Comments on the SU(4) dark matter

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We discuss possible scale of SU(4) dark matter, in form of neutral baryons. We argue that it is very likely that those would have time to cluster into large "nuclear drops" in which they are Bose-condensed.

I. INTRODUCTION

The nature of dark matter remains subject to wide speculations, and experimental searches focus on mass and couplings in wide range of scales. The author, not being a specialist in the field, would not even attempt to give references in respect to various theoretical ideas and current experimental limits.

These comments is focusing on one particular option, of a strongly interacting composite dark matter produced by hypothetical QCD-like theories which, unlike QCD, have the lowest baryons neutral in electroweak charges. Furthermore, if the number of colors is even, these baryons are likely to have spin zero, which reduces their interactions further.

One particular version of that, based on SU(4) color group, has been studied rather extensively on the lattice [1], addressing masses of the mesons and baryons of this theory.

We will consider the number of fermionic flavors be $N_f = 2$ or higher. In this case there exist flavor-asymmetric spin-zero diquarks, which, like in QCD, most likely are deeply bound, and therefore spin-zero baryon can be approximated by a pair of diquarks bound by the confining color flux tube.

II. WHAT MAY THE NATURAL SCALE OF THE SU(4) THEORY BE?

While this question is obviously most important, I have not seen its discussion in literature.

Perhaps the first idea one may try is to assume Grand Unification of the SU(4) theory together with U(1), SU(2), SU(3) parts of the Standard Model at the common scale $\Lambda_{\text{GUT}} \sim 10^{14} \text{GeV}$.

Qualitatively, this idea is attractive because it naturally explains why the scale of this theory must be much higher than the SU(3) scale, $\Lambda_{\text{QCD}}$ a fraction of GeV. Indeed, with larger $N_c$ its coupling runs more quickly, and thus it gets strong closer to $\Lambda_{\text{GUT}}$.

More quantitatively, using the well known one-loop beta function coefficient $b = \frac{11}{3} N_c - \frac{2}{3} N_f$ one has for QCD with $N_f = 6$ (we ignore part of scales in which the effective $N_f$ is smaller than that) $b_{\text{QCD}} = 7$, while for the theory in question it turns out to be exactly twice that, $b(N_c = 4, N_f = 2) = 14$. This will put the scale of this theory exactly in between $\Lambda_{\text{QCD}}$ and $\Lambda_{\text{GUT}}$

$\Lambda(N_c = 4, N_f = 2) = \sqrt{\Lambda_{\text{QCD}} \Lambda_{\text{GUT}}} \sim 10^7 \text{GeV}$

Of course, there can be much larger number of flavors, which would reduce this scale. It is also possible that there is no Grand Unification. Experimental limits on this scale – basically from the non-observed at LHC SU(4) pions – are in hundreds of GeV.

Anyway, if the scale is high, neutral baryons have extremely small cross section [1], even if the quarks themselves have nonzero electroweak charges, similar to those of the usual quarks.

III. THE BARYON CLUSTERING AND THE BOSONIC NUCLEOSYNTHESIS

Another qualitative idea which came to my mind stems from basic nuclear physics as well as from the lessons from Big Bang Nucleosynthesis (BBN).

In QCD baryons can form nuclei, but not a single bound states of any number of neutrons exists. The physics of nuclei has a scale
completely distinct from $\Lambda_{QCD}$: a typical binding per nucleon is a factor 100 smaller than the nucleon mass, $B \sim M_N/100 \sim 10 \text{MeV}$. This happens because of two fine tuned cancellations: (i) between attractive and repulsive forces, related to the specific masses and couplings of scalar and vector mesons of the theory; and (ii) between the potential and kinetic energies.

Generically, there are no reasons for strong cancellations in the $SU(4)$ theory. The second cancellation in particular, due to Fermi energy induced by the fermionic nature of the $SU(3)$ baryons, is no longer there. The $SU(4)$ neutron (to be perhaps called neutrone, large neutron, opposite to neutrino, a small one), which one assumes to be the dark matter, are however bosons, and there is no Fermi energy. The $SU(4)$ nuclei may therefore be completely neutral, with cold Bose condensed constituents, similar to systems of cold atoms at ultra-cold conditions.

Let me remind that even very small binding and very small baryon density at the BBN time $n_N/n_\gamma \sim 10^{-10}$ do not stop nucleon clustering, for the following reason. Consider for example the first reaction

$$p + n \leftrightarrow d + \gamma$$

Huge excess of the photons drive the reaction to the left, unless it is stopped by the Boltzmann factor $\exp(B_d/T)$. Yes, the deuteron binding is tiny $B_d = 2.2 \text{MeV}$, and yet, the temperature at the BBN time can be even much smaller! Slowly but surely, the temperature of the Universe decreases, and when the Boltzmann factor gets large enough

$$\exp(B_d/T) > 10^{10}$$

the reaction proceeds to the right, saving large fraction of the neutrons by putting them inside the deuterons (and eventually other nuclei). We are confident that this mechanism works well, as it produces the deuteron fraction observed today. Furthermore, we can deduce from it rather strong limitations on the variation of fundamental constants between now and the BBN time [2].

Similarly, cosmologically produced $SU(4)$ “neutrones” at the deconfinement transition of that theory will have long time to cluster, during eras with subsequently decreasing temperature, eventually into larger and larger neutral “drops”. Note further, that unlike in the QCD case, there is no global Coulomb energy to limit the sizes of these clusters, so it will be just limited by the available time and the rate of clustering.

Incidentally, the author is now involved in studies of baryonic clustering at the freezeout stages of heavy ion collisions [3]. The corresponding temperature is $T_f \sim 100 \text{MeV}$, high enough to melt any nuclei. And yet, interbaryon forces do induce clustering, which we study with classical molecular dynamics and which lead to correlations detected in the baryon number distributions, in spite of the fact that the time available is very short, $\sim 10 \text{fm/c}$, as compared to cosmological ones available for BBN. Clustering rate can have vastly different scales and be partially effective even at a very long timescales. For example, globular clusters of stars in galaxies continue to capture stars for billions of years, becoming rather large, and yet still capturing only a small fraction of stars.

In summary, if the the dark matter is made of neutral $SU(4)$ baryons, their mass scale can be rather large. It will in this case most likely come in form of “nuclear drops”, maybe even macroscopically large ones. If so, there may be hopes to detect their interaction. As a first practical step to study this hypothetical scenario, one needs to know the value of the deconfinement transition of the $SU(4)$ theory in question, and approximate forces between baryons, which can be calculated on the lattice today.

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[1] T. Appelquist et al. [Lattice Strong Dynamics (LSD) Collaboration], “Composite bosonic baryon dark matter on the lattice: SU(4) baryon spectrum and the effective Higgs interaction,” Phys. Rev. D 89, no. 9, 094508 (2014) [arXiv:1402.6656 [hep-lat]].

[2] V. V. Flambaum and E. V. Shuryak, “Dependence of hadronic properties on quark masses and constraints on their cosmological variation,” Phys. Rev. D 67, 083507 (2003) [hep-ph/0212403].

[3] E. Shuryak and J. M. Torres-Rincon, Baryonic clustering at freeze-out of high energy heavy ion collisions, in progress.