Dark matter from encapsulated atoms

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Abstract

We propose that dark matter consists of collections of atoms encapsulated inside pieces of an alternative vacuum, in which the Higgs field vacuum expectation value is appreciably smaller than in the usual vacuum. The alternative vacuum is supposed to have the same energy density as our own. Apart from this degeneracy of vacuum phases, we do not introduce any new physics beyond the Standard Model. The dark matter balls are estimated to have a radius of order 20 cm and a mass of order $10^{11}$ kg. However they are very difficult to observe directly, but inside dense stars may expand eating up the star and cause huge explosions (gamma ray bursts). The ratio of dark matter to ordinary baryonic matter is estimated to be of the order of the ratio of the binding energy per nucleon in helium to the difference between the binding energies per nucleon in heavy nuclei and in helium. Thus we predict approximately five times as much dark matter as ordinary baryonic matter!
1 Introduction

Recent “precision” cosmological measurements agree on a so-called concordant model (see the Reviews of Astrophysics and Cosmology in [1]), according to which the Universe is flat with $\Omega$, the ratio of its energy density to the critical density, being very close to unity. The energy budget of the Universe is presently dominated by three components: ordinary baryonic matter ($\Omega_{\text{ordinary}} \simeq 0.04$), dark matter ($\Omega_{\text{dark}} \simeq 0.23$) and dark energy ($\Omega_{\Lambda} \simeq 0.73$).

The main evidence for the density of ordinary matter comes from the abundances of the light elements formed in the first three minutes by big bang nucleosynthesis (BBN). The evidence for the dark matter density comes from galactic rotation curves, motions of galaxies within clusters, gravitational lensing and analyses (e.g. WMAP [2]) of the cosmic microwave background radiation. The need for a form of dark energy, such as a tiny cosmological constant $\Lambda$, is provided by the evidence for an accelerating Universe from observations of type Ia supernovae, large scale structure and the WMAP data.

In this paper we shall concentrate on the dark matter component. It must be very stable, with a lifetime greater than $10^{10}$ years. The dark matter density is of a similar order of magnitude as that of ordinary matter, with a ratio of

$$\frac{\Omega_{\text{dark}}}{\Omega_{\text{ordinary}}} \simeq 6$$

Also the dark matter was non-relativistic at the time of the onset of galaxy formation (i.e. cold dark matter).

According to folklore, no known elementary particle can account for all of the dark matter. Many hypothetical particles have been suggested as candidates for dark matter, of which the most popular is the lightest supersymmetric particle (LSP): the neutralino. The stability of the the LSP is imposed by the assumption of R-parity conservation. The LSP density is predicted to be close to the critical density for a heavy neutralino [3] with mass $m_{LSP} \sim 100 - 1000$ GeV, but a priori it is unrelated to the density of normal matter.

However we should like to emphasize that the dark matter could in fact be baryonic, if it were effectively separated from normal matter at the epoch of BBN. This separation must therefore already have been operative 1 second after the big bang, when the temperature was of order 1 MeV. Our basic idea is that dark matter consists of “small balls” of an alternative Standard
Model vacuum degenerate with the usual one, containing close-packed nuclei and electrons and surrounded by domain walls separating the two vacua. The baryons are supposed to be kept inside the balls due to the vacuum expectation value (VEV) of the Weinberg-Salam Higgs field $<\phi_{WS}>$ being smaller, say by a factor of 2, in the alternative phase. The quark and lepton masses

$$m_f = g f <\phi_{WS}>$$

are then reduced (by a factor of 2). We use an additive quark mass dependence approximation for the nucleon mass:

$$m_N = m_0 + \sum_{i=1}^{3} m_{q_i},$$

where the dominant contribution $m_0$ to the nucleon mass arises from the confinement of the quarks. Then, assuming quark masses in our phase of order $m_u \sim 5$ MeV and $m_d \sim 8$ MeV, we obtain a reduction in the nucleon mass in the alternative phase by an amount $\Delta m_N \sim 10$ MeV. The pion may be considered as a pseudo-Goldstone boson with a mass squared proportional to the sum of the masses of its constituent quarks:

$$M^2_{\pi} \propto m_u + m_d.$$  

It follows that the pion mass is also reduced (by a factor of $\sqrt{2}$) in the alternative phase. The range of the pion exchange force is thereby increased and so the nuclear binding energies are larger in the alternative phase, by an amount comparable to the binding they already have in normal matter. We conclude it would be energetically favourable for the dark matter baryons to remain inside balls of the alternative vacuum for temperatures lower than about 10 MeV. These dark matter nucleons would be encapsulated by the domain walls, remaining relatively inert and not disturbing the successful BBN calculations in our vacuum. We should note that a model for dark matter using an alternative phase in QCD has been proposed by Oaknin and Zhitnitsky.

2 Degenerate vacua in the Standard Model

The existence of another vacuum could be due to some genuinely new physics, but here we want to consider a scenario, which does not introduce any new
fundamental particles or interactions beyond the Standard Model. Our main assumption is that the dark energy or cosmological constant $\Lambda$ is not only fine-tuned to be tiny for one vacuum but for several, which we have called \cite{7,8,9,10,11} the Multiple Point Principle (MPP). This entails a fine-tuning of the parameters (coupling constants) of the Standard Model analogous to the fine-tuning of the intensive variables temperature and pressure at the triple point of water, due to the co-existence of the three degenerate phases: ice, water, and vapour.

Different vacuum phases can be obtained by having different amounts of some Bose-Einstein condensate. We are therefore led to consider a condensate of a bound state of some SM particles. Indeed, in this connection, we have previously proposed \cite{12,13,14,15} the existence of a new exotic strongly bound state made out of 6 top quarks and 6 anti-top quarks. The reason that such a bound state had not been considered previously is that its binding is based on the collective effect of attraction between several quarks due to Higgs exchange. In fact our calculations show that the binding could be so strong that the bound state is on the verge of becoming tachyonic and could form a condensate in an alternative vacuum degenerate with our own. With the added assumption of a third Standard Model phase, having a Higgs vacuum expectation value of the order of the Planck scale, we obtained a value of 173 GeV for the top quark mass \cite{11} and even a solution of the hierarchy problem, in the sense of obtaining a post-diction of the order of magnitude of the ratio of the weak to the Planck scale \cite{12,13,14,15}. However this third Planck scale vacuum is irrelevant for our dark matter scenario.

With the existence of just the 2 degenerate vacua domain walls would have easily formed, separating the different phases of the vacuum occurring in different regions of space, at high enough temperature in the early Universe. Since we assume the weak scale physics of the top quark and Higgs fields is responsible for producing these bound state condensate walls, their energy scale will be of order the top quark mass. We note that, unlike walls resulting from the spontaneous breaking of a discrete symmetry, there is an asymmetry between the two sides of the wall. So, in principle, a wall can readily contract to one side or the other and disappear.
3 Formation of dark matter balls in the early Universe

We now describe our favoured scenario for how the dark matter balls formed. Let us denote the order parameter field describing the new bound state which condenses in the alternative phase by $\phi_{NBS}$. In the early Universe it would fluctuate statistically mechanically and, as the temperature $T$ fell below the weak scale, would have become more and more concentrated around the – assumed equally deep – minima of the effective potential $V_{eff}(\phi_{NBS})$. There was then an effective symmetry between the vacua, since the vacua had approximately the same free energy densities. So the two phases would have formed with comparable volumes separated by domain walls. Eventually the small asymmetry between their free energy densities would have led to the dominance of one specific phase inside each horizon region and, finally, the walls would have contracted away. However it is a very detailed dynamical question as to how far below the weak scale the walls would survive. It seems quite possible that they persisted until the temperature of the Universe fell to around 1 MeV.

We imagine that the disappearance of the walls in our phase – except for very small balls of the fossil phase – occurred when the temperature $T$ was of the order of 1 MeV to 10 MeV. During this epoch the collection of nucleons in the alternative phase was favoured by the Boltzmann factor $\exp(-\Delta m_N/T)$. Thus the nucleons collected more and more strongly into the alternative phase, leaving relatively few nucleons outside in our phase. We suppose that a rapid contraction of the alternative phase set in around a temperature $T \sim 1$ MeV.

Due to the higher density and stronger nuclear binding, nucleosynthesis occurred first in the alternative phase. Ignoring Coulomb repulsion, the temperature $T_{NUC}$ at which a given species of nucleus with nucleon number $A$ is thermodynamically favoured is given by:

$$T_{NUC} = \frac{B_A/(A-1)}{\ln(\eta^{-1}) + 1.5 \ln(m_N/T_{NUC})}. \quad (5)$$

Here $B_A$ is the binding energy of the nucleus – in the phase in question of course – $\eta = \frac{n_B}{n_\gamma}$ is the ratio of the baryon number density relative to the photon density, and $m_N$ is the nucleon mass. In our phase, for example, the temperature for $^4$He to be thermodynamically favoured turns out from this
formula to be 0.28 MeV. In the other phase, where the Higgs field has a lower VEV by a factor of order unity, the binding energy $B_A$ is bigger and, with say $\eta \sim 10^{-3}$, $^4$He could have been produced at $T \sim 1$ MeV.

We assume that the alternative phase continued to collect up any nucleons from our phase and that, shortly after $^4$He production, there were essentially no nucleons left in our phase. The rapid contraction of the balls continued until there were more nucleons than photons, $\eta > 1$, in the alternative phase and fusion to heavier nuclei, such as $^{12}$C and $^{56}$Fe, took place, still with $T \sim 1$ MeV. A chain reaction could then have been triggered, resulting in the explosive heating of the whole ball as the $^4$He burnt into heavier nuclei. The excess energy would have been carried away by nucleons freed from the ball.

At this stage of internal fusion, the balls of the alternative phase would have been so small that any nucleons in our phase would no longer be collected into the balls. So the nucleons released by the internal fusion would stay forever outside the balls and make up normal matter. This normal matter then underwent the usual BBN in our phase.

4 Prediction of the ratio of dark matter to normal matter

According to the above internal fusion scenario, the ratio of the normal matter density to the total matter density is given by:

$$\frac{\Omega_{\text{ordinary}}}{\Omega_{\text{matter}}} = \frac{\text{Number of nucleons released}}{\text{Total number of nucleons}}$$

(6)

The fraction of nucleons released from the balls of alternative phase during the internal fusion can be obtained from a simple energy conservation argument.

Before the further internal fusion process took place, the main content of the balls was in the form of $^4$He nuclei. Now the nucleons in a $^4$He nucleus have a binding energy of 7.1 MeV in normal matter in our phase, while a typical “heavy” nucleus has a binding energy of 8.5 MeV for each nucleon [17]. Let us, for simplicity, assume that the ratio of these two binding energies per nucleon is the same in the alternative phase and use the normal binding energies in our estimate below. Thus we take the energy released by the fusion of the helium into heavier nuclei to be 8.5 MeV - 7.1 MeV = 1.4 MeV.
per nucleon. Now we can calculate what fraction of the nucleons, counted as \textit{a priori} initially sitting in the heavy nuclei, can be released by this 1.4 MeV per nucleon. Since they were bound inside the nuclei by 8.5 MeV relative to the energy they would have outside, the fraction released should be \((1.4 \text{ MeV})/(8.5 \text{ MeV}) = 0.165 = 1/6\). So we predict that the normal baryonic matter should make up 1/6 of the total amount of matter, dark as well as normal baryonic. According to astrophysical fits \cite{2}, giving 23\% dark matter and 4\% normal baryonic matter relative to the critical density, the amount of normal baryonic matter relative to the total matter is \(\frac{4\%}{23\%+4\%} = 4/27 = 0.15\). This is in remarkable agreement with our prediction.

5 Properties of dark matter balls

The size of the balls depends sensitively on the order of magnitude assumed for the wall energy density, which we take to be of the weak scale or about 100 GeV. Let us first consider the stability condition for these balls. For a ball of radius \(R\), the wall tension \(s\) is given by

\[
s \approx (100 \text{ GeV})^3
\]

which provides a pressure \(\frac{s}{R}\) that must be balanced by the electron pressure. The energy needed to release a nucleon from the alternative vacuum into our vacuum is approximately 10 MeV. So the maximum value for the electron Fermi level inside the balls is \(\sim 10 \text{ MeV}\), since otherwise it would pay for electrons and associated protons to leave the alternative vacuum. Thus the maximum electron pressure is of order \((10 \text{ MeV})^4\).

In order that the pressure from the wall should not quench this maximal electron pressure, we need to satisfy the stability condition:

\[
s/R = \frac{(100 \text{ GeV})^3}{R} < (10 \text{ MeV})^4 = 10^{-8} \text{ GeV}^4.
\]

This means the ball radius must be larger than a critical radius given by:

\[
R > R_{\text{crit}} = 10^{14} \text{ GeV}^{-1} = 2 \text{ cm}.
\]

If the balls have a radius smaller than \(R_{\text{crit}}\), they will implode. These critical size balls have a nucleon number density of

\[
n_e = (10 \text{ MeV})^3 = \frac{1}{(20 \text{ fm})^3} \simeq 10^{35} \text{ cm}^{-3}.
\]
So, with $R_{\text{crit}} = 2 \text{ cm}$, it contains of order $N_e \simeq 10^{36}$ electrons and correspondingly of order $N_B \simeq 10^{36}$ baryons, with a mass of order $M_B \simeq 10^9 \text{ kg}$. We estimate the typical radius of a dark matter ball in our scenario to be of order 20 cm. It contains of order $N_B = 3 \times 10^{37}$ baryons and has a mass of order $M_B = 10^{11} \text{ kg} = 10^{-19} M_\odot = 10^{-14} M_\oplus$. Therefore dark matter balls can not be revealed by microlensing searches, which are only sensitive to massive astrophysical compact objects with masses greater than $10^{-7} M_\odot$ [18]. Since the dark matter density is 23\% of the critical density $\rho_{\text{crit}} = 10^{-26} \text{ kg/m}^3$, a volume of about $10^{37} \text{ m}^3 = (20 \text{ astronomical units})^3$ will contain on the average just one dark matter ball.

Assuming the sun moves with a velocity of 100 km/s relative to the dark matter and an enhanced density of dark matter in the galaxy of order $10^5$ higher than the average, the sun would hit of order $10^8$ dark matter balls of total mass $10^{19} \text{ kg}$ in the lifetime of the Universe. A dark matter ball passing through the sun would plough through a mass of sun material similar to its own mass. It could therefore easily become bound into an orbit say or possibly captured inside the sun, but be undetectable from the earth. On the other hand, heavy stars may capture some dark matter balls impinging on them.

In the lifetime of the Universe, the earth would hit $10^4$ or so dark matter balls. However they would have gone through the earth without getting stopped appreciably. It follows that DAMA [19] would not have any chance of seeing our dark matter balls, despite their claim to have detected a signal for dark matter in the galactic halo. However EDELWEISS [20], CRESST [21] and CDMS [22] do not confirm the effect seen by DAMA. It is also possible that DAMA saw something other than dark matter. Geophysical evidence for the dark matter balls having passed through the earth would also be extremely difficult to find.

We conclude that the dark matter balls are very hard to see directly. On the other hand, we could imagine that dark matter balls had collected into the interior of a collapsing star. Then, when the density in the interior of the star gets sufficiently big, the balls could be so much disturbed that they would explode. The walls may then start expanding into the dense material in the star, converting part of the star to dark matter. As the wall expands the pressure from the surface tension diminishes and lower and lower stellar density will be sufficient for the wall to be driven further out through the star material. This could lead to releasing energy of the order of $10 \text{ MeV}$.
per nucleon in the star, which corresponds to of the order of one percent of
the Einstein energy of the star! Such events would give rise to really huge
energy releases, perhaps causing supernovae to explode and producing the
canonballs suggested by Dar and De Rujula [23] to be responsible for the
cosmic gamma ray bursts. We should note that a different (SUSY) phase
transition inside the star has already been suggested [24] as an explanation
for gamma ray bursts.

A dark matter ball can also explode due to the implosion of its wall. Such
an implosive instability might provide a mechanism for producing ultra high
energy cosmic rays from seemingly empty places in the Universe. This could
help to resolve the Greisen-Zatsepin-Kuzmin [25, 26] cut-off problem.

6 Conclusion

Under the assumption that there be at least two different phases of the
vacuum with very closely the same tiny energy density or cosmological con-
stant, we have put forward an idea for what dark matter could be. Indeed
we suggest that dark matter consists of baryons hidden inside pieces of an
alternative vacuum with a smaller Higgs field VEV. The SM might provide
such a second vacuum degenerate with our own, due to the condensation of
an exotic $6t + 6\bar{t}$ strongly bound state. The ratio of dark matter to ordinary
matter is expressed as a ratio of nuclear binding energies and predicted to be
about 5. Big bang nucleosynthesis is supposed to proceed as usual in our vac-
uum relatively undisturbed by the crypto-baryonic dark matter encapsulated
in a few balls of the alternative vacuum.

We estimate that a typical dark matter ball has a radius of about 20 cm
and a mass of order $10^{11}$ kg. The dark matter balls are very difficult to detect
directly, but they might be responsible for gamma ray bursts or ultra high
energy cosmic rays.

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