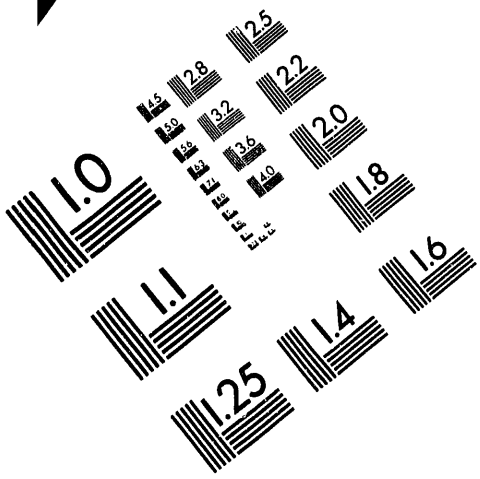

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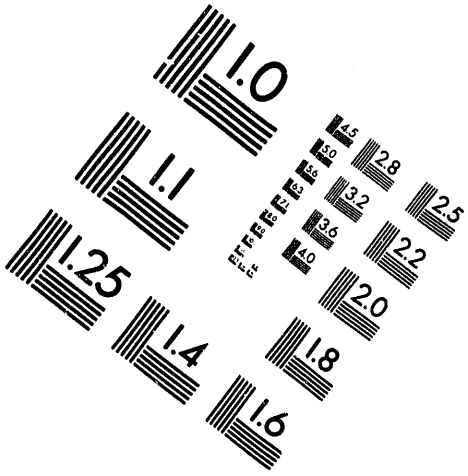

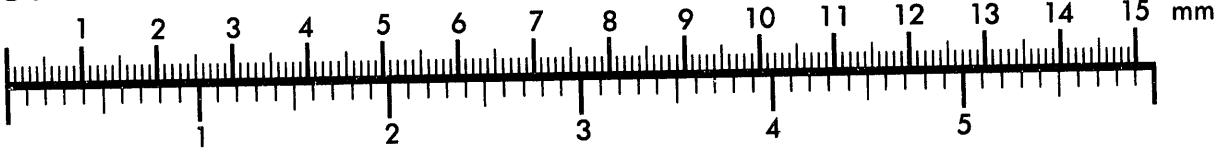

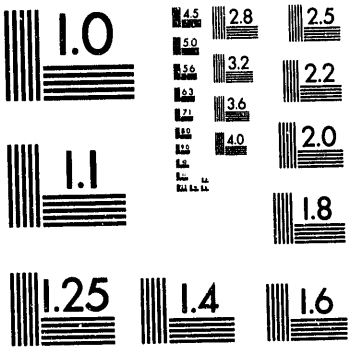

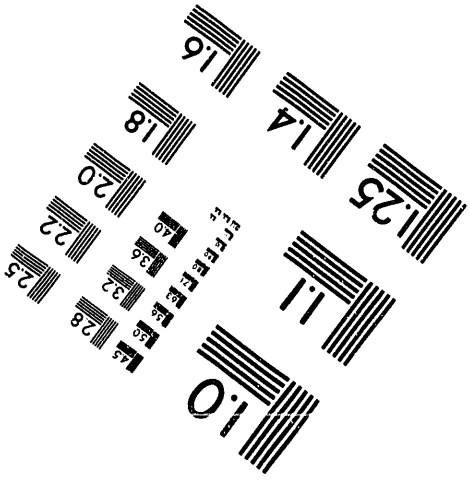

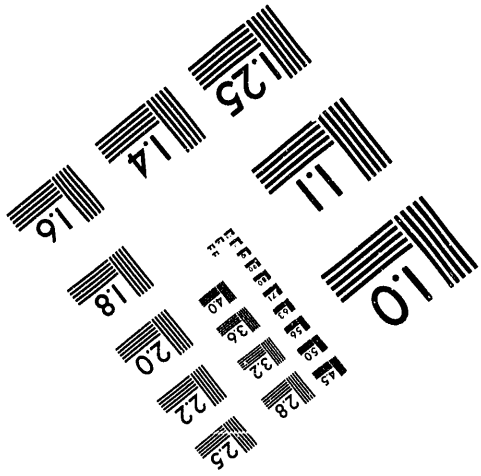

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Doubly Strange Hypernuclei

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Abstract

Doubly strange hypernuclei are fundamental for understanding proposed new particles and states of matter containing two or more units of strangeness. Experiments are required to confirm the existence of $\Lambda\Lambda$ hypernuclei, measure their lifetimes, binding energies, and decay modes, and search for possible anomalies. An experiment[1] to observe and study them is planned utilizing the higher intensity beams now available at the AGS. Detailed study will require further improvements in intensity and facilities. Facility requirements for future experiments are discussed.

Introduction

The possible existence new states of matter[2][3] containing two or more units of strangeness has greatly increased interest in hypernuclei containing two or more strange quarks. The H particle, the simplest of these proposed objects, has the same quantum numbers as a pair of lambda particles in the hypernuclear ground state. Does matter containing u, d and s quarks exist as hypernuclei or as H particles and strangelets?

The lambda is the lightest strange baryon, so that in nuclei, in the conventional picture, strange quarks appear in lambda particles. In general, other hyperons will convert to lambda particles in the nuclear medium so that Σ or Ξ hypernuclear states will have widths typical of the strong interaction. Hypernuclei containing a single lambda particle, on the other hand, have lifetimes of approximately 100 ps. Their states have been studied in many experiments and some gamma ray transitions observed.

Two units of strangeness may exist in a nucleus in the form of a pair of lambda particles or a Ξ particle. If H particles exist, H hypernuclei must also be considered. In the conventional picture, hypernuclei containing two lambda particles are the ground state of matter for S=-2.

There are three reported observations[4] of hypernuclei containing two lambda particles. Each experiment observed a single event in a photographic emulsion. Each event was initiated by the capture of a stopped Ξ^-. Table 1 lists these events along with the K^- flux to which the emulsion was exposed and the number of stopping Ξ^- generated. Clearly the present data is insufficient to answer most important questions. The expected flux and yield of a planned AGS experiment which will be discussed latter in the paper will be two orders of magnitude higher than the last experiment in the table.

There are several possible experimental approaches to detecting double hypernuclei in counter experiments:

1. Missing mass in the formation reaction.
2. Characteristic gamma rays.
3. Observing the decay pion recoiling against the single hyperfragment as for example in ${}_{\Lambda\Lambda}^{5}H \rightarrow \pi^- + {}_{\Lambda}^{5}He$.

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An Experiment to Detect Double Hypernuclei

An experiment[1] is being planned at the AGS to search for double hypernuclei and study their properties. The experiment will utilize an existing beam and spectrometer. It will provide an initial survey of several types of double hypernuclear experiments and could serve as a basis for designing future dedicated facilities and experiments. It will be discussed here in that context.

By using a K^- beam incident on a polyethylene (CH_2) target, several experiments can be performed at once. $\Lambda\Lambda$ hypernuclei may be produced directly through interactions with carbon nuclei; Ξ hypernucei will be formed with cross sections estimated to be several orders of magnitude greater; free Ξ^- particles will be produced on protons.

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

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

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

A K^- beam with a flux 2.8 10^6 K^- per pulse and very good purity is operating at the AGS; The K^- and K^+ identity are established using a combination of time of flight and Cerenkov counter information; Their momenta and directions are measured in magnetic spectrometers. The resolution of the present K^+ spectrometer may not be sufficient to pick out individual states. However, since the energy required to remove a lambda from ${}^{12}_{\Lambda\Lambda}Be$ is 15 Mev, the resolution is sufficient to select the bound $\Lambda\Lambda$ hypernuclear region. Design of a better resolution spectrometer for $\Lambda\Lambda$ hypernuclei is discussed later in the paper.

$\Lambda\Lambda$ hypernuclei will also be formed by the capture of Ξ^- by nuclei. The target configuration is shown in Figure 1. This a single cell in a repeated structure. The free Ξ^- are stopped in the ${}^6Li$ target

$$\Xi^- + {}^6Li \rightarrow {}^{6}_{\Lambda\Lambda}He + n$$

The identity and momentum of the Ξ^- is inferred from observation of the K^- and K^+. The Ξ^- entrance point to a tungsten degrader W is measured by a position sensitive detector D. Pulse height in a silicon pad detector Si following the tungsten identifies a slow Ξ^- which then stops in the ${}^6Li$ hydride. A Ξ^- ${}^6Li$ atom is formed and eventually the Ξ^- is captured by the nucleus. The branching ratio for forming ${}^{6}_{\Lambda\Lambda}He$ has been calculated[5] to be 5%. Neutrons are detected in a large array of plastic scintillators. Their energy is measured by time of flight. Figure 2 shows the expected neutron spectrum due to Ξ^- capture on ^{6}Li. A monoenergetic neutron of approximately 30 MeV signals the formation of ${}^{6}_{\Lambda\Lambda}$He. The continuum is due to the competing reactions which form free lambda particles. Because of its short lifetime, many Ξ^- decay before stopping. These decays result in π^- which stop in nearby material producing the major source of neutron background.

The decays of $\Lambda\Lambda$ hypernuclei are of great interest. Just as in single hypernuclei, the free decay modes are suppressed by Pauli blocking and new decay modes due to the weak interaction of the lambda with protons or neutrons appear. In $\Lambda\Lambda$ hypernuclei, the weak interaction between two lambda particles will occur, for example through the decay mode[7] $\Lambda\Lambda \rightarrow \Sigma^- + p$. The rate of this unusual mode measures how H-like the two lambda particles are.

If the H particle exists, two lambdas in a hypernucleus may fuse to produce it; the H particle will then decay with its own lifetime which has been calculated[6] to be long compared to the lambda lifetime in some cases. For this and other reasons it is important to measure hypernuclear lifetimes and delayed particle emission. The planned experiment will give an initial look at some of these issues.

Gamma-ray Transitions in $\Lambda\Lambda$ Hypernuclei

In the absence of a bound H particle, gamma transitions to the $\Lambda\Lambda$ hypernuclear ground state will precede the weak decay of the hypernucleus. Although the energies of these transitions can only be approximately estimated, they may serve as a signature that a double hypernucleus has been formed. The presence of the second lambda raises the threshold for particle emission; a double hypernucleus can thus emit gamma rays of higher energy than the corresponding nucleus or single hypernucleus. Particular gamma-ray transitions will have energies above those in the nuclear or single hypernuclear backgrounds.

As has proved to be the case for single hypernuclei, it is convenient to consider separately the excitations of the lambda particle and of the nuclear core. For single hypernuclei, gamma rays have been observed due to core states which would be particle unstable in the absence of the lambda. In $\Lambda\Lambda$ hypernuclei, more highly excited core transitions will be particle stable[8].

In light single hypernuclei approximately 10 MeV is required to elevate a lambda to a p state. Gamma rays due to the $p_\Lambda \rightarrow s_\Lambda$ transition of the lambda particle have been observed for the first time in a recent experiment [9]. The corresponding transition in $\Lambda\Lambda$ hypernuclei is $s_\Lambda p_\Lambda \rightarrow s_\Lambda s_\Lambda$. In the special case of ${}^{14}_{\Lambda\Lambda}C$, the p state for lambdas lies below the threshold for particle emission and this gamma transition is expected to occur[5].

Requirements for Future Experiments

Higher intensity K^- beams are an obvious requirement. Full operation of the booster ring and construction of the proposed stretcher ring could bring almost an order of magnitude increase in beam at the AGS. A high intensity hadron facility would further expand the range of possible experiments.

New facilities should include:

1. A K^+ spectrometer designed to study S=-2 hypernuclei.
2. A detector for decay products of $\Lambda\Lambda$ hypernuclei covering as large a solid angle as possible.
3. A 4π detector for $\Lambda\Lambda$ hypernuclear gamma rays.

The design of a K^+ spectrometer to study S=-2 hypernuclei is determined by the following considerations:

The peak of the Ξ^- production cross section is at 1.8 Gev/c. Therefore, this is likely to be the most favorable beam momentum. $\Lambda\Lambda$ hypernuclear ground states determine the highest K^+ momentum required. Assuming a 1.8 Gev/c beam, the highest K^+ momentum for light targets is 1.4 Gev/c. For heavy targets, the binding energy of the two lambda particles is considerable and K^+ momentum up to 1.5 Gev/c is required. Ξ hypernuclei appear at lower K^+ momenta. An 10% $\Delta p/p$ momentum range would cover both Ξ and $\Lambda\Lambda$ hypernuclei in the same spectrometer setting.

The solid angle should be as large as possible given the small expected cross sections for some of the interesting states; 100 msr or more is desirable. A spectrometer resolution of 1 Mev is well matched to the minimum target thickness that gives reasonable counting rate and should be sufficient to resolve many of the states produced

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Table 1

$\Lambda\Lambda$ Hypernuclei Experiments

	N_{K^-}	Ξ^- stop	Events
1963 M. Danysz et al.	10^5	3	1
1965 D.J. Prowse	10^6	30	1
1991 S. Aoki et al.	10^9	300	1

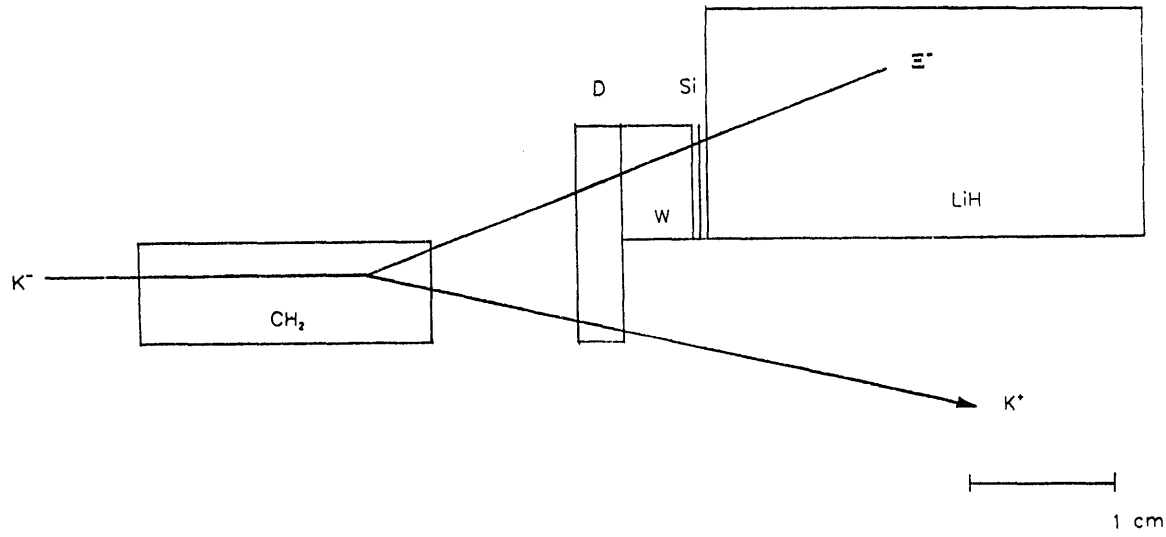

Figure 1: Target configuration. K^- beam strikes a CH_2 target producing double hypernuclei through interactions with carbon and Ξ^- through interactions with protons. K^- and K^+ momenta are measured in magnetic spectrometers. $\Lambda\Lambda$ and Ξ hypernuclei and free Ξ^- production will appear as peaks in missing mass. The free Ξ^- are brought to rest using a tungsten degrader W; their capture on ^6Li can also produce $\Lambda\Lambda$ hypernuclei as described in the text. Position sensitive detector D and silicon pad detector Si track the Ξ^- and measure dE/dx.

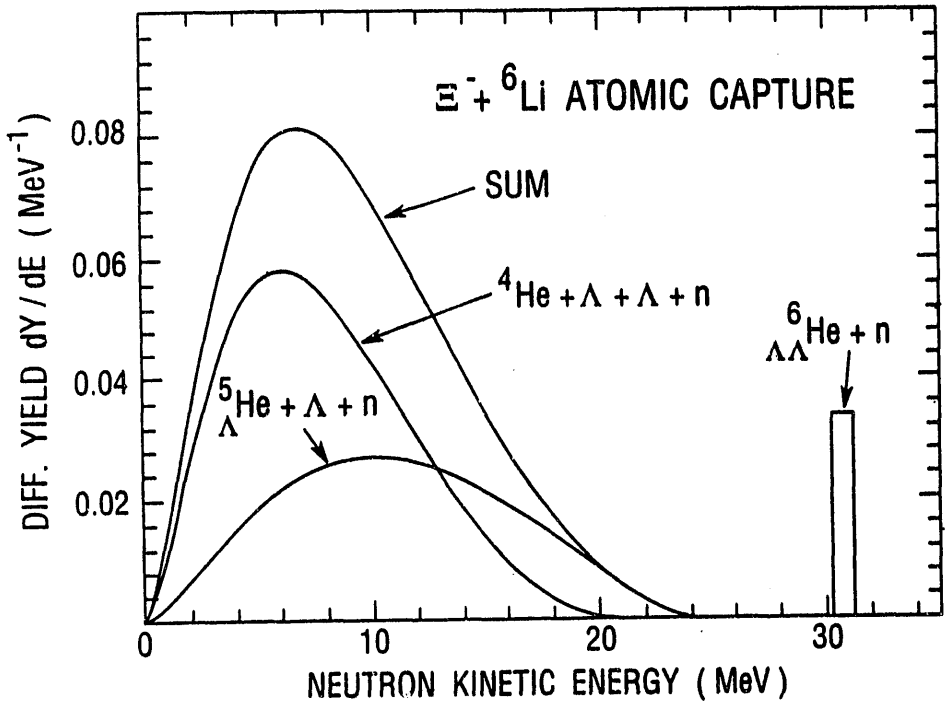

Figure 2: Calculated[5] differential yield as a function of outgoing neutron kinetic energy for $\Xi^- + {}^6Li$.

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