Search for the H-Dibaryon in $^3\mathrm{He}(K^-, K^+)Hn$

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A high-sensitivity search for the strangeness $S = -2$ H dibaryon $(uuddss)$ was conducted at the Brookhaven Alternating Gradient Synchrotron (AGS) using the reaction $^3\mathrm{He}(K^-, K^+)Hn$ at $P_{K^-} = 1.8$ GeV$/c$. The sensitivity was independent of H lifetime and decay modes. No evidence for H production was observed. In a mass range extending from about 50 to 380 MeV$/c^2$ below the $\Lambda\Lambda$ threshold of 2.231 GeV$/c^2$, the resulting upper limits on the H-production cross section are in the range of 0.058 to 0.021 μb/sr, approximately 1 order of magnitude below a theoretical calculation. [S0031-9007(97)03048-2]

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While QCD is the presently accepted theory of the strong interaction, its applications in the nonperturbative regime are clearly limited. One striking example of this is the difficulty in calculating the hadronic mass spectrum from fundamental principles of the theory. These difficulties have led to many QCD-inspired models such as the MIT bag model or quark potential models. Apart from the spectroscopy of standard $(qqq, q\overline{q})$ hadrons, the search for nonstandard hadrons has long been viewed as fundamentally important. These nonstandard hadrons ("exotics") contain more than the minimal number of quarks, and their properties derive from quark configurations rather than from being "hadronic molecules," like the deuteron.

Within the spectrum of six-quark (or dibaryon) states, the strangeness $S = -2$ sector plays a special role. Indeed, among light candidate dibaryons, only a six-quark system containing $(uuddss)$ quarks can exist in an SU(3)-flavor singlet, a configuration which takes maximum advantage of the color-magnetic attraction. It is possible that such a six-quark system might be *stable* with respect to strong decay into all baryon-baryon channels (the lowest being $\Lambda\Lambda$ in the $S = -2$ sector). This was first noted by Jaffe [1], who predicted this $(uuddss)$ state with $J^P = 0^+, I = 0$, called the H particle, to have a mass some 80 MeV$/c^2$ below the $\Lambda\Lambda$ threshold of 2.231 GeV$/c^2$ (60 MeV$/c^2$ below the MIT bag-model prediction for the $\Lambda\Lambda$ mass, $m_{\Lambda\Lambda} = 2.210$ GeV$/c^2$). Since Jaffe's bag-model prediction, many other calculations of the H mass using many different models have appeared [2]. These give a very wide range of predicted H masses, from much more deeply bound than in Jaffe's prediction to unbound relative to the $\Lambda\Lambda$ threshold. Although H-mass calculations are model dependent, the H does *not* appear to be an artifact of the bag model. Increased binding comes from the color-magnetic interaction, which gives the strongest attraction for the most symmetric color-spin representation, corresponding to the most antisymmetric SU(3)-flavor singlet representation. The significance of this symmetric color-spin representation and quark combination is inherent in QCD, hence the H appears in many different models.

Independent of calculational details, one expects that an object with the quantum numbers of the H is the most likely candidate for a stable six-quark bag state. The theoretical uncertainties in the mass and lifetime of the H are substantial, and its existence or nonexistence clearly has to be settled by experiment. An ideal H-search experiment needs to satisfy the following criteria: good sensitivity over as wide a range in H mass as possible, no dependence on the (unknown) lifetime or the decay modes of the H, and the possibility of a direct comparison with theory in order to gauge the experimental sensitivity.

Experiment E836 was designed to satisfy as many of these criteria as possible. It was performed in 1994 at the Brookhaven Alternating Gradient Synchrotron (AGS) D6 line using a separated high-intensity 1.8 GeV/c K^- beam [3] (average K^-/π^- ratio of 1.3 and, on average, 1.4×10^6 K^- per spill; total K^- flux, 3.0×10^{11}) and a 20 cm long liquid ^{3}He target to search for the reaction $^3\mathrm{He}(K^-, K^+)Hn$. Effectively the two protons in ^{3}He are converted into an H by the (K^-, K^+) reaction with the neutron assumed to be a spectator. This reaction is particularly appealing since ^{3}He is a light nucleus with a well-known wave function and two detailed theoretical calculations exist [4,5]. Although previous experiments, in particular KEK experiment E224 [6], have searched for the H in (K^-, K^+) reactions, E836 is the only experiment for which there exists a theoretical calculation which is directly applicable and thus allows, for the first time, a direct comparison between experiment and theory.

For each event, the K^- was momentum analyzed in the final stage of the beam line, and the K^+ was detected at small forward angles in a large-aperture dipole spectrometer (see Fig. 1). Particle identification for incoming and outgoing particles, i.e., separation of pions, kaons, and protons, was accomplished using several complementary techniques. On-line π-K separation for the first-level trigger was achieved via four aerogel Čerenkov detectors (IC1,IC2: $n = 1.03$, active area 10 cm $\times$ 5 cm, typical efficiency of 99%; FC: $n = 1.04$, 25 cm $\times$ 25 cm, 98%; BC: $n = 1.04$, 126 cm $\times$ 189 cm, 98%). A higher index aerogel Čerenkov detector (FC0: $n = 1.12$, 13 cm $\times$ 15 cm) was used for positive kaon registration and simultaneous proton rejection. A high-resolution time-of-flight system, consisting of four vertical scintillators (IT: 3 cm high, 2.5 cm wide) upstream of the target and forty horizontal scintillator bars (BT: 2 m wide, 8.5 cm high; intrinsic time resolution $\sigma = 110$ ps) located $\sim$8 m downstream of the target, was also used for particle identification [7]. The relatively large number of outgoing protons surviving the first-level trigger was further reduced by a second-level trigger which combined trajectory information from the drift chambers in the K^+ spectrometer with the time of flight. Particle masses were determined from momentum and time of flight. The setup is described in more detail in Ref. [8].

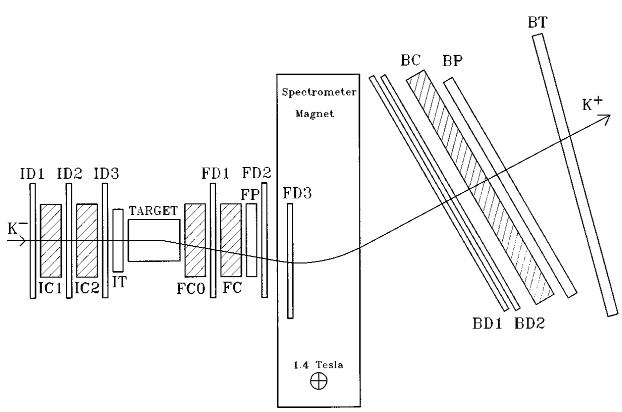

FIG. 1. Side view of the E836 detector setup (not to scale; ID1-target distance $\approx$1 m, target-BT distance $\approx$8 m). ID1–3, FD1–3, and BD1–2 are drift chambers for tracking and momentum measurement. IT, FP, BP, and BT are plastic scintillator hodoscopes for triggering and timing. IC1–2, FC0, FC, and BC are aerogel Čerenkov detectors.

As pointed out by Aerts and Dover [4], a relatively deeply bound H will manifest itself as a well-separated, narrow peak in the K^+ momentum spectrum above the region of quasifree Ξ^- production ($K^-\,{}^3\mathrm{He} \to K^+\Xi^- pn$). Therefore, our main thrust was a search for such a structure beyond the end point of the quasifree region. Excellent particle identification, especially π/K separation, was necessary because both incoming π^- (via $\pi^- p \to \Sigma^- K^+$) and outgoing π^+ (via $K^- p \to \Sigma^- \pi^+$) can produce events beyond the Ξ^- quasifree end point, which, if misidentified, appear as (K^-, K^+) events. Therefore, the responses of our time-of-flight system and of the Čerenkov detectors were monitored in great detail. For instance, during the off-line analysis a timing alignment using secondary kaons was performed detector-to-detector and run-to-run. Also, the efficiencies of the Čerenkov detectors for π, K, and p were measured as a function of momentum in dedicated runs. Combining these efficiencies with the K^+ spectrometer solid angle $\Delta\Omega \approx 0.04$ sr and a correction for K^+ decays results in an overall acceptance which remains flat down to $\approx$1.92 GeV/c^2. Below about 1.92 GeV/c^2, a correction is applied for the vetoing of valid events through the possibility of unintentional detection of kaons by the pion veto counters, FC and BC, and the acceptance drops by about 20% at 1.85 GeV/c^2. The absolute yield was deduced by comparing the observed quasifree yield (corrected for geometric acceptance, K^+ decays, and Čerenkov detector efficiencies) with the quasifree Ξ^- production cross section for which we used 56 μb/sr. This value results from a fit of measured cross sections of the (K^-, K^+) reaction on nuclear targets at an incident K^- momentum of 1.65 GeV/c (angle averaged between 1.7° and 13.6°) [9]. The same reference gives a cross section of about 37 μb/sr for free Ξ^- production off the proton and our resulting yield is consistent with this value. The tail of the quasifree Ξ^- production distribution limits the sensitivity of this experiment for a lightly bound H, i.e., near $\Lambda\Lambda$ threshold. This tail is influenced by the momentum resolution of the K^+ spectrometer, which was measured using free Ξ^- production off hydrogen from $p(K^-, K^+)\Xi^-$ (C and CH_2 targets), resulting in a missing-mass resolution of 16 MeV/c^2 (FWHM). The position of the free Ξ^- production peak was used for the calibration of the missing-mass spectrum (see Stotzer in Ref. [8]).

The most important criteria imposed on the data during off-line analysis consisted of a cleanly reconstructed track through both the final stage of the beam line and the K^+ spectrometer, cuts on reconstructed kaon mass, Čerenkov counter pulse height cuts to reject pions and protons, and a fiducial volume cut on the ^{3}He target vessel. This last cut was determined using target-empty data. The resulting measured secondary momentum spectrum of the outgoing K^+ contains 6183 events and is shown in Fig. 2 (top). It is dominated by the above-mentioned quasifree Ξ^- production. H production would result in a peak at higher momentum than this quasifree peak. No clear signal for H production is seen. The few remaining background events may be misidentified pions or protons. The bottom of Fig. 2 shows the same events as a function of missing mass assuming a (K^-, K^+) reaction. This missing mass was calculated under the assumption that the neutron is a spectator and thus by taking the target mass to be $m_{^3\mathrm{He}} - m_n$, i.e., the pp pair in ^{3}He minus the binding energy of ^{3}He. This procedure was verified by reproducing the calculation of Ref. [4] with a Monte Carlo simulation. Figure 3 shows an expanded view of the missing-mass range (equivalent to H-mass range) over which this experiment was sensitive to H production. Also shown is an example of the expected peak for H-particle formation (assumed $m_H = 2.130$ GeV/c^2) in the model of Aerts and Dover [4], with our experimental missing-mass resolution, geometric acceptance, K^+ decays, and Čerenkov detector efficiencies folded in. One input into the Aerts and Dover calculation is a parametrization of the free Ξ^- production cross sections for the $K^- p \to K^+ \Xi^-$ reaction as a function of K^- momentum. Their parametrization gives a cross section of about 50 $\mu\mathrm{b/sr}$ for free Ξ^- production (p_{K^-} of 1.65 GeV/c, angle averaged between 0° and 18°) off the proton, whereas the value from Ref. [9] is about 37 $\mu\mathrm{b/sr}$. This leads, in the original Aerts and Dover calculation, to a cross section for H production which is too high by a factor of about 1.35. The H-production cross section by Aerts and Dover was calculated for a K^+ angle of 0°, whereas our data represent an angle average over 2° to 14°.

Since no evidence for the H was seen, we proceeded to obtain upper limits on H production from the data of Fig. 3. The spectrum was analyzed from 1.85 up to 2.25 GeV/c^2 assuming a Poisson distributed H signal on top of a Poisson distributed background, using the method described in [10]. The width and shape of the H signal were derived from the Aerts and Dover calculation folded with our experimental resolution. Since we have no *a priori* knowledge of the shape of the background, we assume it, for simplicity, to be flat, with a magnitude equal to the average of the observed number of counts per bin in the region from 1.85 to 2.20 GeV/c^2 excluding the H peak. The mean of the background under the H peak is given by the average number of counts per

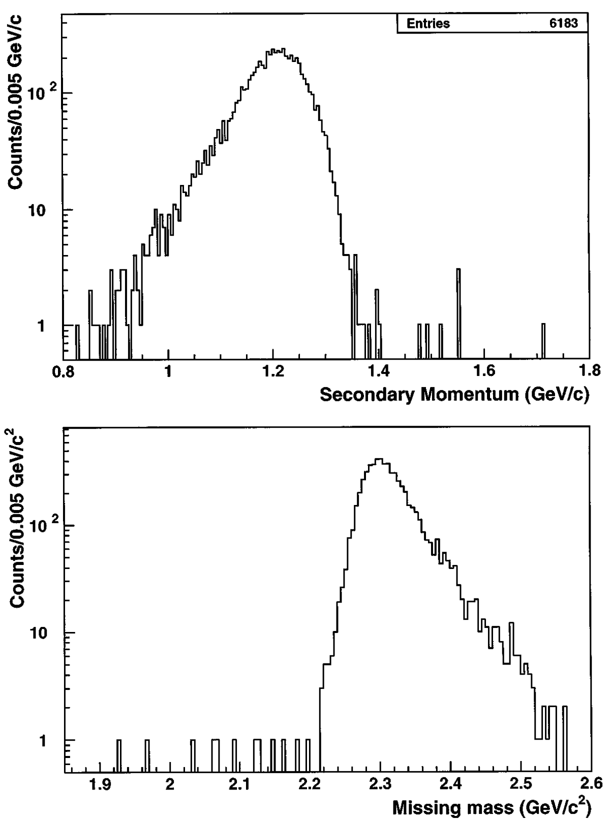

FIG. 2. Measured secondary momentum spectrum of the outgoing K^+ (top) and corresponding missing-mass spectrum (bottom). See text for explanation of the mass scale.

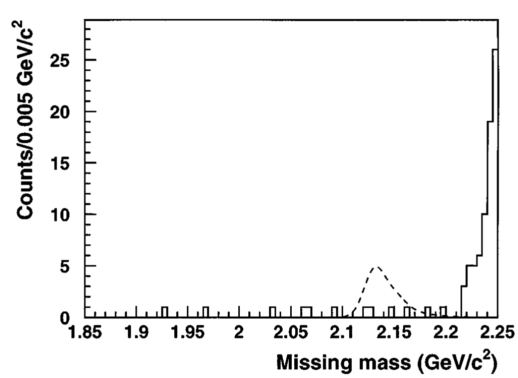

FIG. 3. Expanded view of the missing-mass range with an example of an expected H peak (assumed $m_H = 2.130$ GeV/c^2) in the model of Aerts and Dover (dashed line).

bin summed over the bins covered by the H signal. For each H mass the probability was then calculated, as a function of the number of H-particle events, that the measured spectrum could result from such a peak and background. The resulting 90% C.L. upper limits are shown in Fig. 4 as a function of H mass, again corrected as described above. For comparison, Fig. 4 also shows the theoretically predicted H-production cross section in the Aerts and Dover [4] model (dotted line), in which the short-range correlations in the ^{3}He wave function are neglected. In addition, the dashed line shows the Aerts and Dover calculation, lowered by a factor of 1.35, as described above. Our experimental results should be compared with this modified theoretical prediction only. In their calculation, Aerts and Dover derive the amplitude for $K^- p \rightarrow K^+ \Xi^-$ using a parametrization of experimental, that is, on-shell cross sections. This method cannot be readily extended into the region of a very tightly bound H (below about 2.05 GeV/c^2) since the extrapolation of the off-shell amplitude from the measured on-shell amplitude is no longer justified. For an H mass below 2.180 GeV/c^2, the resulting upper limits on the H-production cross section are in the range of 0.021 to 0.058 μb/sr, approximately 1 order of magnitude below the theoretical calculation.

Several other H-particle search results have recently appeared in the literature. In contrast to this experiment, the results from Brookhaven experiments E810 [11] and E888 [12] depended on H-decay modes and lifetimes. KEK experiment E224 used the same (K^-, K^+) reaction on a scintillating fiber target [6]. Because of the different target, the Aerts and Dover calculation could not be used for a direct comparison. Instead, assumptions had to be made about the number of $^1S_0$ proton pairs in ^{12}C and about the absorption of K^- and K^+ in ^{12}C. Our approach is free from these additional assumptions and estimates.

In conclusion, we have reported upper limits on H-dibaryon production in $^3\mathrm{He}(K^-, K^+)Hn$, covering several hundred MeV binding energies. Over much of this binding-energy range, our limits remain approximately 1 order of magnitude below a theoretical prediction which was directly applicable to the above reaction without any further assumptions. For the first time, all of these high-sensitivity features could be combined in a direct production experiment without any reliance on H-decay properties.

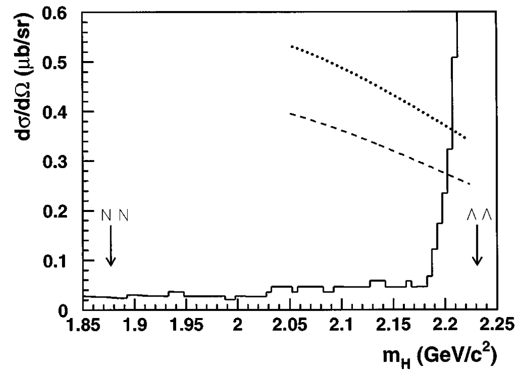

FIG. 4. 90% C.L. upper limit on H production (solid line) compared with the original Aerts and Dover prediction (dotted line) and the modified prediction described in the text (dashed line). The arrows indicate the NN position and the $\Lambda\Lambda$ threshold.

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