Colour entangled orphan quarks and dark energy from cosmic QCD phase transition

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The present day astrophysical observations indicate that the universe is composed of a large amount of dark energy (DE) responsible for an accelerated expansion of the universe, along with a sizeable amount of cold dark matter (CDM), responsible for structure formation. The explanations for the origin or the nature of both CDM and DE seem to require ideas beyond the standard model of elementary particle interactions. Here we show that CDM and DE both can arise from the standard principles of strong interaction physics and quantum entanglement.

During the past few decades, several accurate astrophysical measurements have been carried out and the large amount of data collected makes it possible to test the existing different cosmological models. Based on the knowledge gleaned so far, the present consensus [1–3] is that the standard model of cosmology, comprising the Big Bang and a flat universe is correct. The Big Bang Nucleosynthesis [4] (BBN), which forms one of the basic tenets of the standard model, shows that baryons can at most contribute Ω_B ($\equiv \frac{\rho_B}{\rho_c}$, ρ_c being the present value of closure density $\sim 10^{-47}$ Gev^4) ~ 0.04, whereas structure formation studies require that the total (cold) matter density should be $\Omega_{CDM} \sim 0.23$. Matter contributing to CDM is characterized by a dust-like equation of state, pressure $p \approx 0$ and energy density $\rho > 0$ and is responsible for clustering on galactic or supergalactic scales. Dark energy (DE), on the other hand, is smooth, with no clustering features at any scale. It is required to have an equation of state $p = w\rho$ where $w < 0$ (ideally $w = -1$), so that for a positive amount of dark energy, the resulting negative pressure

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would facilitate an accelerated expansion of the universe, evidence for which has recently become available from the redshift studies of type IA supernovae [3,5]. For a flat universe $\Omega \sim 1$, $\Omega_{DE} \sim 0.73$ [6] implies that ρ_{DE} today is of the order of 10^{-48} GeV^4.

The BBN limit of $\Omega_B \sim 0.04$ has led to the argument that, CDM cannot be baryonic; as a result, various exotic possibilities, all beyond the standard model $SU(3)_c \times SU(2) \times U(1)$ of particle interactions, have been suggested. The situation is even more complicated for DE. The most natural explanation for DE would be a vacuum energy density, which *a priori* would have the correct equation of state ($w = -1$). The difficulty associated with such a possibility is the fact that for any known (or conjectured) type of particle interaction, the vacuum energy density scale turns out to be many orders of magnitude larger than the present critical density. In this paper, we show that it is possible to understand the nature of CDM and DE within the standard model $SU(3)_c \times SU(2) \times U(1)$. They can both arise from the same process of the cosmic quark-hadron phase transition occurring during the microsecond epoch after the Big Bang, provided we admit the existence of quantum entanglement for a strongly interacting system.

In this paper we assume a first order cosmic QCD phase transition. Other crucial *ansätze* in our scenario include that the universe is overall colour neutral at all times, baryogenesis is complete substantially before the QCD transition epoch and that the baryon number is an integer. Together with the assumption of quantum entanglement, the above picture is capable of explaining both dark matter and dark energy. Here we will restrict ourselves mainly to the case of dark energy. For details see [7].

At temperatures higher than the critical temperature T_c, the coloured quarks and gluons are in a thermally equilibrated state in the perturbative vacuum (the quark-gluon plasma). The total colour of the universe is neutral (i.e., the total colour wave function of the universe is a singlet). It is strongly believed from QCD analysis that this thermally equilibrated phase of quarks and gluons exhibits collective plasma-like behaviour, referred to in the literature as the Quark-Gluon Plasma or QGP. Then, as T_c is reached and the phase transition starts, bubbles of the hadronic phase, begin to appear in the quark-gluon plasma, grow in size and form an infinite chain of connected bubbles (the percolation process). At this stage, the ambient universe turns over to the hadronic phase. Within this hadronic phase, the remaining high temperature quark phase gets trapped in large bubbles. As is well known, this process is associated with a fluctuation in the temperature around T_c; the bubbles of the hadronic phase can nucleate only when the temperature falls slightly below T_c. The released latent heat raises the temperature again and so on. It is thus fair to assume that the temperature of the universe remains around T_c at least upto percolation.

The net baryon number contained in these Trapped False Vacuum Domains (TFVD) could be many orders of magnitude larger than that in the normal hadronic phase and they could constitute the absolute ground state of strongly interacting matter [8]. The larger TFVDs with baryon number $\sim 10^{42-44}$, which are stable and separated by large distances (~ 300 m), would have a bearing on the dark matter content of the universe [9]. In all these considerations, it has been tacitly assumed that in a many-body system of quarks and gluons, colour is averaged over, leaving only a statistical degeneracy factor for thermodynamic quantities. Here we argue that such simplification may have led us to overlook a fundamentally important aspect of strong interaction physics in cosmology.

Let us now elaborate on the situation in some detail. In the QGP, all colour charges are neutralised within the corresponding Debye length, which turns out to be $\sim \frac{1}{g_s(T)T}$, where g_s is the strong coupling constant. For Debye length smaller than a typical hadronic radius, hadrons cannot exist as bound states of coloured objects. The lifetime of the QGP may be roughly estimated by the temperature when the Debye screening length becomes larger than the typical hadronic radius, and formation of hadrons as bound states of coloured objects becomes possible.

The size of the universe being many orders of magnitude larger than the Debye length, the requirement of overall colour neutrality is trivially satisfied. Another condition required for the existence of the QGP would be the occurrence of sufficient number of colour charges within the volume characterised by the Debye length; otherwise the collective behaviour responsible for the screening would not be possible. For the cosmic QGP, these conditions are satisfied till temperatures $\sim$ 100 - 200 MeV, the order of magnitude for the critical temperature for QCD.

So one would argue that all the physics of the QGP is contained within a Debye length. A quick estimate would show that upto T_c, the Debye length is less than a fermi and the total number of colour charges (including quarks, antiquarks and gluons) within the corresponding volume is greater than 10. Note, however, our emphasis on the second ansatz above, that the baryogenesis has already taken place much before T_c is reached and the value of $\frac{n_b}{n_\gamma} \sim 10^{-10}$ has already been established. Firstly, it has to be realised that this baryon number is carried in quarks at this epoch, so that the net quark number $(N_q - N_{\bar{q}})$ in the universe at all times is an exact multiple of 3. The net quark number within a Debye volume then turns out to be $\sim 10^{-9}$. Thus, to ensure overall colour neutrality and an integer baryon number, one must admit of long-range correlations beyond the Debye length in the QGP, the quantum entanglement property [10], which was identified as an essential feature of quantum mechanics by Schrödinger in as early as 1927 but was experimentally established only recently.

Let us now consider the process of the cosmic quark-hadron phase transition from the quantum mechanical standpoint of colour confinement. As already mentioned, the colour wave function of the entire universe prior to the phase transition must be a singlet, which means it cannot be factorized into constituent product states; the wave functions of all coloured objects are completely entangled [10] in a quantum mechanical sense. This also ensures the integer baryon number condition [7]. In such a situation, the universe is characterized by a vacuum energy corresponding to the perturbative vacuum of Quantum Chromodynamics (QCD). As the phase transition proceeds, locally colour neutral configurations (hadrons) arise, resulting in gradual decoherence of the entangled colour wave function of the entire universe. This amounts to a proportionate reduction in the perturbative vacuum energy density, which goes into providing the latent heat of the transition, or in other words, the mass and the kinetic energy of the particles in the non-perturbative (hadronic) phase (the vacuum energy of the non-perturbative phase of QCD is taken to be zero). In the quantum mechanical sense of entangled wave functions, the end of the quark-hadron transition would correspond to complete decoherence of the colour wave function of the universe; the entire vacuum energy would disappear as the perturbative vacuum would be replaced by the non-perturbative vacuum.

The earlier discussions imply that in order for the TFVDs to be stable physical objects, they must be colour neutral. This is synonymous with the requirement that they all have integer baryon numbers, i.e., at the moment of formation each TFVD has net quark numbers in exact multiples of 3. For a statistical process, this is, obviously, most unlikely and consequently, most of the TFVDs would have some residual colour at the percolation time. Then, on the way to becoming colour singlet they would each have to shed one or two coloured quarks.

Thus, at the end of the cosmic QCD phase transition there would be a few coloured quarks, separated by spacelike distances. Such a large separation, apparently against the dictates of QCD, is by no means unphysical. The separation of coloured TFVDs occurs at the temperature T_c, when the effective string tension is zero, so that there does not exist any long range force. By the time the TFVDs have evolved into colour neutral configurations, releasing the few orphan coloured quarks in their immediate vicinity, the spatial separation between these quarks is already too large to allow strings to develop between them; see below. (Such a situation could not occur in the laboratory searches for quark-gluon plasma through energetic heavy ion collisions as the spatial extent of the system is ∼few fermi and the reaction takes place on strong interaction time scales.) Therefore, the orphan quarks must remain in isolation. In terms of the quantum entanglement and decoherence of the colour wave function, this would then mean that their colour wave functions must still remain entangled and *a corresponding amount of the perturbative vacuum energy would persist in the universe.*

In this sense, the orphan quarks are definitely not in asymptotic states and no violation of colour confinement is involved. If we naively assume that the entanglement among these orphan quarks imply collective behaviour like a plasma, then one can estimate the corresponding Debye screening length for this very dilute system of quarks, which would still be governed primarily by the temperature. At temperatures of ∼ 100 MeV, the scale being much smaller than the mutual separation between the orphan quarks, the formation of bound states of orphan quarks would be impossible.

Presently, it is not possible to calculate this persisting, or even the full, perturbative vacuum energy, from first principles in QCD. For the latter

quantity, one may adopt the phenomenological Bag model [11] of confinement, where the Bag parameter B ($\sim (145 MeV)^4$) is the measure of the difference between the perturbative and the non-perturbative vacua. Thus we can assume that at the beginning of the phase transition, the universe starts out with a vacuum energy density B, which gradually decreases with increasing decoherence of the entangled colour wave function. A natural thermodynamic measure of the amount of entanglement during the phase transition could be the volume fraction ($f_q \equiv V_{colour}/V_{total}$) of the coloured degrees of freedom; at the beginning, f_q is unity, indicating complete entanglement, while at the end, very small but finite entanglement corresponds to a tiny but non-zero f_q due to the coloured quarks. Accordingly, the amount of perturbative vacuum energy density in the universe at any time is the energy density B times the instantaneous value of f_q; within the scenario discussed above, the remnant perturbative vacuum energy at the end of the QCD transition would just be B $\times f_{q,O}$, where $f_{q,O}$ is due solely to the orphan quarks. An order of magnitude estimate for $f_{q,O}$ can be carried out in the following straightforward manner. On the average, each TFVD is associated with 1 orphan quark so that the number $N_{q,O}$ of orphan quarks within the horizon volume at any time is about the same as the number N_{TFVD} of TFVDs therein. It is well known from the study of percolating systems [12] that percolation is characterized by a critical volume fraction $f_c \sim 0.3$ of the high temperature phase. So in the present case, f_q in the form of TFVD-s would be ~ 0.3. Following the ansatz of Witten [8] that the most likely length scale for a TFVD is a few cm, one can estimate N_{TFVD} (and hence $N_{q,O}$) within the horizon at the percolation time of about 100 μsec [9] to be about 10^{18-20}. The inter-TFVD separation comes out to be ~ 0.01 cm at that time. (It is obvious that the orphan quarks, separated by distances of 0.01 cm, cannot develop colour strings between them, even if there is some non-zero string tension generated at temperatures slightly lower than T_c.) Then, if we naively associate an effective radius of $\sim 10^{-14} cm$ (estimated from $\sigma_{qq} = \frac{1}{9}\sigma_{pp}$; $\sigma_{pp} \sim 20mb$) with each orphan quark, we obtain $f_{q,O} \sim N_{q,O} \times (v_{q,O}/V_{total}) \sim 10^{-42} - 10^{-44}$ (where $v_{q,O}$ is the effective volume of an orphan quark), so that the residual pQCD vacuum energy comes out to be in the range 10^{-46} to $10^{-48} GeV^4$ [7], just the amount of DE.

To conclude, we have shown that the existence of DE (along with CDM) can be explained entirely within the standard model of particle interactions, without invoking any exotic assumption. It is remarkable that this simple picture gives quantitatively correct amount without any fine-tuning of parameters. Moreover, the picture presented here satisfies, in our opinion, the most stringent criterion of a scientific theory, that of naturalness.

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