were two reports[10,11] of events identified as double hypernuclei in photographic emulsion experiments. No further data was forthcoming until the hybrid emulsion experiment at KEK whose results[12] were published in 1991. Each of these experiments reported a single fully reconstructed $\Lambda\Lambda$

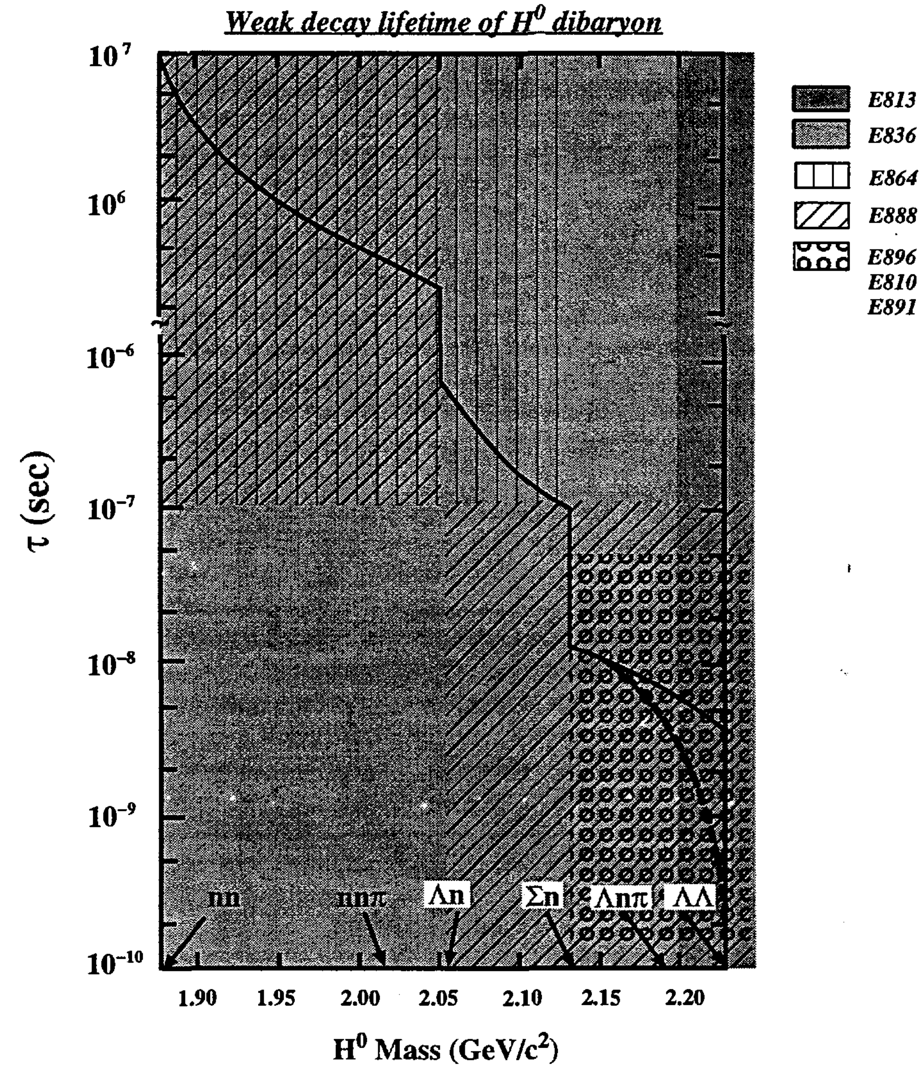

Figure 1: Regions of sensitivity of several AGS experimental searches for the H particle compiled by Philip Pile The curve is the relationship between τ_H and m_H according to the calculation of Donoghue et al.

hypernucleus. The best prospect of strengthening the $\Lambda\Lambda$ hypernucleus data are two experiments[13,14] at the Brookhaven AGS; Experiment 885 which has completed the bulk of its data taking and Experiment 906 which will begin taking data in the spring of 1997. Each hopes to observe hundreds of $\Lambda\Lambda$ hypernuclei, taking advantage of the excellent high intensity beams available at the AGS.

A hybrid emulsion experiment[15] at KEK is planned for 1998 to continue the work of KEK 176.

3.1 Photographic Emulsion Experiments

The signature of a $\Lambda\Lambda$ hypernucleus in a photographic emulsion is the sequential pionic decay of the two Λ particles. In a fully reconstructed event, 3 vertices - the production vertex and the two decay vertices - are resolved and all decay products are charged. In the early experiments, a block of emulsion was exposed to a K^- beam and then scanned; no other detector information was available.

The first report of a $\Lambda\Lambda$ hypernucleus was by Danysz et. al.[10] in 1963. A single ${}^{10}_{\Lambda\Lambda}Be$ event was observed. The experimenters were extremely fortunate to observe this event since in a total exposure of the emulsion to 10^5 K^-, one would expect at the very most two Ξ^- to stop in the emulsion. In order for one of the stopping Ξ^- to result in the observed event, several steps had to occur: 1. Capture on a light constituent of the emulsion so that the recoiling hyperfragment could be observed after the first Λ decay (30% probability). 2. Both Λ particles bind to the nucleus to form a $\Lambda\Lambda$ hypernucleus 3. Both Λ particles decay by π^- emission (4% probability). 4. All decay products charged. The event was subjected to intense scrutiny by physicists within and outside[16] of the collaboration which discovered the event.

The second event was reported in 1966 Prowse[11], a $\Lambda\Lambda$ hypernucleus he identified as ${}^{6}_{\Lambda\Lambda}He$.

More recently, KEK Experiment 176 used a hybrid emulsion technique in which formation of Ξ^- in a photographic emulsion target was tagged through magnetic analysis of an incident K^- and the outgoing K^+. The (K^-, K^+) vertex position in the emulsion was later scanned for hyperfragments. This approach permits a much more sensitive search than previous experiments. A single event[12] was found which was identified as either ${}^{10}_{\Lambda\Lambda}Be$ or ${}^{13}_{\Lambda\Lambda}B$; this uncertainty is due to particle identification ambiguity in determining whether a track was a proton or triton. The part of the binding energy of the hypernucleus due to the interaction between the two Λ particles is deduced to be either +4.9 or -4.9 MeV depending on the interpretation chosen. This is the best event we have. It is superior to the events found in earlier experiments since it is initiated by a identified Ξ^-.

KEK 176 found additional double strangeness hypernuclei candidates which were not fully reconstructed, and whose charge and mass could not be identified. Some of these were heavy hyperfragments[17] where the large energy release from a single point within the resolution of the emulsion suggested that two s quarks decayed in the same nucleus.

In order to definitively establish the subject of $\Lambda\Lambda$ hypernuclei, an experiment will need detect several events of the same species with consistent mass. KEK 373 which will take data in 1998 expects to observe 10 $\Lambda\Lambda$ hypernuclei in a hybrid-emulsion experiment[15]. Particle identification ambiguities will be reduced in this experiment by the use of finer-grained emulsion. Counter experiments may have earlier results.

3.2 Experiment AGS 885

The best route to producing a $\Lambda\Lambda$ hypernucleus may be the capture of a Ξ^- on a nucleus; the three emulsion events discussed above were all initiated in this way. The Ξ^- has a very short lifetime, so energetic Ξ^- tend to decay before they come to rest. A Ξ^- produced on a free proton

$$K^- + p \rightarrow K^+ + \Xi^-$$

has a momentum of 500 MeV/c. A K^- interacting with a carbon nucleus can produce a Ξ^- almost at rest due to the Fermi momentum in the target:

$$K^- + {}^{12}C \rightarrow K^+ + \Xi^- + X.$$

The Ξ^- can then be captured at rest on another ${}^{12}C$ nucleus within the target. In some cases the Ξ^- capture will result in $\Lambda\Lambda$ hypernuclei[18,19]

$$\Xi^- + {}^{12}C \rightarrow {}^{12}_{\Lambda\Lambda}Be + n.$$

The energy of the neutron determines the binding energy of the $\Lambda\Lambda$ hypernucleus.

Experiment[13] 885 uses a man-made diamond target for maximum stopping power. The target is $5 \times 8 \times 1$ cm rectangular solid weighing 700 carats and is within a few percent of natural diamond density. Approximately 20000 Ξ^- captures occur in the target per 10^{12} incident kaons. This is two orders of magnitude more stopping Ξ^- than obtained by previous experiments.

The K^+ momentum can be used to select stopped Ξ^-. The slowest Ξ^- particles correspond to the fastest K^+. Fig. 2 shows a Monte Carlo calculation

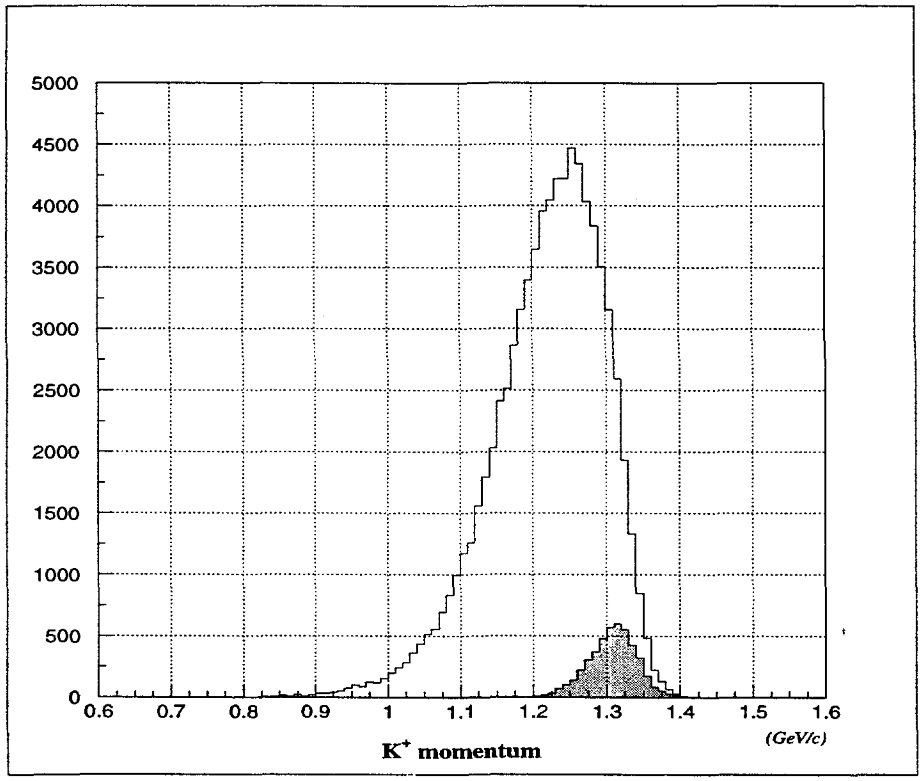

Figure 2: Monte Carlo calculation of quasi-free Ξ^- production in diamond target. The larger peak includes all Ξ^- produced; the small shaded peak corresponds to the Ξ^- that stop in the target.

of quasi-free Ξ^- production in our diamond target. The larger peak includes all Ξ^- produced; the small shaded peak are the Ξ^- that stop in the target. The calculation has been checked by comparison with KEK emulsion data[20]. As is clear from the figure, a cut on K^+ momentum yields an enriched sample of stopping Ξ^-.

Fig. 3 shows the apparatus. The K^- beam is momentum analyzed using the chambers ID1-3 and a hodoscope and spectrometer not shown in the figure. A 48D48 dipole magnet flanked by drift chambers FD0-3 and BD1,2 momentum analyzes the K^+. Aerogel Cherenkov counters FC0, FC, and BC distinguish the K^+ from π^+ and protons. Protons are the most serious problem at the trigger level; a second-level trigger makes a secondary mass cut using a

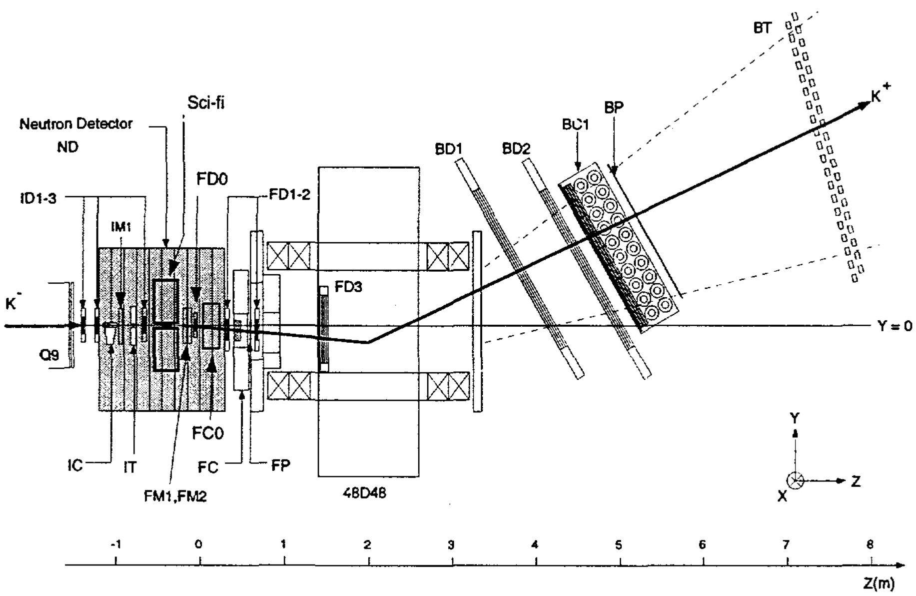

Figure 3: Apparatus of Experiment 885. Drift chambers ID1-3 and gas microstrip chamber IM1 determine incoming K^- trajectory and are combined with upstream hodoscope data to determine K^- momentum. Drift chambers FD1-3, BD1,2 and microstrip chambers FM1,2 determine K^+ momentum from deflection in spectrometer magnet 48D48. Scintillators IT and BT determine K^+ time-of-flight. Hodoscopes FP and BP determine spectrometer acceptance. Aerogel Cherenkov counters IC1, FC and BC reject pions. High density aerogel counter FC0 rejects protons. Scintillating fiber array Sci-fi and neutron time-of-flight array ND surround target.

matrix of FD3 and BT elements combined with time of flight measurements between scintillators IT and BT. Walls of thick, highly segmented scintillator ND on either side of the target measure neutron energy by time of flight. The same spectrometer was used for the H search experiments AGS 813 and 836, and will be used for the $\Lambda\Lambda$ hypernucleus search AGS 906.

Fig. 4 is an close-up of the target region. Scintillating fiber arrays for detecting the decay products of the double hypernucleus are mounted above and below the target. The arrays are composed of 20,000 1.0 mm fibers in alternate u and v planes viewed by image intensifier tubes (IIT) with a CCD readout. Light output in each fiber is recorded. The scintillating fiber is used for study of decay products of hypernuclei and also to help suppress backgrounds.

The sensitivity of AGS 885 to Ξ hypernuclei is discussed in other sections

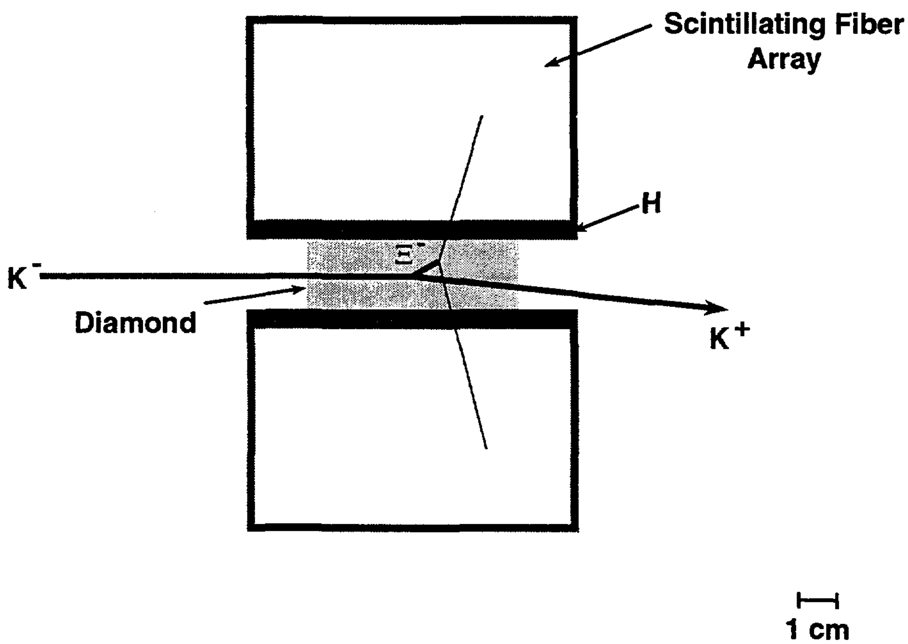

Figure 4: Target region in AGS 885. Ξ^- produced by the reaction $K^- + {}^{12}C \rightarrow K^+ + \Xi^- + X$ are captured on a second carbon nucleus in the diamond target to produce $\Lambda\Lambda$ hypernuclei. Decay products of the hypernuclei pass through a hodoscope H and are detected in the scintillating fiber arrays.

of this paper. AGS 885 data will also permit a sensitive search for the H particle in several decay and production channels.

3.3 Experiment AGS 906

Experiment[14] 906 will detect $\Lambda\Lambda$ hypernuclei by observing their characteristic π^- decays. The Cylindrical Detector System (CDS) was built by INS and has been installed at the Brookhaven AGS. Data taking will begin in April 1997. The goal is to form the light hyperfragments ${}^{5}_{\Lambda\Lambda}He$ and ${}^{6}_{\Lambda\Lambda}He$. A K^- is incident on a ${}^{9}Be$ target, with the K^+ detected in the spectrometer described in the previous section. There are several mechanisms for forming the light hyperfragments. One possible route is

$$K^- + {}^{9}Be \rightarrow {}^{5}_{\Lambda\Lambda}He + nnnn + K^+.$$

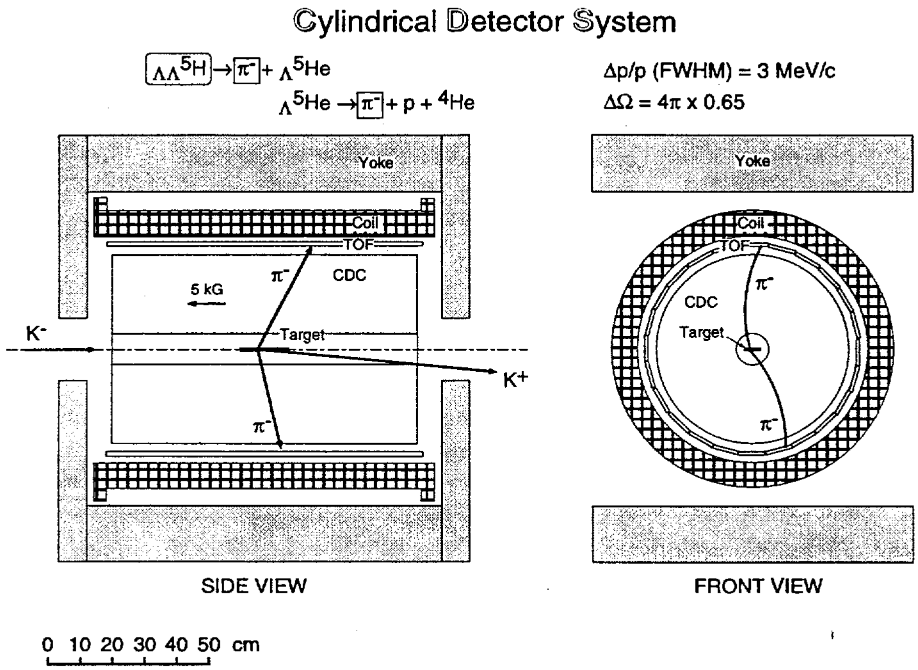

Figure 5: Cylindrical Detector System used in AGS 906

The event can be observed in the CDS if both Λ particles decay by $\Lambda \rightarrow p + \pi^-$ ($T_p = 5$ MeV). The probability of a two body final state is large because of the low kinetic energy of the proton:

$$ {}^{5}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + \pi^- . $$

The second lambda decay may produce a 3 body final state and still result in a narrowly defined pion energy due to the small energy release:

$$ {}^{5}_{\Lambda}He \rightarrow \alpha + p + \pi^- . $$

Motoba[21] has calculated that the spread in energy of the π^- in the above reaction will be less than 1 MeV.

Fig. 5 shows the CDS which is a drift chamber system inside a .5 Tesla solenoid magnet. The magnetic field volume is 35 cm in radius and 1.2 meters long. A pion from hypernuclear decay has momentum $\approx$ 100 MeV and will have a 60 cm radius of curvature in the solenoid. From a radius of 5 to 30 cm a drift chamber with 550 wires fills the solenoid. Half of the wire planes are axial and half are small-angle stereo. Surrounding the drift chamber is a multi-wire chamber with cathode strip readout to define the axial coordinate of the tracks. The outermost layer is a hodoscope of 22 elements each subtending 15°.

4 Ξ Hypernuclei

Except in special cases, Ξ hypernuclear states will have strong interaction widths since a Ξ^- can interact with a proton to form two Λ particles

$$\Xi^- + p \rightarrow \Lambda + \Lambda \qquad Q = 28MeV.$$

However, the release of energy is small and can be further reduced by binding effects when the proton is a component of a nucleus. These factors lead to the conclusion that Ξ hypernuclear states may be narrow. Recent calculations by Millener[19] and his collaborators, and by Ikeda and his collaborators[22] give ≈ 1.5 MeV for the width of these states. Since this is narrow compared to the spacing between states, a spectroscopy may be possible. In some special cases such as $(\Xi^- nn)$ charge conservation prevents the conversion of the Ξ^- to Λ particles; in this system the Ξ^- will decay weakly.

We hope to learn from experiment the binding energy of the Ξ, and to deduce the Ξ - nucleus potential leading to a greater understanding of the baryon-baryon interaction. Strange hadronic matter will exist only if the Ξ - nucleus potential is sufficiently strong. All these questions are still open.

4.1 Strange Hadronic Matter

The proposal for the existence of strange hadronic matter[23] rests on the observation that $\Xi + N \rightarrow \Lambda + \Lambda$ can be Pauli blocked by the presence of Λ particles. Adding more Λ particles to the nucleus becomes quickly unprofitable as energetics begin to favor $\Lambda + \Lambda \rightarrow \Xi + N$. Strange hadronic matter can be thought of as a large Ξ - Λ hypernucleus. The presence of many neutral Λ and negative Ξ particles gives it properties very similar to strangelets - charge to mass ratio $q/A \approx .1$, strangeness to mass ratio $S/A \approx 1$ and density approximately twice normal nuclear matter density.

4.2 Ξ Hypernuclei - Data and Future Experiments

Seven Ξ hypernuclei candidates reported in emulsion experiments over the period 1959-1969 were analyzed by Dover and Gal in their 1983 review[24]. Commenting on the quality of the data they said "none of these interpretations is statistically unique, and in some cases the evidence is far from being compelling". However, using this data they determined the Ξ- nucleus central potential to be $V_{0\Xi} \approx 24$ MeV.

The hybrid emulsion experiment KEK 176, which was discussed previously in connection with ΛΛ hypernuclei, found 2 Ξ hypernucleus events[25]. These events are superior to the previous emulsion events because they are initiated by an identified Ξ^- captured at rest. However, there is still a non unique interpretation of the events. KEK 373, the successor to this experiment will take data in 1998 and expects 20 Ξ hypernuclei events.

Ξ hypernuclei could also be detected by a missing mass experiment. For example in the reaction

$$K^- + {}^{12}C \rightarrow {}^{12}_{\Xi}Be + K^+$$

a momentum analysis of the K^- and K^+ can be used to determine the spectrum of states of the Ξ hypernucleus. Momentum resolution of 5×10^{-4} would give the 2 MeV energy resolution required. So far experiments have not achieved this precision; they can, however look for an event excess in the bound state region. KEK 224 has presented low statistics data[26] possibly suggestive of a potential $V_{0\Xi}$ weaker than 24 MeV. AGS 885 has data with much greater statistics and better resolution; the data is now being analyzed. There is an obvious need for an experiment with a spectrometer which could resolve individual Ξ hypernuclear states. Such a spectrometer could make initial measurements at BNL and later be moved to the Japan Hadron Facility when it becomes operational.

5 Summary of Status

Events and spectra found in the last few years have brought us a glimpse of what lies ahead. In the next few years, BNL and KEK will have many new and exciting results. There is much work to be done and present experiments are intensity limited. Many exciting experiments are marginal at the present intensities, for example, gamma-ray transitions in ΛΛ hypernuclei. A rich program of physics will remain to be explored at the JHP.

Acknowledgements

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