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DARK MATTER AND THE SOLAR NEUTRINO PROBLEM; CAN PARTICLE PHYSICS PROVIDE A SINGLE SOLUTION ?

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I Introduction and Review of the Cosmion Idea

It has been known for some time that weakly interacting massive particles (WIMPS or cosmions) can simultaneously solve both the dark matter and solar neutrino problems [1]. The idea is quite simple and elegant: such particles being the constituents of dark matter [2] would, if sufficiently massive, accrete in the core region of the sun. As they orbit in the sun's interior, they transfer heat from the inner to the outer regions thereby cooling the core. Lowering the core temperature (T_c) by only 10 % is sufficient to reduce the predicted output of observable neutrinos by a factor of 3-4 leading to a resolution of the solar neutrino problem [1]. The crucial point is that almost 80 % of the observable neutrinos (which represent only 10^{-6} of the total neutrino output of the sun!) result from the decay $^8B \to {}^8Be^* + e^+ + \nu_e$ and the rate for this is very sensitive to T_c. On the other hand, solar models which accurately describe bulk properties of the sun such as its total luminosity, radius, mass and surface abundance of elements are not very sensitive to T_c. Indeed, changing T_c by 10 % has only a negligible effect on these gross properties, including the total neutrino output of the sun [1]. Roughly speaking the necessary properties of the cosmion, such as its mass (M_c) and cross-section off of protons (σ) can be deduced by requiring that it lowers T_c by $\sim 10\%$ without appreciably affecting the temperature beyond a radius $\sim 0.1 R_\odot$, where most of the solar luminosity ($L_\odot$) originates.

Let us review the cosmion properties that follow from detailed calculations [1]:

a) Suppose cosmions reach thermal equilibrium in the sun's core, then, by equipartition, they are concentrated at a radius r_c given by

$$\frac{3}{2} k T_c = \frac{2}{3} \pi G \rho_0 r_c^2 M_c \tag{1}$$

where G is Newton's constant and ρ_0 is the core density of the sun. Now, as already remarked, we require $r_c \lesssim 0.1 R_\odot$ to avoid disturbing the observed solar luminosity, etc.; this leads through eq. (1) to the constraint that $M_c \lesssim 8$ GeV. There is a corresponding lower limit coming from the fact that if r_c is too small, cosmions sit at the center of the sun and become very inefficient at transferring heat. This leads to $M_c \gtrsim 2$ GeV.

[1] Talk presented at the Fourth Family Symposium held in Santa Monica, March 1989

b) A rough estimate of the heat flux carried by cosmions can be obtained from elementary kinetic theory: one finds

$$\text{Flux} \approx \left(\frac{N_c}{N_p}\right)\left(\frac{M_p}{M_c}\right)^{\frac{1}{2}} \times 4 \times 10^{12} L_\odot \times \min\left(\frac{\sigma_o}{\sigma}, \frac{\sigma}{\sigma_o}\right) \tag{2}$$

Here $\frac{N_c}{N_p}$ is the number of cosmions in the sun relative to that of protons and $\sigma_o = \left(\frac{M_p}{M}\right) R^2$ is a cross-section corresponding to one cosmion interaction per orbit inside the sun. When $\sigma = \sigma_o$ the flux is maximized. Physically it represents the cross-over from conduction ($\sigma > \sigma_o$) to convection ($\sigma < \sigma_o$) and can be understood as follows: if σ is large then the mean free path inside the sun is very small and there are many scatterings leading to inefficient transportation. On the other hand, if σ is too small the mean free path eventually exceeds r and there are simply insufficient interactions to transfer heat. There is therefore some optimum value of the cross-section: $\sigma = \sigma_o \approx 4 \times 10^{-36} cm^2$; any deviation from this requires an increase in N_c in order to obtain the same efficiency of heat transfer. Notice that if $\sigma = \sigma_o$, then a cosmion concentration of only roughly one part in 10^{12} is required to effectively transport the total solar luminosity! Cosmions are a remarkably efficient mechanism for lowering T_o.

c) If cosmions are identified with dark matter then N_c is a calculable quantity; basically it is just the number of dark matter particles captured by the sun during its lifetime $\tau \approx 5 \times 10^9$ years. Of course, some cosmions are lost by evaporation through interactions with nuclei in the sun and some are lost via annihilation with their anti-particles, as illustrated in fig. 1. This is expressed by the rate equation

$$\dot{N}_c = C_c - C_A N_c N_{\bar{c}} - C_E N_c \tag{3}$$

together with its conjugate equation for $N_{\bar{c}}$ (where $c \rightleftharpoons \bar{c}$ in the subscripts). Now the evaporation rate has a generic Boltzman structure

$$C_E \propto N_p \sigma e^{-M_c V/kT} \tag{4}$$

where V is the gravitational potential energy. The relatively sharp cut-off with M_c has the consequence that, if $M_c \lesssim 4$GeV, evaporation dominates and essentially all of the captured cosmions are lost. This result is fairly insensitive to model details, so from here on, we shall require $M_c \gtrsim 4$GeV and neglect the evaporation term in (3). Let us now examine the effects of annihilation, represented in (3) by C_A. This is clearly proportional to the thermally averaged $c\bar{c}$ annihilation rate $\langle \sigma_A V_c \rangle$ where V_c is the mean cosmion velocity. First, suppose that cosmions are Majorana particles, then $N_c = N_{\bar{c}}$ and equilibrium is eventually reached where $N_c = N_{\bar{c}} \approx (C_c/C_A)^{\frac{1}{2}}$. Requiring $N_c/N_p \approx 10^{-12}$ then leads to the requirement that

$< \sigma_A V_c > \lesssim 10^{-40} cm^2$. Suppose, however, that cosmions are Dirac particles, then, like ordinary baryons, we can expect a cosmic asymmetry to have developed so that $N_c \gg N_{\bar{c}}$. In that case annihilation is irrelevant and N_c grows linearly with time, $N_c = C_c \tau_\odot$. A detailed calculation yields:

$$\frac{N_c}{N_p} \approx 3 \times 10^{11} \left(\frac{M_p}{M_c}\right) \left(\frac{V_e}{V_c}\right) \left(\frac{\rho_c}{0.01\, M_\odot/pc^3}\right) \min\left(1, \frac{\sigma}{\sigma_o}\right) \qquad (5)$$

Here V_e is the escape velocity from the sun ($\approx$ 600 km./sec.) and ρ_c the cosmion density in the galaxy. With cosmions identified as dark matter particles we have $V_c \sim 300$km /sec and $\rho_c \sim 0.01\, M_\odot/pc^3$. Thus, with $\sigma \approx \sigma_o$ and $M_c \sim 5\, M_p$, eq. (5) gives $N_c/N_p \sim 10^{-11}$ which is just enough cosmions captured to solve the solar neutrino problem! Notice that when this is combined with eq. (2) **we are forced into having** $\sigma \approx \sigma_o \approx 4 \times 10^{-36} cm^2$. The fact that the sun captures precisely the right number of dark matter particles required to lower its expected core temperature by the $\sim$ 10% needed to solve the solar neutrino problem is certainly intriguing and is one of the major motivations for believing in the cosmion solution. It is worth pointing out in this context that the rate equations allow a determination of $N_{\bar{c}}$, the number of anti-cosmions captured by the sun: $N_{\bar{c}} \approx (\rho_{\bar{c}}/\rho_c)(C_A \tau_\odot)^{-1}$. This can then be used to estimate the rate of production of hard muon neutrinos with energy $\sim M_c$ coming from $c\bar{c}$ annihilation in the sun. Such neutrinos can be detected by underground proton decay detectors thereby giving limits on possible dark matter candidates[4]. We shall return to this briefly below.

d) Cosmions must be stable (or, effectively so). This is usually accomplished by making them the lightest particle carrying a conserved quantum number. This makes supersymmetric (SUSY) particles, such as the photino, the most natural candidate. Alternatively, but less natural from a theoretical standpoint, is a massive Dirac neutrino carrying a conserved lepton number. Again, we shall return to these possibilities below.

e) In principle it is possible to estimate ρ_c and $\rho_{\bar{c}}$ if these particles are imbedded in some generic grand unified model. One can follow standard scenarios of baryogenesis extended to a "cosmion sector". In various classes of models, such arguments lead to the conclusion that

$$\frac{\rho_{\text{dark matter}}}{\rho_{\text{luminous matter}}} \approx \frac{\rho_c}{\rho_p} \sim \frac{M_c}{M_p} \qquad (6)$$

Observationally [2] this ratio is known to be ~ 10 leading to $M_c \sim 10$GeV. This is very gratifying since this is precisely the order of magnitude required for M_c if it is to solve the solar neutrino problem. This, therefore, supports the idea that the WIMP that solves the solar neutrino problem can be identified with dark matter.

II What is the Cosmion and How does it Interact ?

In the previous section we saw that a particle with the following properties can simultaneously be the constituent of dark matter and resolve the solar neutrino problem:

a) it must be neutral;

b) it must be stable;

c) its mass must lie in the range 4GeV $\lesssim M_c \lesssim$ 8GeV;

d) its cross-section of off protons is $\sigma \sim 10^{-36} cm^2$;

e) either it is a Majorana particle with $< \sigma_A V_c > \lesssim 10^{-40} cm^2$ or

f) it is a Dirac particle with a cosmic asymmetry generated at the GUT scale.

We now want to discuss what this particle could be and how it interacts. Our attitude will be to try to stay as near the standard model as possible. As already mentioned the most natural candidate is the lightest SUSY particle, such as the photino. Less attractive from the present theoretical dogma is a massive Dirac neutrino which could be identified with a new fourth generation lepton. As far as the interaction of the cosmion is concerned we need to consider the three neutral currents embedded in the standard model: Z^o , γ and h^o exchange. Obviously one can go beyond this but, for the present purposes, it is most natural to remain within these confines so we shall consider them one at a time.

i) Z^o - The Neutral Weak Current

A typical cross-section for the scattering of cosmions from proton via Z^o- exchange is $\sigma \approx (3/8\pi) G_F^2 M_p^2 \approx 10^{-39} cm^2$ which is much too small. On the other hand, a typical annihilation rate is $\sigma_A \approx G_F^2 M_W^2 / 8\pi \approx 10^{-36} cm^2$ which is much too large for Majorana particles. Even taking into account s-wave suppression this cross-section typically remains too large to allow Majoranas to be viable candidates[6]; [see below, for a possible exception to this]. This is the basic reason we shall focus for the rest of this discussion on massive Dirac fermions and think of the cosmion as a new fourth generation massive neutrino.

ii) Photon Exchange (and New Heavy Charged Leptons)

This must proceed through a presumed anomalous magnetic moment of the cosmion; for this reason such a cosmion was dubbed a "**magnino**"[5]. The total cross section for the scattering of a magnetic moment (μ_c) from a charge (Z) is logarithmically divergent. However, what is actually relevant here is not the usual scattering cross-section but rather the energy transport cross-section and this is what σ refers to in the previous discussion above[1]. This quantity is finite and is given by [5] $\sigma \approx (\pi\alpha^2 / M_c^2)\mu_c^2 [Z^2 + 2\mu_T^2]$ where μ_T is the target magnetic moment. For the sun, which is 88% hydrogen and 11% helium, this is clearly dom inated by protons, for which $\mu_\tau = 2.79$. To obtain $\sigma \approx 10^{-36} cm^2$ requires $\mu_c \sim 5 \times 10^{-3}$ (in units of its own magneton). Is this is a reasonable number – is it large or is it small? To answer this we clearly need to have a specific model from which μ_c can be calculated as a radiative correction. As already mentioned the simplest and most natural identification is to make the cosmion a massive neutrino. To do so, we simply add a new fourth generation left-handed doublet to the standard model together with a right-handed piece for the neutrino. We find that in order to obtain $\mu_c \sim 5 \times 10^{-3}$ (with $M_c \sim$5GeV) requires, among other things, the mass splitting between the new charged lepton (C^+) and its neutrino (C^0 – the cosmion) must be small. Specifically $M_{c^+} - M_{c^0} \lesssim$3GeV. Put slightly differently, this says that this version of the cosmion requires a relatively large magnetic moment. This constraint on the mass splitting has an interesting experimental consequence that can be tested: it predicts that there should be a **new charged lepton with mass in the range 4GeV$\lesssim M_{c^+} \lesssim$10 GeV**.

It so happens that, in spite of intensive heavy lepton searches over the years, little (if any) attention had been paid to "close-mass pairs" such as proposed here. All charged lepton searches presumed a decay into a <u>massless</u> neutrino. Fortunately, concurrent with the above proposal, Perl[7] brought attention to this omission pointing out that there were <u>no</u> limits at that time on a lepton pair with precisely the properties required of our cosmion, namely that $M_{c^+} - M_{c^0} \lesssim$3GeV and $M_{c^+} \gtrsim$4GeV! Since then old data (from PEP) has been carefully analyzed by two different groups[8] and new experiments [9] (at TRISTAN) performed with the result that the window has been closed considerably. Roughly speaking, for $M_{c^+} \gtrsim$4GeV, a new close-mass lepton pair has been conservatively ruled out unless the mass difference lies in the range 150MeV$\lesssim M_{c^+} - M_{c^0} \lesssim$400 MeV. It is expected that this window will be further reduced by present experiments at Tristan undertaken by the AMY collaboration[10]. Thus, unless nature is playing a diabolic trick it seems unlikely that the magnino hypothesis will survive. We therefore turn to the last component of the standard model, namely higgs exchange.

iii) <u>Higgs Exchange</u>

Like Z-exchange, but in contrast to photon-exchange, the couplings of the higgs to both the cosmion and to matter in the sun are known. There is a low energy theorem [11] which dictates the coupling of a standard higgs to ordinary baryons (B) made of only u and d quarks:

$$< B|h^0|B > = (\sqrt{2}G_F)^{1/2} \sum_q < B|m_q \bar{q}q|B > \tag{7}$$

$$(\sqrt{2}G_F)^{1/2} \left(\frac{2\, n_H}{33 - 2\, n_L} \right) M_B \tag{8}$$

where the sum is over all quarks, $n_{H(L)}$ is the number of heavy (light) quark species. The separation into light and heavy quarks is, roughly speaking, governed by the QCD scale. Thus the assignment of the s-quark is somewhat ambiguous [12] through the consequences of its assignment do not strongly affect the conclusions. The cross-section is readily determined to be [13]

$$\sigma = \frac{8G_F^2}{\pi}\left(\frac{M_B M_W}{M_B + M_W}\right)^2 \left[\frac{n_H M_B M_W}{(33 - 2n_L)m_h^2}\right]^2 \tag{9}$$

The only "unknown" here is m_h. Taking n_L=3 and n_H=5 (assuming that there is a fourth generation of quarks mirroring the presumed fourth generation of leptons) we find that a higgs with mass in the range 700-1000MeV will give a value of $\sigma \sim 10^{-36}cm^2$. Notice, incidentally, that $\sigma \sim M_B^4$ so that heavy elements have enormous cross-sections associated with them. Indeed, one finds that, although helium represents cnly ~10% of the sum, it actually dominates the transport and capture of the cosmions! Furthermore, such large nuclear cross-sections considerably ameliorate the detection of cosmions.

Thus, the existence of a relatively light higgs is necessary for this mechanism to work. Note, incidentally, that in this scenario the mass of any charged partner to the cosmion is no longer constrained and can be as large as one wishes. The above equations were derived assuming the standard single higgs minimal model. However, in such a case there exists a well-known bound [14]: $m_h \gtrsim$7GeV. This bound, can be avoided if there exists either a heavy fermion such as the t-quark with mass ~80GeV or there is more than a single higgs doublet[15]. In the latter case the quoted formulae eqs. (8) and (9) can be amended leading to similar conclusions concerning the lightest higgs [13].

The question now arises as to experimental constraints on such a light higgs. Although this question has recently received considerable attention, the situation is still somewhat murky[16],[17]. This is not the place to try to give anything like a comprehensive review of the problem, however, some general remarks are certainly in order. It is well-known that the higgs is notoriously difficult to pin down mostly because its coupling is so weak [17]. For example, its contribution to $(g-2)_{e,\mu}$ is of order 2×10^{-14} for the election and 1×10^{-9} for the muon both of which are too small, by almost an order of magnitude, to be observed. This is to be compared to the famous $\alpha/2\pi$ for the analogous photon contribution. In the mass range of interest here, limits on the higgs are typically derived from rare K and B decays: e.g. $K \to \pi + h$ or $B \to h + X$ with the subsequent decay $h \to \mu^+\mu^-$ being the signature. Until recently there was serious disagreement in the theoretical estimates of these decays revolving around the strong interaction dynamics. There appears now to be some sort of consensus and recently we[16] have used this to critically re-examine all relevant experiments in this mass range. Our conclusions are illustrated in fig. 2 where the shaded area represents the region excluded by experiment. The bounds are plotted versus m_t since this plays a crucial rôle in the theoretical estimates, due to the fact that the higgs couples to mass. Indeed, typical rates grow like m_t^4.

Another uncertainty in deriving these bounds is the question of the branching ratio for the higgs decay into $\mu^+\mu^-$; below 1GeV, the only other seriously competing mode is that into 2π. This branching ratio can be quite small, its precise value depending sensitively on possible resonant effects or enhancements in the s-wave $\pi\pi$ channel [18]. A recent experiment at Cornell by the CLEO collaboration [19] (reported at this meeting, but not included in fig. 2) has circumvented this problem by detecting both channels (2μ and 2π) in the decay $B \rightarrow K + h$. In this manner they appear to have ruled out a minimal higgs below 1Gev by taking m_t ~80 GeV and assuming only three generations. The question of the number of generations enters these estimates (and is yet another source of uncertainty) through the KM mass matrix. If there are four generations, as we might require for consistency in our model, then this new bound can be circumvented because of uncertainties in the relative phases of the unknown parts of the KM matrix [20]. It should also be re-emphasized that once one goes beyond the minimal model, definitive statements are hard to come by, again because cancellations can "easily" occur, as has been explicitly demonstrated in SUSY models [21].

We should also mention a potentially elegant method for searching for a light higgs, namely through the decay $Y \rightarrow h + \gamma$[22]. This clearly avoids the question of the higgs decay branching ratio even above the 2K threshold since the signature is the detection of a single hard photon. Unfortunately, however, a new problem arises coming from QCD corrections. The width, up to first order α_s radiative corrections, is given by [23]

$$\Gamma(Y \rightarrow h + \gamma) = \Gamma_o \left[1 - \frac{4\alpha_s}{3\pi} a\right] \tag{10}$$

where Γ_o is the tree-graph contribution. Unfortunately, for $M_Y \gg m_h$, a $\approx$10; thus if α_s ~0.2 the correction is ≈85% of the leading term! More importantly, it is negative. This means, that, from a conservative viewpoint (which is the only viable one when making claims about the existence or non-existence of higgs particles!) this formula cannot be trusted. As a measure, however, of where the experiments stand one can use it to compare with the data. The most recent results of the CUSBII collaboration claim that, if one were to take the calculation seriously, then a (minimal) higgs in the range 200 MeV< M_h <5GeV is ruled out [24]. As with the other experiments further theoretical considerations are clearly warranted before general definitive statements can be made.

We therefore conclude that a light higgs ($m_h \lesssim$1GeV) is still very much a viable possibility [18]. In that case, it could, together with a massive neutrino, solve the dark matter and solar neutrino problems. An interesting SUSY variant of this has recently been proposed [25]; recall that typical Majoranas have too small a σ and too large a $\sigma_A V$. However, by defining the lightest neutralino to be a linear combination of the photino, zino and higgsino, one can use the ordinary higgs to enhance σ and the s-wave suppression to suppress $\sigma_A V$. Couplings are not fixed here and some fine-tuning is required for the model to work. Nevertheless, the use of light higgs-exchange is a natural way of resurrecting the possibility of having the lightest SUSY particle play the rôle of the cosmion.

III Direct (and Indirect) Detection of Dark Matter

Up to now we have discussed various particle physics implications of the cosmion hypothesis focusing on the predictions for new heavy leptons and light higgs. We now change focus and briefly discuss ways of directly or indirectly detecting cosmions.

We have already mentioned the possibility of using proton decay detectors to detect energetic neutrinos from cosmion-anticosmion annihilation in the sun: i.e. $c+\bar{c} \rightarrow Z^o \rightarrow \nu_\mu + \bar{\nu}_\mu$. One first needs to estimate how many cosmions are frozen out during the expansion of the universe (i.e. a determination of ρ_c and $\rho_{\bar{c}}$). This is then used as input into eq. (3) to estimate how many $\bar{c}$'s are captured by the sun and then how many neutrinos are subsequently expected to be seen in a typical detector [4]. Clearly, important assumptions need to be made in order to accurately estimate the expected neutrino flux. Nevertheless, there are already interesting (and believable) limits from both Kamioke and Frejus based on an event rate of $\lesssim 2$ per kiloton year[26]. For example, sneutrinos in the range 3-15 GeV and Majorana neutrinos in the range 15-27 GeV are ruled out. Dirac neutrinos, with mass in the range 4-25GeV are also ruled out <u>if</u> they have no cosmic asymmetry. On the other hand, with such an asymmetry (constrained to keep $\Omega = 1$), preliminary estimates indicate that the bound disappears [27]. This is certainly true for the magnino case; for the light higgs case where cross-sections can be enhanced because of the coupling to mass, the situation is becoming a little tight and further improvement in the data could well lead to a serious confrontation with the model.

Other indirect signals for dark matter particles have been suggested [28], such as excess $\bar{p}$'s, e^+'s, γ's etc. from annihilation in the galactic halo however, none of these are as compelling or as reliably estimable as the energetic ν's from the sun. In any case, for the situation we are interested in here, there exists the truly exciting possibility of **direct detection of cosmions** using germanium or silicon diode detectors [29]. When cosmions strike a nucleus they excite electrons into the conduction band creating an electron-hole pair whose current is detected. The small band gap in Ge (0.67eV at 77°K) and, in particular, in Si make these elements ideal dark matter detectors for spin-independent interactions. The present Ge detector [29] is sensitive to nuclear recoil kinetic energies $\sim$10keV which is sufficient to rule out cosmions down to $\sim$7GeV. Further developments in the near future, especially Si, should take the sensitivity down to $\sim$4GeV, **enough to completely rule out the cosmion idea**. The sensitivity depends only mildly on σ; however, in the higgs case because σ is so large for nuclear targets (growing like A^2) one can do a little better. Remarkably, if this scenario is correct, one should observe several thousand events per day per kg. of detector! This is to be compared to approximately 150 events per day per kg. in the magnino case. In either case, it is clear that cosmions are "easy" to detect (and, therefore, easy to rule out!) There are, of course, other detectors being planned which will ultimately be more sensitive (especially to spin-dependent forces) but require a more sohpisticated technology. However, by the time that they are in operation the cosmion question will presumably have been settled.

IV Conclusions

We have tried to show how a relatively simple extension of the standard model can give a "natural" explanation for both the solar neutrino and dark matter problems. What is required is a new stable neutral lepton with a mass in the 4-8 GeV range. One possibility is a fourth generation neutrino interacting with matter either electromagnetically or via higgs-exchange (in addition, of course, to Z^o-exchange). In the former case, a new charged lepton with mass $\sim$10GeV would be required in order to generate a sufficiently large magnetic moment. The present experimental situation makes this possibility rather doubtful. In the latter case, a light higgs with mass $\sim$1GeV is required; this is still not ruled out experimentally. In any case, direct (or indirect) detection of dark matter will, during the next year, seal the fate of this model.

Perhaps one of the most appealing virtues of this model is that it has led to many eminently testable predictions. The particles we have talked about all have masses in a range easily accessible to present-day facilities. Indeed many experiments had already been done before these ideas were expounded – they had simply not been analyzed in a sufficiently general manner and had, by definition of the analysis, already ruled out the predictions! It is refreshing to have a model bearing on fundamental problems, which can be definitively ruled out by experiment. We look forward to the confrontation.

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