Non-binding of Flavor-Singlet Hadrons to Nuclei

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Abstract

Strongly attractive color forces in the flavor singlet channel may lead to a stable H dibaryon. Here we show that an H or other compact, flavor singlet hadron is unlikely to bind to nuclei, so that bounds on exotic isotopes do not exclude their stability. Remarkably, a stable H appears to evade other experimental constraints as well, when account is taken of its expected compact spatial wavefunction.

1 Introduction

The spectrum of QCD may include a state of six quarks which is simultaneously a singlet in color, flavor and spin, namely the H dibaryon, with a quark content $uuddss$. It is a scalar with charge 0 and strangeness -2, and is an isospin singlet and a flavor singlet: $I(J^P) = 0(0^+)$. In 1977, Jaffe predicted using the bag model that the H would have a mass below $2M_N$ [1] and thus be strong-interaction stable. Since then, there have been many theoretical efforts to determine the mass and production cross section of the H and, on the experimental side, many inconclusive or unsuccessful attempts to produce and detect it; see for example [2]. An underlying assumption has generally been that the H is not deeply bound.

In our work we examine the possibility that the H is lighter than two nucleons, $m_H < 2m_N$. The motivation comes from phenomenological and theoretical analyses of QCD, as is detailed in [3]. Briefly, the phenomenological argument springs from the proposal that the puzzling properties of the $\Lambda(1405)$ and $\Lambda(1520)$ are explained by their being hybrid baryons consisting of a gluon bound to $uds$ quarks in a flavor singlet-color octet state, to make an overall color singlet[4]. If the $\Lambda(1405)$ and $\Lambda(1520)$ are hybrids and the glueball mass is $\sim 1.5$ GeV, a naive constituent quark model estimate leads to an H mass in the range $\sim 1.3 - 1.5$ GeV[3]. The other approach is direct calculation
using instanton liquid or color-flavor locking arguments, which are known to imply strong attraction in the diquark channel. Indeed, ref. [5] states that an instanton liquid calculation leads to \( m_H = 1780 \text{ MeV} \).

A tightly bound state generally is small in size. In the instanton liquid model this explains why \( r_\pi < \frac{1}{2} r_N \). Both instanton liquid and lattice calculations indicate that the glueball is even more compact, so the \( H \leftrightarrow \text{glueball} \) analogy suggests \( r_H \approx r_G \lesssim \frac{1}{4} r_N \).

In this and companion papers we explore the phenomenological constraints on a stable \( H \) with mass in the range \( 1.3 \lesssim m_H \lesssim 2m_p \) and with radius \( r_H \approx (1/6 - 1/4)r_N \). Elsewhere we show that such an \( H \) can be consistent with the stability of nuclei and with \( \Lambda \) decays in doubly-strange hypernuclei [6]. Here we investigate the binding of the \( H \), or more generally of any flavor singlet, to nuclei. We determine the strength of coupling between the \( H \) and the \( \sigma \) meson or glueball which would be required for the \( H \) to bind, and conclude that the \( H \) would not bind to nuclei if it is as compact as hypothesized. Thus the strong constraints on the abundance of exotic isotopes do not exclude the existence of a stable \( H \). If the \( H \) is stable and produced at the appropriate level in the early Universe, it would be a good dark matter candidate [3]. A mechanism which provides the correct dark matter abundance will be described in [7].

In section 2 we summarize the relevant experimental constraints on exotic nuclei. In section 3, we summarize the theory of nuclear binding, to set the framework for and to make clear the limitations of our computation. In section 4 we analyze the binding of a flavor singlet scalar to nuclei, and calculate the minimum values of coupling constants needed for binding. Corresponding limits on nucleon-H scattering are given in section 5. Other flavor-singlets are also considered, in section 6 and elsewhere. We summarize the results and give conclusions in section 7.

2 Experimental constraints on the \( H \) binding

If the \( H \) binds to nuclei, experiments searching for anomalous mass isotopes could be sensitive to its existence. Accelerator mass spectroscopy (AMS) experiments generally have high sensitivity to anomalous isotopes, limiting the fraction of anomalous isotopes to \( 10^{-18} \) depending on the element. We discuss binding of the \( H \) to heavy and to light isotopes separately.

The \( H \) will bind more readily to heavy nuclei than to light ones because their potential well is wider. However, searches for exotic particles bound to heavy nuclei are limited to the search for charged particles in Fe [8] and to the experiment by Javorsek et al. [5] on Fe and Au. The experiment by Javorsek
searched for anomalous Au and Fe nuclei with $M_X$ in the range 200 to 350 atomic mass units u. Since the mass of Au is 197 u, this experiment is sensitive to the detection of an exotic particle with mass $M_X \geq 3$ u and is not sensitive to the H with a mass $M_H \leq 2$ u.

A summary of limits from various experiments on the concentrations of exotic isotopes of light nuclei is given in [10]. Only the measurements on hydrogen [11] and helium [12] nuclei are of interest here because they are sensitive to the presence of a light exotic particle with a mass of $M_X \sim 1$ GeV. It is very improbable that the H binds to hydrogen, since the Λ does not bind to hydrogen in spite of having attractive contributions to the potential not shared by the H, e.g., from the $\eta$ and $\eta'$. Thus we consider only the limit on helium. The limit on the concentration ratio of exotic to non-exotic isotopes for helium comes from the measurements of Klein, Middleton and Stevens who quote an upper limit of $\frac{HeX}{He} < 2 \times 10^{-14}$ and $\frac{HeX}{He} < 2 \times 10^{-12}$ for primordial He [13].

3 Nuclear binding-general

QCD theory has not yet progressed enough to predict the two nucleon interaction ab initio. Models for nuclear binding are, therefore, constructed semi-phenomenologically and relay closely on experimental input.

The long range part of the nucleon-nucleon interaction (for distances $r \geq 1.5$ fm) is well explained by the exchange of pions, and it is given by the one pion exchange potential (OPEP). The complete interaction potential $v_{ij}$ is given by $v_{ij}^\pi + v_{ij}^R$, where $v_{ij}^R$ contains all the other (heavy meson, multiple meson and quark exchange) parts. In the one boson exchange (OBE) models the potential $v_{ij}^R$ arises from the following contributions:

- In the intermediate region (at distances around $r \sim 1$ fm) the repulsive vector meson ($\rho, \omega$) exchanges are important. A scalar meson denoted $\sigma$ was introduced to provide an attractive potential needed to cancel the repulsion coming from the dominant vector $\omega$ meson exchange in this region. Moreover, a spin-orbit part to the potential from both $\sigma$ and $\omega$ exchange is necessary to account for the splitting of the $P^3$ phase shifts in NN scattering.
- At shorter scales ($r \lesssim 1$ fm), the potential is dominated by the repulsive vector meson ($\rho, \omega$) exchanges.
- For $r \lesssim 0.5$ fm a phenomenological hard core repulsion is introduced.

However, many of these OBE models required unrealistic values for the meson-nucleon coupling constants and meson masses. With this limitation the OBE theory predicts the properties of the deuteron and of two-nucleon scattering,
although, it cannot reproduce the data with high accuracy.

A much better fit to the data is obtained by using phenomenological potentials. In the early 1990’s the Nijmegen group\cite{14} extracted data on elastic NN scattering and showed that all NN scattering phase shifts and mixing parameters could be determined quite accurately. NN interaction models which fit the Nijmegen database with a $\chi^2/N_{data} \sim 1$ are called ‘modern’. They include Nijmegen models\cite{15}, the Argonne $v_{18}$\cite{16} and CD-Bonn\cite{17} potentials. These potentials have several tens of adjustable parameters, and give precision fits to a wide range of nucleon scattering data.

The construction of ‘modern’ potentials can be illustrated with the Nijmegen potential. That is an OBE model based on Regge pole theory, with additional contributions to the potential from the exchange of a Pomeron and $f, f', A_2$ trajectories. These new contributions give an appreciable repulsion in the central region, playing a role analogous to the soft or hard core repulsion needed in semi-phenomenological and OBE models.

Much less data exists on hyperon-nucleon interactions than on NN interactions, and therefore those models are less constrained. For example the extension of the Nijmegen potential to the hyper-nuclear (YN) sector\cite{18} leads to under-binding for heavier systems. The extension to the $\Lambda\Lambda$ and $\Xi N$ channels cannot be done without the introduction of extra free parameters, and there are no scattering data at present for their determination.

The brief review above shows that the description of baryon binding is a difficult and subtle problem in QCD. Detailed experimental data were needed in order to construct models which can describe observed binding. In the absence of such input data for the H analysis, we must use a simple model based on scalar meson exchange described by the Yukawa potential, neglecting spin effects in the nucleon vertex in the first approximation. We know from the inadequacy of this approach in the NN system that it can only be used as a crude guide. However since the strength of couplings which would be needed for the H to bind to light nuclei are very large, compared to their expected values, we conclude that binding is unlikely. Thus limits on exotic nuclei cannot be used to exclude the existence of an H or other compact flavor singlet scalar or spin-1/2 hadron.

4 Binding of a flavor singlet to nuclei

The H cannot bind through one pion exchange because of parity and also flavor conservation. The absorption of a pion by the H would lead to an isospin $I = 1$ state with parity $(-1)^{J+1}$, which could be $\Lambda\Sigma^0$ or heavier $\Xi p$ composite...
states. These states have mass \( \gtrsim 0.7 \) GeV higher than the mass of the H, which introduces a strong suppression in 2nd order perturbation theory. Moreover, the baryons in the intermediate state must have relative angular momentum \( L = 1 \), in order to have odd parity as required; this introduces an additional suppression. Finally, production of \( \Lambda \Sigma^0 \) or \( \Xi N \) states is further suppressed due to the small size of the H, as explained in \[6\]. Due to all these effects, we conclude that the contribution of one or two pion exchange to H binding is negligible.

The first order process can proceed only through the exchange of a flavor singlet scalar meson and a glueball. The lightest scalar meson is \( f(400-1100) \) (also called \( \sigma \)). The mass of the glueball is considered to be around \( \sim 1.5 \) GeV. In Born approximation, the Yukawa interaction leads to an attractive Yukawa potential between nucleons

\[
V(r) = -\frac{gg'1}{4\pi r} e^{-\mu r} \tag{1}
\]

where \( \mu \) is the mass of the exchanged singlet boson \( s (\sigma \) or glueball\) and \( gg' \) is the product of the \( s-H \) and \( s\)-nucleon coupling constants, respectively. The potential of the interaction of H at a position \( \vec{r} \) with a nucleus, assuming a uniform distribution of nucleon \( \rho = \frac{4}{V} \) inside a nuclear radius \( R \), is then

\[
V = -\frac{gg' A}{4\pi V} \int \frac{e^{-\mu|r'-\vec{r}|}}{|r'-\vec{r}|} d^3r' \tag{2}
\]

where \( A \) is the number of nucleons, \( V \) is the volume of the nucleus and \( \vec{r} \) is the position vector of the H. After integration over the angles the potential is

\[
V = -\frac{3 gg'}{2 4\pi (1.35 \text{ fm} \mu)^3} f(r) \tag{3}
\]

where we used \( R = 1.35 A^{1/3} \) fm;

\[
f(r) = \begin{cases} 
2\mu \left[1 - (1 + \mu R) e^{-\mu R \frac{\sinh[\mu R]}{\mu R}} \right] & r \leq R \\
2\mu [\mu R \cosh[\mu R] - \sinh[\mu R]] e^{-\mu R} & r \geq R
\end{cases}
\]

Throughout, we use \( \hbar = c = 1 \) when convenient.

Figure 1 shows the potential the nucleus presents to the H for \( A=50 \), taking the mass of the exchanged boson to be \( \mu =0.6 \) and 1.5 GeV. The depth of the potential is practically independent of the number of nucleons and becomes shallower with increasing scalar boson mass \( \mu \).
Note that Born approximation is applicable at low energies and for small coupling constants; it may not be valid for H binding. Born approximation is valid when

$$\frac{m \, gg'}{\mu \, 4\pi} << 1,$$

where $m$ is the reduced mass and $\mu$ the mass of the exchanged particle. As we shall see, this condition is actually not satisfied for values of $gg'$ which assure binding for the H-mass range of interest. This underlines the fact that no good first principle approach to nuclear binding is available at present.

We can now calculate the value of $c_* = \left( \frac{gg'}{4\pi} \right)_*$ for which the potential is equal to the minimum value needed for binding; in square well approximation this is given by

$$V_{\text{min}} = \frac{\pi^2}{8R^2m}. \tag{5}$$

Figure 2 shows the dependence of $c_*$ on the mass of the exchanged particle, $\mu$. The maximum value of $c_*$ for which the H does not bind decreases with increasing H mass, and it gets higher with increasing mass of the exchanged particle, $\mu$.

The H does not bind to light nuclei with $A \leq 4$, as long as the product of couplings $c_* \leq [0.27, 0.73, 1.65]$, for $\mu = [0.6, 1, 1.5]$ GeV, where $c = g_{NN\sigma} \, g_{HH\sigma}/(4\pi)$ or $g_{NNG} \, g_{HHG}/(4\pi)$. The H will not bind to heavier nuclei if $c_* \leq [0.019, 0.054, 0.12]$, for $\mu = [0.6, 1, 1.5]$ GeV. In the next sections we will compare these values to expectations and limits.

It should also be noted that binding requires the product of coupling constants,
Fig. 2. Critical value $c_*$ of the coupling constant product versus nuclear size needed for the H to just bind, for $\mu[\text{GeV}] = 0.7$ (dotted), 1.3 (dashed) and 1.5 (solid).

$gg'$ to be positive and this may not be the case. Even in the case of hyperons, experimental information was necessary to decide whether the $\Xi$ has a relative positive coupling \[19\].

5 Limits on $cm$ from Nucleon H scattering

The nucleon-H elastic scattering cross section is expected to be very small, due to the compact size of the H and the suppression of color fluctuations on scales $\lesssim 1$ GeV$^{-1}$ in the nucleon. Ref. \[3\] estimates $\sigma_{HN} \lesssim 10^{-3}$ mb. This can be translated to an estimated upper limit on the product $cm$ which determines the potential presented to the H by a nucleus, as follows. In the one boson exchange model, the elastic H-N cross section due to the $\sigma$- or glueball-mediated Yukawa interaction is given by

$$\frac{d\sigma}{d\Omega} = (2mc)^2 \frac{1}{(2p^2(1-\cos \theta) + \mu^2)^2}. \quad (6)$$

In the low energy limit

$$\sigma_{HN} = (2mc)^2 \frac{4\pi}{\mu^4}. \quad (7)$$

Writing $\sigma_{HN} = \sigma_{-3}10^{-3}$ mb and $\mu = \mu_{\text{GeV}}$ 1 GeV, this gives

$$cm = 0.007\sqrt{\sigma_{-3}} \mu_{\text{GeV}}^2 \text{GeV}. \quad (8)$$
Comparing to the values of $c^*$ needed to bind, we see that for $m_H < 2m_p$ this is too small for the H to bind, even to heavy nuclei\(^1\).

If dark matter consists of relic H’s, we can demonstrate that H’s do not bind to nuclei without relying on the theoretical estimate above for $\sigma_{HN}$. It was shown in \([20]\) that the XQC experiment excludes a dark matter-nucleon cross section $\sigma_{XN}$ larger than about 0.03 mb for $m_X \sim 1.5$ GeV. Thus if dark matter consists of a stable H it would require $\sigma_{XN} \leq 0.03$ mb, implying $c \leq [0.01, 0.03, 0.06]$ for $\mu = [0.6, 1.0, 1.5]$ GeV and the H would not bind even to heavy nuclei.

A generic new scalar flavor singlet hadron X which might appear in an extension of the standard model, might not have a small size and correspondingly small value of $\sigma_{XN}$, and it might not be dark matter and subject to the XQC limit. In that case, it is more useful to turn the argument here around to give the maximum $\sigma_{XN}^*$ above which the X would bind to nuclei in the OBE approximation. From eqn (3),(5) and $f(0) = 2\mu$ we have

$$c^* = \frac{\pi^2(1.35 \text{ fm})\mu^2}{24A^{2/3}m}. \quad (9)$$

Then eqn (7) leads to

$$\sigma_{XN}^* \approx 155 A^{-4/3} \text{ mb}. \quad (10)$$

That is, for instance, if it is required that the X not bind to He then it must have a cross section on nucleons lower than 25 mb.

### 6 Flavor singlet fermion

The analysis of the previous sections can be extended to the case of a flavor singlet fermion such as the glueballino – the supersymmetric partner of the glueball which appears in theories with a light gluino\([21]\). In this case the possible exchanged bosons includes, in addition to the $\sigma$ and the glueball, the flavor-singlet component of the pseudoscalar meson $\eta'$ ($m'_{\eta} = 958$ MeV). However the size of the $R_0$ should be comparable to the size of the glueball, which was the basis for estimating the size of the H. That is, we expect $r_{R_0} \approx r_G \approx r_H$ and thus $\sigma_{R_0N} \approx \sigma_{HN}$\([3]\). Then arguments of the previous section go through directly and show the $R_0$ is unlikely to bind to light nuclei\(^2\).

\(^1\) We have summarized the net effect of possibly more than one exchange boson (e.g., $\sigma$ and glueball) by a single effective boson represented by a $c^*_{\text{eff}}$ and $\mu_{\text{eff}}$.

\(^2\) Nussinov\([22]\) considered that the $R_0$ would bind to nuclei, by assuming that the depth of the potential presented by the nucleus to the $R_0$ is at least 2-4 MeV for...
Summary and Conclusions

As discussed in section 2, experimental constraints on the binding of a stable H or other flavor singlet scalar hadron to nuclei are most restrictive for helium. We reviewed the theory of nuclear binding and emphasized that even for ordinary nucleons and hyperons there is not a satisfactory first-principles treatment of nuclear binding. We showed that exchange of any pseudoscalar meson, or of two pseudoscalar octet mesons, or any member of the vector meson octet, makes a negligible contribution to the binding of an H or other flavor singlet scalar hadron to a nucleon. The dominant attractive force comes from exchange of a glueball or a σ (also known as the f(400-1100) meson), which we treated with a simple one boson exchange model. The couplings of σ and glueball to the H are strongly constrained by limits on σ_{HN}, to such low values that the H cannot be expected to bind, even to heavy nuclei.

Thus we conclude that the strong experimental limits on the existence of exotic isotopes of He and other nuclei do not exclude a stable H. More generally, our result can be applied to any new flavor singlet scalar particle X, another example being the S^0 supersymmetric hybrid baryon (udsg) discussed in [21]. If σ_{XN} ≤ 25 mb GeV/m_X, the X particle will not bind to light nuclei and is “safe”. Conversely, if σ_{XN} >> 25 mb GeV/m_X, the X particle could bind to light nuclei and is therefore excluded unless it there is some mechanism suppressing its abundance on Earth, or it could be shown to have an intrinsically repulsive interaction with nucleons. This means the self-interacting dark matter (SIDM) particle postulated by Spergel and Steinhardt[23] to ameliorate some difficulties with Cold Dark Matter, probably cannot be a hadron. SIDM requires σ_{XX}/M_X ≈ 0.1 – 1 b/GeV; if X were a hadron with such a large cross section, then on geometric grounds one would expect σ_{XN} ≈ 1/4σ_{XX} which would imply the X binds to nuclei and would therefore be excluded by experimental limits discussed above.

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References

[1] R. Jaffe. Perhaps a stable dihyperon... *Phys. Rev. Lett.*, 38:195, 1977.
[2] T. Sakai. H dibaryon. *Prog.Theor.Phys.Suppl.*, 137:121, 2000.
[3] G. R. Farrar. A stable H dibaryon. to be submitted to hep-ph.

16 ≤ A ≤ 56. However the discussion of the previous sections, with σ_{R_0 N} = 10^{-3} \sigma_{-3} mb, gives a potential depth of 0.07 MeV \sqrt{\sigma_{-3}}/(m_{R_0}/GeV).
[4] Olaf Kittel and Glennys R. Farrar. Masses of flavor singlet hybrid baryons. 2000. hep-ph/0010186.
[5] N. I. Kochelev. Ultra-high energy cosmic rays and stable H-dibaryon. *JETP Lett.*, 70:491–494, 1999.
[6] G. R. Farrar and G. Zaharijas. Transitions of two baryons to the $H$ dibaryon in nuclei. to be submitted to hep-ph.
[7] G. R. Farrar and G. Zaharijas. Dark matter and the baryon asymmetry from $H$ and $\bar{H}$ dibaryons. to be submitted to hep-ph.
[8] E. B. Norman, S. B. Gazes, and D. A. Bennett. Searches for supermassive X-particles in iron. *Phys. Rev. Lett.*, 58:1403–1406, 1987.
[9] D. Javorsek II. Experimental limits on the existence of strongly interacting massive particles bound to gold nuclei. *Phys. Rev.*, D64(012005), 2001.
[10] T.K. Hemmick. Search for low-Z nuclei containing massive stable particles. *Phys. Rev.*, D41:2074, 1990.
[11] P. F. Smith et al. A search for anomalous hydrogen in enriched D-2 O, using a time-of-flight spectrometer. *Nucl. Phys.*, B206:333–348, 1982.
[12] Proceedings of the Symposium on Accelerator Mass Spectroscopy (Argonne National Laboratory Report No. ANL/PHY-81-1, 1981.
[13] R. Plaga. How to search for primordial light gluinos. *Phys. Rev.*, D51:6504, 1995.
[14] V. G. J. Stoks, R. A. M. Klomp, M. C. M. Rentmeester, and J. J. de Swart. Partial wave analysis of all nucleon-nucleon scattering data below 350-meV. *Phys. Rev.*, C48:792–815, 1993.
[15] V. G. J. Stoks, R. A. M. Klomp, C. P. F. Terheggen, and J. J. de Swart. Construction of high quality NN potential models. *Phys. Rev.*, C49:2950–2962, 1994.
[16] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla. An accurate nucleon-nucleon potential with charge independence breaking. *Phys. Rev.*, C51:38–51, 1995.
[17] R. Machleidt, F. Sammarruca, and Y. Song. The non-local nature of the nuclear force and its impact on nuclear structure. *Phys. Rev.*, C53:1483–1487, 1996.
[18] P. M. M. Maessen, T. A. Rijken, and J. J. de Swart. Soft core baryon-baryon one boson exchange models. 2. hyperon - nucleon potential. *Phys. Rev.*, C40:2226–2245, 1989.
[19] C.B. Dover. Hyperon nucleus potentials. *Prog. Part. Nucl. Phys.*, 12:171, 1984.
[20] Benjamin D. Wandelt et al. Self-interacting dark matter. 2000. astro-ph/0006344.
[21] Glennys R. Farrar. Light gluinos. *Phys. Rev. Lett.*, 53:1029, 1984.
[22] Shmuel Nussinov. Comments on glueballinos (R0 particles) and R0 searches. *Phys. Rev.*, D57:7006–7018, 1998.
[23] David N. Spergel and Paul J. Steinhardt. Observational evidence for self-interacting cold dark matter. *Phys. Rev. Lett.*, 84:3760–3763, 2000.