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A Stable H-Dibaryon: Dark Matter Candidate Within QCD?

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Particle physics arguments suggest that the H-dibaryon—a state consisting of two u, two d, and two s quarks—may have a mass $\approx 1.5 \pm 0.2$ MeV, and that $r_{\mathrm{H}} \lesssim \frac{1}{4} r_{\mathrm{N}}$. Remarkably, the observed stability of nuclei and other experimental limits do not exclude this scenario at present, as discussed here. If they are present in sufficient abundance, relic H's would be the cold dark matter. Tests of this scenario are discussed.

KEY WORDS: H-dibaryon; dark matter.

1. INTRODUCTION

Despite intensive experimental and observational efforts, the identity of the dark matter particle remains a mystery. So far, all phenomenologically satisfactory proposals for dark matter have required invoking physics beyond the standard model. Yet large portions of the parameter space for popular beyond-the-standard-model particle physics candidates have been excluded, and the remaining allowed regions of parameter space are increasingly difficult to motivate.

Surprisingly, a suitable dark matter candidate may be provided by QCD. The nonperturbative forces of QCD confinement could be such that the H-dibaryon, which consists of two u, two d, and two s quarks, is the lowest-energy-per-baryon state of matter. If so, the H is stable and there will be a relic population of H's. The effects responsible for confinement and hadronic mass generation may have a temperature dependence that would allow the relic H abundance to have the required value; that question will be addressed elsewhere.[2] Here we will concentrate on the issue of the possible stability of the H.

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[2] Because of the exponential sensitivity of the relic density to the H mass and freezeout temperature, greater care must be given to the temperature dependence of condensates and masses, and to competing reactions, than in the simplistic estimate given in my ArkadyFest talk.

If the H were stable, nuclei would be unstable. However, nuclear decay rates are extremely sensitive to the short distance properties of nuclei and the size of the H. Within the constraints imposed by present observations, nuclear lifetimes can easily be beyond experimental sensitivity. Other constraints on a stable H are also reviewed. Finally, we discuss how this scenario can be experimentally confirmed or excluded. It is virtually indistinguishable cosmologically from conventional CDM, but may be accessible in direct searches.

2. PROPERTIES OF THE H

As the density of a fermionic system such as quarks in a neutron star increases, it eventually becomes energetically favorable to replace some of the light quarks ($m_u \approx 5$MeV, $m_d \approx 10$ MeV) with strange quarks ($m_s \approx 50$–100 MeV), thereby reducing the Fermi levels of the u, d quarks at the expense of the mass of the strange quarks. Thus, in systems of ultrahigh baryon number, the ground state of matter is presumably strange quark matter (Edward, 1984; Edward and Jaffe, xxxx). In addition to this purely "exchange force" effect, which would be present even without QCD interactions, the interaction between quarks depends on their relative spin and color configuration. The spin–color configuration of a color-singlet state of quarks is controlled by its overall spin and flavor state owing to Fermi statistics. As initially pointed out by Jaffe in the bag model, QCD binding is particularly strong in the flavor-singlet, spin-0 state of six quarks (uuddss). He argued that two Λ's (uds; $m_\Lambda = 1115$ MeV) could form a bound state that he called the H-dibaryon (Jaffe, 1977), based on a perturbative bag model estimate of the hyperfine interaction. With a mass in the 1.9–2.2 GeV region, the H would be strong-interaction-stable: it could not decay to $\Lambda\Lambda$, but would not be absolutely stable because it could decay to two nucleons via weak interactions. There have been many searches for such an H, and recent results appear to rule it out (Ahn *et al.*, 2001; Takahashi *et al.*, 2001). These will be reconsidered below, after the new proposal is outlined.

There are two lines of reasoning, which indicate that the H might have a low enough mass to be stable. The first was put forth some time ago and is purely empirical and phenomenological. It starts from the observation (Farrar, xxxx; Kittel and Farrar, 2000) that the properties of the problematic $\frac{1}{2}^-$ baryon resonance $\Lambda(1405)$ and its spin $3/2$ partner $\Lambda(1520)$ are nicely explained if these are "hybrid" baryons—bound states of uds quarks in a flavor-singlet color-octet state with a gluon. The similarity of $\Lambda(1405)$, $\Lambda(1520)$, and glueball masses ($\sim$1.5 GeV) suggests, in the hybrid-baryon interpretation of the $\Lambda(1405)$ and $\Lambda(1520)$, that the color-singlet bound state of two $(\text{uds})_8$'s would also have a mass ≈ 1.5 GeV (Kittel and Farrar, 2000.). The $\Lambda(1405)$ and $\Lambda(1520)$ have eluded satisfactory explanation in other models, as explained in Dalitz (2000) and Kittel and Farrar (2000), and so this indirect hint of a light H is worth pursuing.

The second line of reasoning that suggests the H may be stable starts from the improved understanding of the phase structure of QCD due to Wilczek and colleagues, which has given persuasive evidence for color-flavor locking(Alford *et al.*, 1999; Schafer and Wilczek, 1999). They apply a gap-equation approach at high chemical potential, and so their results are not directly applicable to the H, but they suggest that nonperturbative attractive forces in the color-flavor-spin singlet 6 quark state may be very strong. It has also been noted that instantons produce a strong attraction in the scalar diquark channel(Rapp *et al.*, 1998), explaining the observed quark–diquark structure of the nucleon. The H has a color-flavor-spin structure that permits a large proportion of the quark pairwise interactions to be in this highly attractive spin-0, color $\bar{\mathbf{3}}$ channel, again suggesting the possibilty of a light H.[3]

A new observation offered here is that there is a symmetry reason that the H in particular could be anomalously light compared to the naive quark model. If the QCD attraction leading to color-flavor locking were sufficiently strong, and m_u were exactly zero instead of $\lesssim 5$ MeV $\ll \Lambda_{QCD} \sim 100$ MeV, then baryon number could be spontaneously violated because of formation of a $\langle$uuddss$\rangle$ condensate and the H would be the Goldstone boson. This is not in contradiction to the Vafa–Witten theorem, which excludes the spontaneous breaking of a vectorial global symmetry *in a theory with massive fermions*(Vafa and Witten, 1984). The Vafa–Witten theorem shows that the Goldstone-boson-wannabe's mass would vanish only in the limit in which the lightest quark mass vanishes.

The analogy $(\mathrm{uds})_8 \leftrightarrow g$ suggests that the radius of the H is comparable to that of the glueball, i.e., a factor 4–6 smaller than that of a nucleon (Schafer and Shuryak, 1995). A small radius is also expected on the basis of instanton-liquid arguments, which explain why $r_\pi = 0.38$ fm and $r_N = 0.88$ fm. More generally, a small radius would naturally be associated with tightly bound state. As we will see below, a small radius is phenomenologically essential if the H is stable, and we

[3] It was suggested in Kochelev (1999), based on an instanton-gas estimate giving $m_H = 1718$, that stable H's could be the messenger particles accounting for ultrahigh energy cosmic rays (UHECRs), since the GZK energy threshold increases in proportion to the mass of the messenger (Chung *et al.*, 1998) and there is evidence for a directional association between the highest energy UHECRs distant-shrouded AGNs (Farrar and Biermann, 1998). However, the proposal that the H is the UHE messenger particle can be excluded by the following argument. The H's, being neutral, cannot themselves be accelerated via shock acceleration or other astrophysical acceleration mechanisms that are applicable to protons, and producing them via a beam-dump mechanism from protons accelerated in a powerful AGN(Farrar and Biersmann, 1998) would in the absence of fine-tuning imply a far larger flux of protons than messengers, since the production cross section for H's is very small as shown here. But as shown in Farrar and Piron (2000), the GZK problem is not overcome by a messenger mechanism unless the flux of protons from the source is less than a few percentage of the messenger flux from the source. Furthermore, the acceleration mechanism suggested in Kochelev (1999), that high energy H's could be generated by supernova implosion to strange matter, would yield H's with GeV energies rather than $\sim 10^{11}$ GeV energies as required for them to be UHECRs. Nor did Kochelev (1999) consider the relic dark matter possibility or address the crucial problems associated with a stable H: nuclear stability, exotic isotopes, and doubly strange hypernuclei.

will therefore assume henceforth that $r_{\rm H}$–$r_{\rm N}/4$. An instanton analysis of the mass and size of the H would be valuable.

Lattice QCD efforts to determine the H mass have been unable to obtain clear evidence for a bound H. The analysis above suggests that this may be due to inadequate spatial resolution. Even the best lattice calculation used ≈ 0.15 fm lattice spacing (Pochinsky *et al.*, 1999), whereas the lattice spacing should be much smaller than the size of the state to get a robust result.

The H has spin-0 and therefore cannot have a dipole or higher multipole moment. If it were pointlike it would have no interactions, since it is color and charge neutral. It interacts with other hadrons only if it has a nonvanishing color charge radius, and thus a crude estimate of its scattering cross section with a nucleon is $\sigma_{\rm HN} \sim (r_{\rm H}/r_{\rm N})^4 \sigma_{\rm NN}$. The value of the coefficient in this scaling relationship reflects the density of the color charge inside the H and nucleon; taking it to be $\approx$1 gives $\sigma_{\rm HN} \approx 0.05\,(5R_{\rm H}/R_{\rm N})^4$ mb. If the column density of color charge inside the H is sufficient that it is opaque to another H, the H–H cross section would be geometric: $\sigma_{\rm HH} \approx 4\pi R^2{}_{\rm H} \approx 4(5R_{\rm H}/R_{\rm N})^2$ mb. Because the H wavefunction is spatially so dissimilar to that of the nucleon, conversion of pairs of baryons to an H is highly suppressed. This will be calculated below.

3. POTENTIAL OBSTACLES TO A STABLE H

- *Stringent bounds exclude exotic-mass isotopes*. If the H were to bind to nuclei and had a relic abundance sufficient to account for dark matter, it could be excluded because there are strong limits on the abundance of exotic isotopes of many nuclei. However, in this scenario the H does not bind to nuclei. Exchange of a single pseudoscalar meson, which produces a strong and long-range attraction between nucleons, is not possible because the H is a flavor singlet and so absorption of a flavor-octet meson leads to a flavor-octet dibaryon, which is not a bound state. Nor does exchange of a pair of pseudoscalar mesons provide adequate attraction, since the flavor-octet dibaryon intermediate state has a small amplitude of creation and a large energy denominator. The attractive interaction between nucleons and H due to exchange of flavor-singlet states like the σ and glueballs is unlikely to be strong enough to produce a bound state, given the short range of these attractive potentials, even if $g_{\rm HH\sigma} \times g_{\rm NN\sigma}$ or $g_{\rm HH\sigma} \times g_{\rm NN\sigma}$ were $\approx$1. However, in fact the H–H–σ vertex is small because of the small size of the H, and the N–N–G vertex is small because of the small size of the glueball, and so we conclude that the H does not bind to nuclei. Quantitative results will appear in a forthcoming paper (Farrar and Zaharijas, manuscript in preparation).
- *There is no evidence for an H in accelerator searches*. There have been many unsuccessful attempts to produce and detect the H, but they were

all designed to be sensitive to m_{H} around 2 GeV or higher and they are generally inapplicable for an H whose mass is $\sim$1.5 GeV. Even in the conventional picture of a loosely bound H it is difficult to make reliable production cross-section estimates and therefore it has not been possible to interpret the absence of a signal for H production as proof that the H does not exist. In the present scenario the small size of the H means its production cross section is highly suppressed, and so direct H-search experiments could not be expected to have observed a signal. The most sensitive experiment to put limits on a light stable strongly interacting particle was carried out by Gustafson *et al.* (1976), which used time-of-flight, but it is not sensitive to masses below $\sim$2 GeV because of neutron background, and therefore does not constrain this scenario.

- *Stability of nuclei and neutron stars*. Conversion of two nucleons to an H is suppressed because the process must change strangeness by two units and is thus second-order in the weak interactions. In addition, the small size of the H, along with the hard core repulsion in the nucleon–nucleon wavefunction in a nucleus, produces a suppression in the amplitude for six quarks in two nucleons to convert to an H. Taking dimensional factors in the weak amplitudes to be 100 MeV, the rate at which two nucleons in a nucleus convert to an H with emission of a pion is approximately

$$\Gamma \approx (\sin\theta_{\mathrm{C}} G_{\mathrm{F}} (100\ \mathrm{MEV})^2)^4 \alpha_{\mathrm{s}} O^2 \cdots, \tag{1}$$

where O is the N–N–H spatial wavefunction overlap and the ellipsis includes factors of order 1 and the flavor-color wavefunction overlap. This leads to a lifetime for nuclear disintegration $\tau \sim 1$ year/O^2. Super-Kamiokande has an exposure of $\approx 10^{31}$ nuclei-years and so although a limit has not been published, a lifetime shorter than $\approx 10^{30}$ years should produce an observable rate of appearance of pions with energy $\sim$350 MeV.

The spatial overlap of the quark wavefunctions can be estimated using the Isgur–Karl oscillator model for quarks in the baryons, convoluting with the nuclear two-body wavefunction for nucleons to be in a relative s-wave, and making the ansatz that the wavefunction for the quarks in the H is of the Isgur–Karl form but with the characteristic length scale decreased by the factor $r_{\mathrm{H}}/r_{\mathrm{N}}$. As expected, the result is extremely sensitive to the short distance nuclear wavefunction and the size of the H. Nuclear wavefunctions are not constrained by experiment for distances $\lesssim$0.7 fm (Akmal and Pandharipande, 1997), and so for illustration a Bethe-Goldstone wavefunction with hard core radius $r_{\mathrm{c}} = 0.4$–0.7 fm is used. Figure 1 were shows the square of the spatial wavefunction overlap amplitude. The flavor wavefunction overlap of six quarks in two nucleons with those in an H is not included in Fig. 1. It implies a substantial further suppression in O^2, and

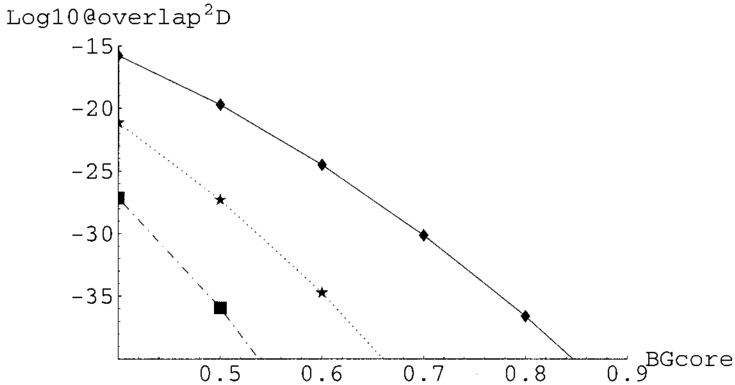

Fig. 1.

so the total wavefunction overlap can easily be small enough to preclude a detectable signal in Super-Kamiokonde.

- *Existence of doubly strange hypernuclei*. Recently, evidence has been presented for the production of hypernuclei containing two Λ's (Ahn *et al.*, 2001; Takahashi *et al.*, 2001). If two Λ's in a nucleus combine to produce an H before decaying via the weak interaction ($\tau_\Lambda = 3 \times 10^{-10}$ s), the observed signatures for Λ decay would not be seen. The lifetime for H production is about $10^{-23}/O^2$ s. Given the overlap estimates discussed above, the lifetime for ΛΛ in a hypernucleus to convert to an H is of the order of or longer than the lifetime for Λ decay, and so the observation of hypernuclei decaying to a Λ does not exclude the existence of a stable H.

4. COSMOLOGY OF THE H

It is commonly said that observed primordial abundances and nucleosynthesis theory imply that baryons contribute only a few percentage of the closure density. A more precise statement is that the *ratio* of ordinary nucleons to the total entropy at $T \sim 1$ MeV is constrained by nucleosynthesis. Since nucleon–H interconversion freezes out well above nucleosynthesis, and the H does not bind to nucleons or nuclei, the effect of H's on nucleosynthesis is no different than that of conventional nonbaryonic cold dark matter.

Spergel and Steinhardt (2000) estimated that a dark matter self-interaction satisfying $\sigma_{XX}/m_X \approx 0.1$–1 barn/GeV would account for apparent discrepancies between the predictions of collisionless cold dark matter and observations at small scales, without affecting the excellent predictions of CDM for the dark matter distributions at large scales. Although the H is strongly interacting in the technical sense that its interactions derive from QCD, $\sigma_{HH} \ll 0.1$ mb is too small for it to be called SIDM in the Spergel–Steinhardt sense. Nor do most experimental constraints on a SIDM particle apply to the H, as we shall see below.

5. TESTING THE H DARK MATTER HYPOTHESIS

If relic H's provide the observed dark matter density, their number density in our galactic neighborhood is the dark matter mass density divided by the H mass, or $\approx 0.2\ \mathrm{cm}^{-3}$. The solar system is moving at ~ 300 km/s with respect to the galaxy, and so the H flux on the Earth's atmosphere is $\sim 50\ \mathrm{m}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$. The column depth of the atmosphere is $\sim 1000\ \mathrm{g/cm}^2$, which is about 0.1 interaction lengths for an H–N cross section of 0.03 mb. The typical kinetic energy of the H in the Earth rest frame is approximately keV, but the fractional energy transfer is small if the detector is not made of light nuclei. Data from the XQC balloon experiment are nearly sensitive enough to find dark matter if the H is responsible. Wandelt *et al.* (2000) used XQC data to set a rough limit of $\sigma_{\mathrm{HN}} \gtrsim 0.03$ mb—tantalizingly close to the naive estimate above. If a method of discriminating the H flux from background can be devised, a dark matter search could be done at the Earth's surface. Furthermore, the sensitivity of balloon experiments can probably be increased sufficiently to probe smaller H–N cross sections.

6. DISCUSSION

To summarize, it has been proposed here that the H-dibaryon may be the ground state of baryonic matter. We have shown that this is consistent with particle physics constraints, if the H is sufficiently compact. A stable H would explain the observed properties of dark matter, if its relic abundance is adequate. A lattice gauge theory calculation of the H mass and wavefunction, at very much finer lattice spacing, could dispose of the possibility that the H is stable, or if a low mass H is indicated, it would motivate further experimental and theoretical work to discover it.

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