lem is negligible. A purely energetic definition of a hydrogen bond becomes unphysical at weak V_{HB}, because then electrostatic dipolar interactions with more distant interaction partners have the same magnitude as weak nearest-neighbor interactions. To take these difficulties into account, we also analyzed the tape by eliminating from the list of directly bonded partners of molecule i all molecules j whose separation $|r_i - r_j|$ exceeds 3.5 Å. We found only minor differences between the two approaches.

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[9]In comparing the present calculations with small-angle x-ray experiments, one should keep in mind that (i) the "electronic" R_G is presumably larger than our R_G (e.g., our R_G is zero for clusters $s = 1$) and (ii) contributions from the spanning clusters are not included in our calculations. Thus we would expect that the characteristic length scale obtained experimentally would be somewhat larger than that we have calculated.

[10]We have also calculated the Guinier function for clusters of four-bonded molecules, and found, for $n_{HB} > 2$, a strong increase as q decreases below 0.5 Å^{-1}; perhaps coincidentally, data for $S(q)$ display a minimum at roughly 0.5 Å^{-1} for $T = 253$ K.

(K^-, K^+) Reaction and the Dibaryon H

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Cross sections for the reaction $^3\mathrm{He}(K^-, K^+n)H$ are estimated. This process affords a promising way of producing the stable six-quark dibaryon H (0^+, $I = 0$, strangeness -2) predicted by the bag model.

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In the past few years, there has been intense interest in the spectroscopy of multiquark states. Beyond the simplest Q^3 baryon and $Q\overline{Q}$ meson configurations, numerous authors have speculated on the existence of long-lived multiquark systems such as the $Q^2\overline{Q}^2$ "baryonium" states,[1] $Q^4\overline{Q}$ baryons (the Z^* resonances,[2] for instance), and Q^6 dibaryon[3] configurations. The six-quark (Q^6) states which are predicted come with several values of strangeness S. For $S = 0$ and -1, one predicts a whole spectrum of Q^6 composites, all of which are unstable with respect to strong decay into, e.g., nucleon-nucleon or hyperon-nucleon channels. Thus to identify these objects experimentally, one must be able to disentangle the signature of a genuine multiquark state from enhancements[4] due, for example, to the opening up of new strong decay channels, such as $N\Delta$ and $\Delta\Delta$ for $S = 0$ and ΣN for $S = -1$. The experimental and theoretical situation on the existence of multiquark states remains unclear.

For $S = -2$, the situation for dibaryon states is somewhat different. In the bag model, an $S = -2$ particle (called the H) was predicted by Jaffe,[5] which is *stable* with respect to strong decay. The H, with $J^\pi = 0^+$ and isospin $I = 0$, has a calculated mass $m_H \approx 2150$ MeV, some 80 MeV below the $\Lambda\Lambda$ threshold in Ref. 5; a somewhat smaller binding was found by Aerts, Mulders, and deSwart.[6] The value for m_H is clearly model dependent. A recent evaluation by Liu and Wong,[7] which approximately includes center-of-mass corrections in the bag model, yields a mass for the H some 10 MeV *above* the $\Lambda\Lambda$ threshold. In any case, the H is the lowest-lying $S = -2$ dibaryon. Its configuration $(uuddss)_{0^+, I=0}$, with all six quarks in the $1s$ ground state, takes maximum advantage of the color-magnetic binding forces of quantum chromodynamics (the H is somewhat analogous to the α particle in nuclear physics, but containing *three* different types of constituents). The H could be formed by the fusion of two three-quark bags, corresponding to the $\Lambda\Lambda$, ΞN or $\Sigma\Sigma$ channels, without the need for any quarks to be promoted to higher orbitals in the composite system.

If the H is indeed stable, it is a unique object in multiquark ($n > 3$) physics, and warrants a high degree of experimental and theoretical attention. Its discovery would provide the first definitive example of an n-quark state with $n = 6$. A dibaryon with the quantum number of the H *cannot* be generated in ordinary potential models involving meson exchange: Using the SU(3) one-boson-exchange models of Nagels *et al.*,[8] we have verified that the $\Xi^- p$, $\Lambda\Lambda$, or $\Sigma\Sigma$ potentials are much too weak to generate any deeply bound states, or even any that are weakly bound, analogous to the deuteron. Thus the H, if it exists, is a unique prediction of the quark model.

An experiment to find the $\boldsymbol{H}$ in the reaction $p+p \to K^+ + K^+ + H$ has been conducted at Brookhaven National Laboratory by Carroll *et al.*[9] No evidence for the H was seen, but the cross-section upper limit of 40–50 nb for $2.1 < m_H < 2.23$ GeV is not very restrictive. In this Letter, we argue that the reaction ${}^3\mathrm{He}(K^-, K^+n)H$ represents a more promising way of forming the H, if it is stable. The reaction mechanism we envisage is shown in Fig. 1(a). The strangeness-exchange process $K^- p \to K^+ \Xi^-$ is followed by $\Xi^- p$ fusion to form the H. The quasielastic background is shown in Fig. 1(b). If one performs a "missing mass" experiment in which both the K^+ and the neutron are detected in coincidence, the H production will show up as a peak, which, if $m_H < 2m_\Lambda$, is distinct from the generally much larger quasielastic cross section.

To estimate the cross section for H production on a ^{3}He target, we need models for the two-body amplitude f for $K^- p \to K^+ \Xi^-$, the quark fusion vertex Γ, and the ^{3}He ground-state wave function. The $\theta_{K^+} = 0°$ two-body laboratory cross section

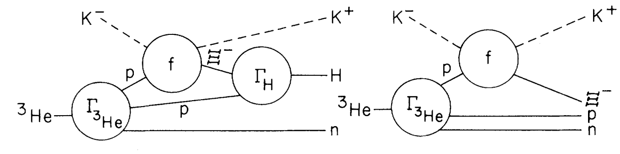

FIG. 1. (a) The mechanism considered here for H production in the reaction ${}^3\mathrm{He}(K^-, K^+n)H$. (b) One process contributing to the "quasielastic" background. Note that if the H lies below the $\Xi^- p$ and $\Lambda\Lambda$ thresholds, it will appear isolated from the background in an invariant-mass plot.

$|f|^2$ is strongly momentum dependent,[10] and peaks at about 55 μb/sr for $k_L \approx 1.8$–1.9 GeV/c; since the momentum transfer to the Ξ^- (≈ 350 MeV/c on ^{3}He) is essentially independent of k_L near the peak of $|f|^2$, this range of incident momentum is optimal for H production. We employ the on-shell approximation for f. For ^{3}He, we use the harmonic-oscillator approximation for the wave function, with oscillator parameter $b = 1.7$ fm (corrected for nucleon size effects and c.m. motion) to describe the dependence on relative coordinates. Short-range correlations are neglected; estimates indicate that their effect on $d\sigma/d\Omega(0°)$ is of the order of 10%–20%. Plane waves are used for the K^- as well as the final-state particles. For the vertex Γ, we use the wave-function overlap

$$\Gamma(\vec{k}_p, \vec{k}_\Xi) = \int d^3k_1 \cdots d^3k_6\, \psi_{H, \vec{k}_H}(\vec{k}_1, \ldots, \vec{k}_6)\psi_{p, \vec{k}_p}(\vec{k}_1, \vec{k}_2, \vec{k}_3)\psi_{\Xi^-, \vec{k}_\Xi}(\vec{k}_4, \vec{k}_5, \vec{k}_6), \tag{1}$$

where the $\vec{k}_i$ label the momenta of the quarks contained in the H, p, or Ξ^- particles. For the wave functions ψ, we use an oscillator approximation (as for ^{3}He) for N quarks confined to a bag of radius R:

$$\psi_{N, \vec{k}}(\vec{k}_1, \ldots, \vec{k}_N) = \delta^{(3)}(\vec{k} - \sum_{i=1}^{N} \vec{k}_i)\Phi_N, \quad \Phi_N = N^{3/4}(R^2/\pi)^{3(N-1)/4} \exp(-\tfrac{1}{2}R^2 \sum_{i=1}^{N-1} \bar{k}_i^{\,2}), \tag{2}$$

where $\{\bar{k}_i\}$ is an appropriate set of $N-1$ *relative* momenta and k is the total momentum. For Γ, we find

$$\Gamma(\vec{k}_p, \vec{k}_\Xi) = \Gamma_0 \left(\frac{2R_p R_H}{R_H^{\,2} + R_p^{\,2}}\right)^3 \left(\frac{2R_\Xi R_H}{R_H^{\,2} + R_\Xi^{\,2}}\right)^3 \exp\left(-\frac{R_H^{\,2}}{12}(\vec{k}_p - \vec{k}_\Xi)^2\right) \delta^{(3)}(\vec{k}_H - \vec{k}_p - \vec{k}_\Xi)\left(\frac{2R_H^{\,2}}{3\pi}\right)^{3/4}. \tag{3}$$

In our calculation, we have chosen the radii R_Ξ and R_p equal to a common value 0.8 fm and $R_H = 0.86$ fm. The color-spin-flavor recoupling coefficient Γ_0 is obtained from the following approximate wave-function decomposition[11] of the H:

$$\psi_H \approx (\tfrac{4}{5})^{1/2} |\underline{8}_c \times \underline{8}_c\rangle + (\tfrac{1}{10})^{1/2} |\Xi N\rangle_{I=0} - (\tfrac{1}{40})^{1/2} |\Lambda\Lambda\rangle + (\tfrac{3}{40})^{1/2} |\Sigma\Sigma\rangle_{I=0}. \tag{4}$$

Since $\Xi^- p$ is 50% $I=0$, we have $\Gamma_0 = (\frac{1}{20})^{1/2}$. Note that the H prefers to virtually dissociate into two color octets $\underline{8}_c$, rather than two color singlets.

The vertex Γ, except for the momentum-conserving δ function, is seen to depend only on the *relative* momentum $\vec{k}_R = \vec{k}_p - \vec{k}_\Xi$ of the $\Xi^- p$ pair. Small relative momentum is clearly preferred for H production in a baryon-baryon fusion process. In the case of a nuclear target, the Fermi motion of the protons provides a region of phase space where $\vec{k}_R$ is small. In the $p+p \to K^+ + K^+ + H$ reaction,[8] on the other hand, for which the simplest mechanism involves two dissociations p

$\rightarrow K^+\Lambda$ followed by $\Lambda\Lambda \rightarrow H$ recombination, the relative $\Lambda\Lambda$ momentum is large and the Λ's are far off shell, making it difficult to produce an H; the (K^-, K^+) reaction is much more favorable in this regard. For the ^{3}He target, the two protons are automatically in the $^1S_0$ state, and hence the $\Xi^- p$ pair is also produced as $^1S_0$ in $K^-(pp) \rightarrow K^+(\Xi^- p)$ for a K^+ at 0° (no spin flip), exactly as needed for the H. This Pauli effect enhances the cross section by a factor of 2. In alternative reactions involving a deuterium target, i.e., $K^- d \rightarrow K^+(\Xi^- n)_{I=1}$ or $K^- d \rightarrow K^0(\Xi^- p)_{S=1}$ at 0°, the $\Xi^- N$ pair is prepared with the wrong spin or isospin (or both) to become an H.

The cross sections for the process $^3\mathrm{He}(K^-, K^+ n)H$ in the laboratory frame were calculated by employing standard techniques[12]; relativistic kinematics is used throughout. The momentum dependence of the $K^- p \rightarrow K^+ \Xi^-$ cross section is included, with a simple parametrized form (in μb/sr)

$$\left(\frac{d\sigma(K^- p \rightarrow K^+ \Xi^-)}{d\Omega}\right)_{\mathrm{lab},0°} \approx 66\left(1 - \frac{k_{\mathrm{thr}}^2}{k_L^2}\right)^{1/2} \exp\left[-\left(\frac{k_L - k_{\max}}{\Delta k}\right)^2\right], \qquad (5)$$

where $k_{\mathrm{thr}} = 1.046$ GeV/c is the laboratory threshold momentum, $k_{\max} = 1.75$ GeV/c, and $\Delta k = 0.6$ GeV/c. Some typical cross-section results are shown in Fig. 2. The middle curve in Fig. 2 shows the momentum spectrum of the K^+ in $^3\mathrm{He}(K^-, K^+)nH$; it is peaked near the edge of the available phase space. The dynamics of the reaction, mainly the clear preference for $k_R \approx 0$ in Γ as discussed above, and the initial distribution of nucleon momenta in ^{3}He, produce a marked distortion of the K^+ spectrum from what would be expected on the basis of phase-space considerations alone (which gives a more spread out spectrum peaked at lower momentum). In the lower part of Fig. 2, we display the double-differential cross section for $^3\mathrm{He}(K^-, K^+ n)H$ at 1.9 GeV/c; here the K^+ is detected at 0° and the neutron laboratory angle is allowed to vary. The neutron is seen to be preferentially emitted in the backward direction, with a rather featureless angular distribution. The double-differential cross section is small but possibly measurable with currently available K^- fluxes.

In the top part of Fig. 2, we show the single-differential cross section at 0° (K^+ only detected), as a function of the mass of the H. In the region between 2.1 and 2.2 GeV/c^2 where the H mass is predicted[5,6] to lie, the cross section is about $\frac{1}{2}$ μb/sr. This is to be compared with the total $\Xi^- p$ quasielastic production [Fig. 1(b)], which is of the order of 100 μb/sr for a K^+ at 0°; the branching ratio for H production in $\Xi^- p$ colli-

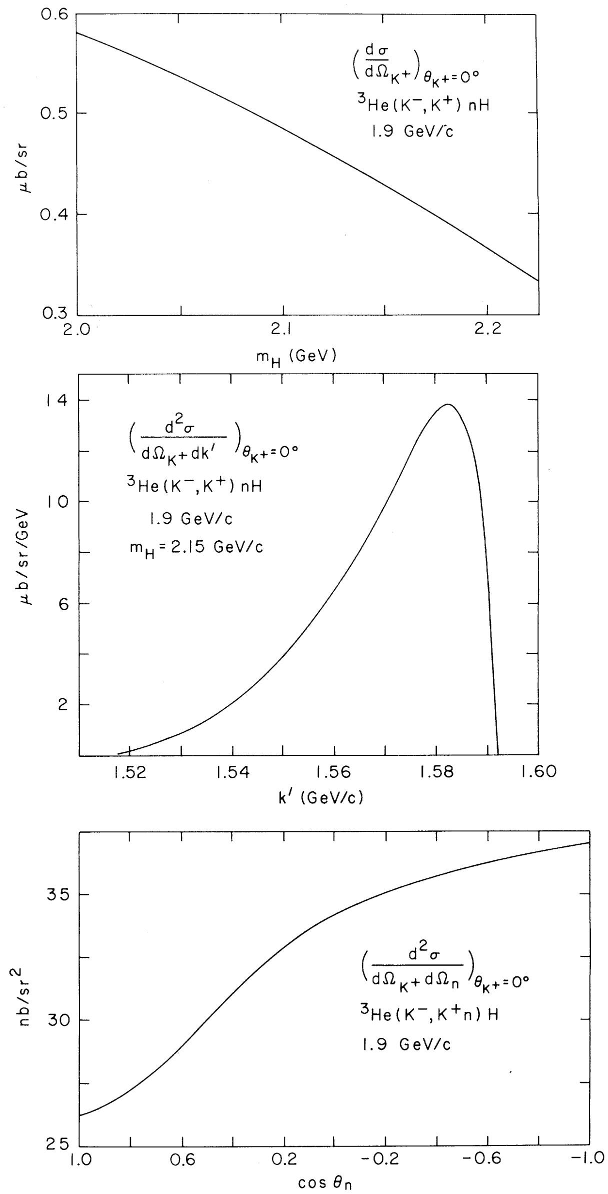

FIG. 2. Differential cross sections for H production on a ^{3}He target. The top curve shows the forward differential cross section for $^3\mathrm{He}(K^-,K^+)nH$ at 1.9 GeV/c as a function of the mass of the H. The middle curve shows the laboratory cross section for a K^+ at 0°, as a function of the momentum k' of the K^+. The bottom curve displays the laboratory double-differential cross section for $^3\mathrm{He}(K^-,K^+n)H$ as a function of the cosine of the neutron angle θ_n, for a K^+ detected at 0°.

sions is then roughly 5×10^{-3}. Note that if the H lies too close to the $\Lambda\Lambda$ threshold, it may be difficult to separate from an enhancement due to final-state interactions.

One may also consider H production in the (K^-, K^+) reaction on heavier targets. However, because of optical-model distortion effects (particularly for the K^-), the effective number of diproton pairs is expected to grow much less rapidly than $Z(Z-1)$, in analogy to the slow N dependence of the effective neutron number in (K^-, π^-) reactions.[13] For heavier targets, it also becomes more difficult to separate H production from the quasielastic background. If one detects both K^+ and neutron, the ^{3}He$(K^-, K^+n)H$ reaction seems to offer the best hope for observing the H. This experiment is well worth doing.

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