Search for the Weak Decay of an *H* Dibaryon

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We have searched for a neutral H dibaryon decaying via $H \to \Lambda n$ and $H \to \Sigma^0 n$. Our search has yielded two candidate events from which we set an upper limit on the H production cross section. Normalizing to the inclusive Λ production cross section, we find $(d\sigma_H/d\Omega)/(d\sigma_\Lambda/d\Omega) < 6.3 \times 10^{-6}$ at 90% C.L., for an H of mass ≈ 2.15 GeV/c^2. [S0031-9007(96)00050-6]

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The theory of quantum chromodynamics imposes no specific limitation on the number of quarks composing hadrons other than that they form color singlet states. Although only qqq and $q\bar{q}$ states have been observed, other combinations can form color singlets. Jaffe [1] has proposed that a six-quark state *uuddss* may have sufficient color-magnetic binding to be stable against strong decay. Such a state, which Jaffe named H, would decay weakly, and the resultant long lifetime would allow the possibility of observing such particles in neutral beams. Theoretical estimates [2] of m_H have varied widely, ranging from a deeply bound state with $m_H < 2.10$ GeV/c^2 to a slightly unbound state with m_H near the $\Lambda\Lambda$ threshold, 2.23 GeV/c^2. In this mass range the H would decay almost exclusively to Λn, $\Sigma^0 n$, and $\Sigma^- p$ [3]. Several previous experiments have searched for H's but with no compelling success [4]. The search described here is sensitive to H's having mass and lifetime in a previously unexplored range.

We have searched for $H \to \Lambda n$ and $H \to \Sigma^0 n \to \Lambda\gamma n$ decays by looking in a neutral beam for $\Lambda \to p\pi^-$ decays in which the Λ momentum vector does not point back to the production target. The experiment, E888, was performed in the B5 beam line of the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory. A second phase of the experiment searched for long-lived H's by using a diffractive dissociation technique [5]. The detector used for the decay search (Fig. 1) was essentially that used for the E791 rare kaon decay experiment and has been described in detail elsewhere [6]. In brief, a neutral beam was produced using the 24 GeV/c proton beam from the AGS incident on a 1.4 interaction length Cu target. The targeting angle was 48 mrad. After passing through a series of collimators and two successive sweeping magnets, the neutral beam entered a 10 m long vacuum decay tank within which candidate Λ's decayed. Downstream of the tank was a two arm spectrometer consisting of two magnets with approximately equal and opposite p_T impulses and 5 drift chamber (DC) stations located before, after, and in between the magnets. Downstream of the spectrometer on each side

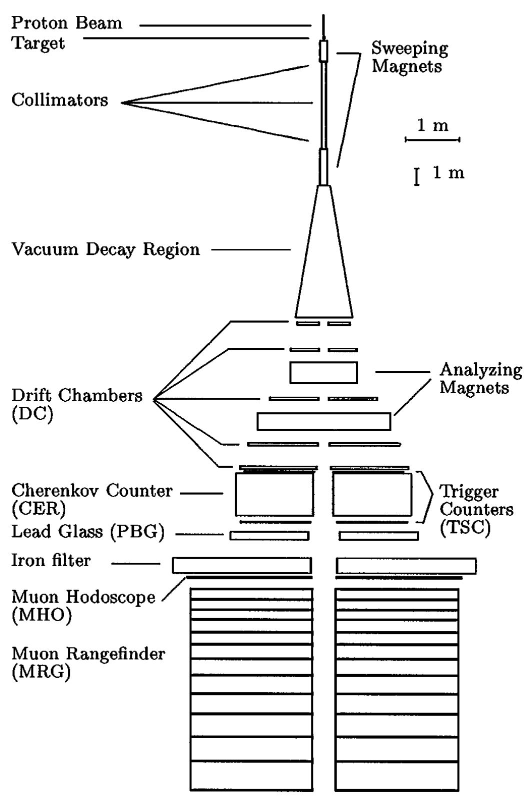

FIG. 1. The E888 detector and beam line.

of the beam were a pair of trigger scintillator hodoscopes (TSCs), a threshold Cherenkov counter (CER), a lead-glass array (PbG), 0.91 m of iron to filter out hadrons, a muon-detecting hodoscope (MHO), and a muon range finder (MRG) consisting of marble and aluminum slabs interspersed with streamer tubes. For the first half of the run the Cherenkov counters were filled with a He-N mixture ($n = 1.000\,114$) to identify electrons; for the second half the left-side counter was filled with freon ($n = 1.0011$) to identify protons from $\Lambda \rightarrow p\pi^-$ (due to *lack* of light). Only the left counter was used for this purpose as the soft pion from $\Lambda \rightarrow p\pi^-$ decay is accepted only when on the right; when it is on the left, the first magnet bends it back across the beam line, and it is not reconstructed. The PbG array consisted of two layers: a layer of front blocks 3.3 radiation lengths (r.l.) deep and a layer of back blocks 10.5 r.l. deep. The PbG was used to identify electrons by comparing the total energy deposited ($E_{\rm tot}$) with the track's momentum. A minimum bias trigger was defined as a coincidence between all four TSC counters and signals from the three most upstream DC stations. A level 1 trigger (L1) was formed by putting minimum bias triggers in coincidence with veto signals from the Cherenkov counters and muon hodoscope. All events passing L1 were passed to a level 3 software trigger which used hit information from the first three DC stations to calculate an approximate two-body mass. Events with $m_{p\pi^-} < 1.131$ GeV$/c^2$ were written to tape.

Off-line, all events containing two opposite-sign tracks forming a loose vertex were kinematically fit [6] and subjected to the following cuts: there could be at most one extra track-associated hit or one missing hit in the ten DC planes which measure the x (bending) view of each track; the χ^2's per degree of freedom resulting from the track and vertex fits had to be of good quality; the Λ vertex had to be within the decay tank and downstream of the fringe field of the last sweeper magnet; both tracks had to be accepted by CER, PbG, MHO, and MRG detectors and have $p > 1$ GeV$/c$; neither track could intersect significant material such as the flange of the vacuum window; to reject background from $K_L^0 \rightarrow \pi^0\pi^+\pi^-$, $m_{\pi^+\pi^-}$ had to be $> m_{K_L} - m_{\pi^0}$; and to reject background from $K_S^0 \rightarrow \pi^+\pi^-$ resulting from secondary interactions, $|m_{\pi^+\pi^-} - m_{K_L}|$ had to be >4 times the mass resolution of $K_L^0 \rightarrow \pi^+\pi^-$ decays (1.55 MeV$/c^2$).

Events passing these cuts were subjected to particle identification criteria in order to reject background from $K_L^0 \rightarrow \pi e \bar{\nu}$ (K_{e3}) and $K_L^0 \rightarrow \pi \mu \bar{\nu}$ ($K_{\mu 3}$) decays. To reject electrons, we require that there be no track-associated Cherenkov hit and that tracks with $p > 2$ GeV$/c$ (<2 GeV$/c$) have $E_{\rm tot}/p < 0.60$ (<0.52). The low-momentum track on the right side of the detector was required to deposit $< 0.66E_{\rm tot}$ in the front PbG blocks. To reject muons which passed the MHO veto in the trigger, we cut events with a hit in the MRG which was consistent with the projection of a track and which corresponded to at least 65% of the expected range of a muon with that track's momentum.

Lambda candidates were selected by requiring that $|m_{p\pi^-} - m_\Lambda|$ be less than 4 times the mass resolution of $\Lambda \rightarrow p\pi^-$ decays (0.55 MeV$/c^2$). The data were then divided into two streams: a normalization stream consisting of Λ's which project back to the production target, and a signal stream consisting of Λ's which do not. The former were selected by requiring that the square of the collinearity angle θ_Λ be less than 1.5 mrad^2, where θ_Λ is the angle between the reconstructed Λ momentum vector and a line connecting the production target with the decay vertex. This sample contains negligible background. The signal sample was selected by requiring that $p_T > 145$ MeV$/c$, where p_T is the Λ momentum transverse to the line connecting the production target with the decay vertex. This cut value was chosen to eliminate $\Xi^0 \rightarrow \Lambda\pi^0$ decays, which have a kinematic end point of 135 MeV$/c$. The p_T distribution of Λ's from two-body $H \rightarrow \Lambda n$ decays exhibit an approximate Jacobian peak (not exact because the vertex is the Λ's) with an end point which depends upon m_H. A large fraction of high-p_T Λ's were found to project back to a collimator located just upstream of the decay tank. We thus required that the point in our beam line to which a Λ projects back be located downstream of this collimator: $z_{\rm proj} > 9.65$ m.

A signal region for H candidates was defined by the criteria $p_T > 174$ MeV$/c$ and $N_\tau > 5$, where N_τ is the distance in proper lifetimes between the decay vertex and the nearest material (beam-line element) to which the momentum vector projects back. The p_T cut rejects $K_{\ell 3}$ decays which survive the CER, PbG, MHO, and MRG vetoes due to detector inefficiency, while the N_τ cut rejects Λ's which originate from collimators, flanges, and other beam-line elements. All cuts were determined without looking at events in the signal region, in order that our final limit on H's be unbiased. After fixing cuts we looked in the signal region and observed two events. The estimated background is 0.15 event from Λ's originating from beam-line elements, and < 0.21 event from $K_{\ell 3}$ decays (all K_{e3} as the p_T is too high for $K_{\mu 3}$). The former is estimated by studying the N_τ distribution of Λ's originating from a "hot" flange located immediately upstream of 9.65 m. The latter is estimated by first counting the number of final events cut because the low-momentum track had $E_{\rm tot}/p > 0.7$ (these are electrons); this is then multiplied by the ratio of the number of electrons passing PbG analysis cuts to the number having $E_{\rm tot}/p > 0.7$, as determined from a sample of K_{e3} decays. The N_τ vs p_T plot for the final high-p_T Λ sample is shown in Fig. 2. In this figure the Cherenkov veto for the freon counter is not imposed. A band of $K_{\mu 3}$ decays is visible at $p_T \approx 150$ MeV$/c$ which results from the $p_T > 145$ MeV$/c$ cut and the $m_{\pi\pi} > m_{K_L} - m_{\pi^0}$ cut; this latter cut constrains p_T from above. Λ's which originate from beam-line elements are visible at low N_τ. For the freon subset, when we require that there

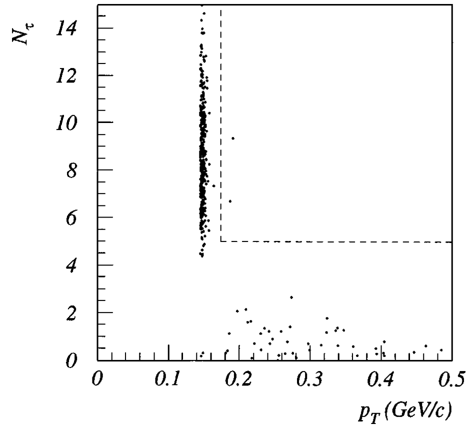

FIG. 2. N_τ vs p_T for the high-p_T Λ sample. The signal region is denoted by dashed lines. The band of events from $p_T = 145$ to $\approx$150 MeV/c are $K_{\mu 3}$ decays; the left-most edge is due to a p_T cut, while the right-most edge is due to a lower cut on $m_{\pi\pi}$.

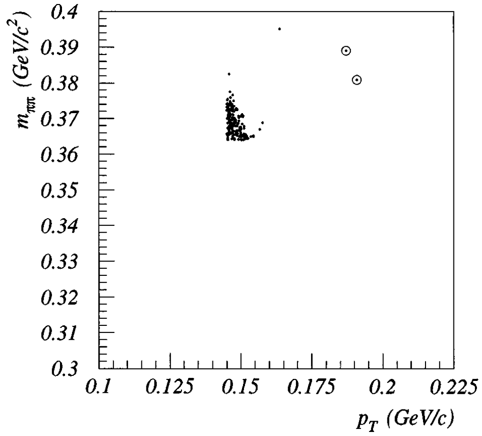

FIG. 3. $m_{\pi\pi}$ vs p_T for the final high-p_T Λ sample. The two events in the signal region are circled. The cluster of events at $p_T \approx 150$ GeV/c, $m_{\pi\pi} \approx 365$ GeV/c^2 are consistent with Monte Carlo simulated $K_{\mu 3}$ decays.

be no signal in the left Cherenkov counter, all but two $K_{\mu 3}$ decays are eliminated while all Λ's at low N_τ remain.

Also visible in Fig. 2 are our two candidates, which have p_T of 187 and 191 MeV/c and N_τ of 6.7 and 9.4. The p_T values correspond to a Jacobian peak from $H \rightarrow \Lambda n$ decay if $m_H \approx 2.09$ GeV/c^2. The probability for a $K_{\mu 3}$ decay to have such high p_T is extremely small, as it is kinematically forbidden for a $K_{\mu 3}$ decay to have both $m_{\pi\pi} > m_{K_L} - m_{\pi^0}$ and $p_T > 160$ MeV/c (Fig. 3). The probability for a K_{e3} decay to look like these events is also very small, as the PbG response for the electron candidate tracks is very uncharacteristic of electrons: $E_{\rm tot}/p = 0.44$ and 0.27, and for both events $E_{\rm front}/E_{\rm tot} = 0$ (Fig. 4). This response is typical of pions from $\Lambda \rightarrow p\pi^-$ decay. To investigate background from neutrons in the beam interacting with residual gas molecules in the decay tank, we recorded and analyzed a sample of data equivalent to 1% of the total sample with the decay tank vacuum spoiled by a factor 2.7×10^3. This sample yielded one event in the signal region, implying a background level in the rest of the data of 0.04 event. We also studied potential background from $\Xi^0 \rightarrow \Lambda\pi^0$ decays where the Ξ^0 originates from a beam-line element; from Monte Carlo simulation and the number of Λ's observed originating from beam-line elements, we estimate a background of less than 0.10 event. The total background estimate from known sources is less than 0.50 event. The probability of 0.50 event fluctuating up to two or more events is 0.090; if such a fluctuation occurred, it is remarkable that the p_T of the events is so similar.

A 90% C.L. upper limit on the H production cross section can be expressed in terms of the inclusive Λ production cross section as follows:

$$\frac{d\sigma_H}{d\Omega} < \frac{\xi}{N_\Lambda^{\rm targ}} \frac{A_\Lambda}{A_H} \frac{B(\Lambda \rightarrow p\pi^-)}{B(H \rightarrow \Lambda X)} \frac{d\sigma_\Lambda}{d\Omega}, \qquad (1)$$

where $N_\Lambda^{\rm targ} = 20\,433$ is the number of Λ's originating from the target, A_Λ and A_H are geometric acceptances for Λ's originating from the target and from H decays, respectively, $B(\Lambda \rightarrow p\pi^-)$ and $B(H \rightarrow \Lambda X)$ are branching ratios, $d\sigma_\Lambda/d\Omega$ is the inclusive Λ production cross section, and ξ is the factor which multiplies the single-event

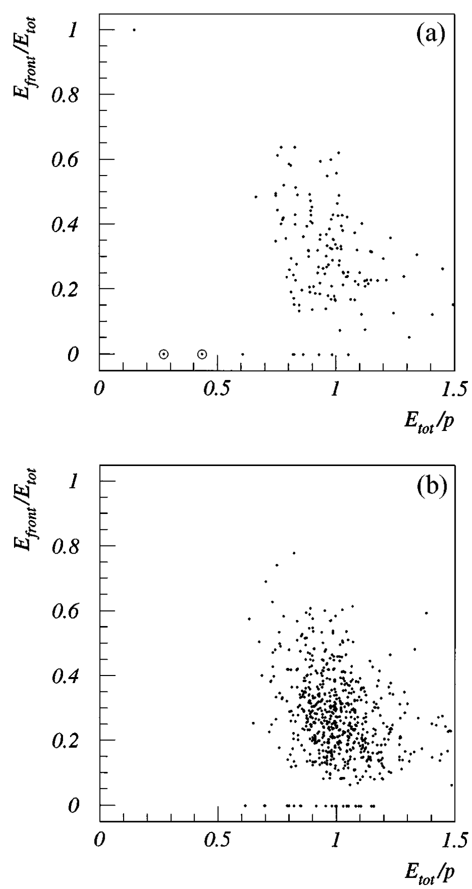

FIG. 4. $E_{\rm front}/E_{\rm tot}$ (PbG) vs $E_{\rm tot}/p$ for (a) the low-momentum track of Λ's from the final high-p_T sample, and (b) low-momentum electrons from K_{e3} decay. In (a), the tracks from the two events in the signal region are circled. There are 4.7 times as many events in (b) as in (a).

sensitivity to give the value of $d\sigma_H/d\Omega$ which has a 10% chance of producing ≤ 2 detected events. Here we conservatively assume no background and take $\xi = 5.32$. The acceptance A_H accounts for the fact that Λ's from H's must project back to a restricted region of the beam line. Since $\Lambda \rightarrow p\pi^-$ decays are common to both signal and normalization channels, all trigger and detection efficiencies divide out of Eq. (1).

The acceptances A_Λ and A_H were determined from Monte Carlo simulation using several different estimates of the production momentum spectra. For the H simulation, a central production spectrum was used with a broad peak at $x_F = 0$. A spectrum corresponding to a $\Lambda\Lambda$ coalescence model for H production [7] resulted in a limit on $d\sigma_H/d\Omega$ about 50% lower. We quote here the more conservative limit resulting from the central production spectrum. The inclusive Λ production spectrum was taken from a measurement by Abe *et al.* [8]; comparison with our data shows very good agreement.

The acceptance A_H also depends crucially on the H lifetime and branching fractions. Here we assume the relationship between these quantities and m_H calculated in Ref. [3], and obtain 90% C.L. upper limits on $(d\sigma_H/d\Omega)/(d\sigma_\Lambda/d\Omega)$ as a function of m_H. Our acceptance is maximum for $\tau_H \approx 8$ ns and becomes small for $\tau_H \lesssim 1$ ns due to the $z_{\text{proj}} > 9.65$ m cut. Our limits for $(d\sigma_H/d\Omega)/(d\sigma_\Lambda/d\Omega)$ are plotted in Fig. 5. For $m_H \approx 2.15$ GeV/c^2, Jaffe's original prediction,

$$\left.\frac{d\sigma_H}{d\Omega}\right|_{48\,\text{mrad}} < (6.3 \times 10^{-6}) \left.\frac{d\sigma_\Lambda}{d\Omega}\right|_{48\,\text{mrad}} (90\%\ \text{C.L.})\,. \tag{2}$$

From Abe *et al.* [8], $d\sigma_\Lambda/d\Omega|_{48\,\text{mrad}} = 366$ mb/sr, so $d\sigma_H/d\Omega|_{48\,\text{mrad}} < 2.3$ μb/sr. For $m_H = 2.09$ GeV/c^2, consistent with the observed Λ p_T, the acceptance is lower and the two candidate events correspond to a differential cross section of 44^{+58}_{-28} μb/sr. The authors of Ref. [3] note that τ_H may be shorter than their predicted value by up to a factor of 2; this would increase our acceptance for $m_H \lesssim 2.18$ GeV/c^2 and decrease our acceptance for m_H greater than this value. The resultant 90% C.L. upper limits are plotted as the dashed contour in Fig. 5. If we assume that the invariant cross section $E\,d^3\sigma/dp^3$ has the form $A(1 - |x|)^B e^{-Cp_T^2}$, then our limit (2) corresponds to $\sigma_H < 60$ nb for a wide range of values for B and C.

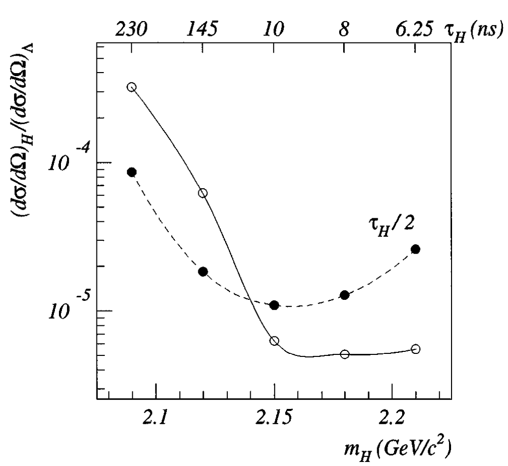

FIG. 5. 90% C.L. upper limits on the H production cross section vs m_H or τ_H (see Ref. [3]). The dashed contour corresponds to an H lifetime half that given on the top scale.

There are few theoretical predictions of the H production cross section. Cousins and Klein [7] predict a differential cross section of ~ 100 μb/sr for p-Cu interactions at our targeting angle based on a $\Lambda\Lambda$ coalescence model. Cole *et al.* [9] consider $\Lambda\Lambda$ and $\Xi^0 n$ coalescence and predict $\sigma_{\text{tot}} \approx (3 \times 10^{-5})\sigma_{\text{inelas}}$ for p-Cu collisions at AGS energies; taking $\sigma_{\text{inelas}} \approx 780$ mb [10] gives $\sigma_{\text{tot}} \approx 23$ μb. Rotondo [11] considers only $\Xi^0 n$ coalescence at FNAL energies and predicts $\sigma_{\text{tot}} \approx 1.2$ μb.

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