1983Ap&SS..89..421S

ASTROPHYSICAL CONSEQUENCES OF BARYTINOS

C. SIVARAM

Indian Institute of Astrophysics, Bangalore, India

(Received 12 August, 1982)

Abstract. Some astrophysical consequences of the newly introduced barytino (massless fermions having baryon number, analogous to the massless neutrino having lepton number) are considered. It is pointed out that the existense of such particles would have interesting implications for understanding astrophysical enigmas like the violation of baryon number conservation in gravitational collapse into black holes and the observed baryon asymmetry of the Universe.

1. Introduction

An inevitable feature of attempts to incorporate gravitation in the framework of grand unified gauge theories of weak electromagnetic and strong interactions through local Fermi–Bose supersymmetry (i.e., supergravity) has been the prediction of the existense of a plethora of massless particles these chiefly being the fermionic counterparts to the gauge bosons mediating the fundamental interactions of the unified theories. For instance one of the main particles postulated is the gravitino, the massless spin-$\frac{3}{2}$ fermionic counterpart to the spin-2 graviton which mediates the gravitational interaction (Freedman *et al.*, 1976). In the $N = 8$ extended supergravity theories one has as many as eight different types of gravitinos (Ellis *et al.*, 1980). Further one has the massless fermionic (spin-$\frac{1}{2}$) counterparts to the other gauge bosons such as the photon, the gluon, etc., these being dubbed the photino and the gluino respectively, one even has the goldstino, the fermionic partner of the Goldstone boson! (Fayet, 1977, 1979). Whereas earlier we just had the neutrino (with all its profound consequences for astrophysics especially in the late stages of stellar evolution) we now have a whole Zoo of massless fermi particles.

Recently the possibility of a new massless fermi particle existing in nature was postulated, i.e. the barytino, the 'baryonic' counterpart to the neutrino (Sivaram, 1981). Briefly the following reasons were given for thinking that such a particle (i.e., a massless spin-$\frac{1}{2}$ particle with baryon number) might exist:

(a) As is well known the massive leptons, i.e., the electron and the muon are accompanied by massless counterparts in the electron and the muon neutrinos respectively, these particles having the same lepton number as the massive particles. We shall not consider the recently raised possibility that the neutrinos may have a small rest mass. Since all leptons have massless counterparts, which can substitute for them in weak interactions, in the spirit of unification, baryon-lepton symmetry would imply that massless particles with baryon number can exist, i.e., a baryon like the proton can also be accompanied by a massless spin-$\frac{1}{2}$ particle. Usually in theories of grand unification, leptons and quarks (constituents of baryons) are put in the same multiplet so that a

Astrophysics and Space Science **89** (1983) 421–428. 0004–640X/83/0892–0421$01.20.

quark can decay or be transformed into a lepton implying that quark composites such as the proton can also decay into a lepton. As quarks have a baryon number (fractional) and leptons do not, this is the basis for proton decay violating baryon number conservation.

(b) The notion that particles having baryon number must necessarily be massive (example given usually is that the proton is much heavier than the electron) is not true. Although quarks carry baryon number, they are supposed to be very light which is part of the reason for quark-lepton unification. For instance the '*u*' quark should ideally have zero mass, at most it can be a few times heavier than the electron (mass of a few Mev). So is the case with the *d* quark. Thus if quarks can have baryon number and be practically massless (as compared to the quark composites, i.e., mesons and baryons) there is no reason why one cannot have zero mass particles with baryon number. Quarks interact strongly (i.e., via strong interactions) in spite of their being light like leptons (such as the electron) not because of their baryon number but because of their colour charge (their flavour being in three colours) and these colour charges are the source of the gluon field which mediates the strong interactions binding the quarks. The colour charge is strong interaction analogue of the electric charge which is the source of the electromagnetic interaction. The electron has no colour charge and thus cannot participate in strong interactions. The barytino is massless and has unit baryon number but unlike the quark has no colour charge and will not therefore interact strongly.

(c) The most recent views on unified models of particles and interactions, believe that quarks and leptons themselves are not elementary but are composites of prequarks (preons), preons possibly being in turn composites of pre-preons etc. These theories involve intermediate mass scales much more closely spaced than the uncomfortably widely spaced mass scales of conventional unified theories. The vast separation between successive energy-breaking scales and far too many Higgs multiplets are some of the 'unnatural' features of the grand unified theories where leptons and the quarks are the elementary entities. The simplest preonic model (Curtright and Freund, 1979) with quarks and leptons as composites of preons assumes 8 preons, 2 flavons, 3 chromons carrying colour and three familons, the light preons corresponding to an SU(8) symmetry. Another model embodying the preoinic theory with its quarks and leptons as preon composites is the Harari–Seiberg model (Harari and Seiberg, 1981) where there are 18 preons. The preons can bind into both light and heavy composites so that even the light electron and the massless neutrino (chirality protecting it from acquiring a mass) can be pictured as composites of preons. As quarks with their light masses and baryon number are themselves preon composites, it is not difficult to picture a massless particle with baryon number as yet another derived particle. This would be the barytino analogous to the massless neutrino (which has lepton number and is itself a preon composite!).

2. Interactions of the Barytino

The existence of the barytino would have interesting implications for particle physics. In the grand unified theories, proton decay into positrons, muons or pions inevitably implies a violation of baryon number conservation as neither mesons nor leptons carry baryon number. However as discussed above the massless barytino would have a baryon number enabling the proton to decay as

$$p \to e^+ + \nu_e + \nu_B , \tag{1}$$

where ν_e is the electron neutrino with unit lepton number and ν_B is the symbol adopted for the barytino with unit baryon number. We see that the decay process (1), conserves both baryon and lepton numbers unlike the usual decay schemes for the proton such as $p \to e^+ + \pi^0$, $p \to \mu^+ + \nu$, etc.; of course all these decay schemes as predicted by the unified theories would also be there and would not be affected by the additional decay scheme, (1) made possible by the presence of the barytino ν_B. It will be seen that (1) is analogous to the decay of the muon – i.e., $\mu \to e + \nu_e + \nu_\mu$ – which is made possible by the existence of the muonic neutrino having the same lepton number as the muon thus leading to the lepton number conserving decay. The decay of the muon into an electron and two distinct neutrinos has a transition rate determined as is well known by the four-fermion, Fermi weak interaction. The expression for the muon lifetime as calculated from this interaction is given by

$$\frac{1}{t_\mu} = \frac{7M_\mu^5 c^4 G_\mathrm{F}^2}{7680\pi^3 \hbar^7} , \tag{2}$$

where G_F is the universal Fermi constant and M_μ is the mass of the muon. The value of t_μ turns out to be $\sim 2 \times 10^{-6}$ s.

We can use a similar expression to estimate the proton decay rate by the reaction (1). In fact this is justified as grand unified theories predict nucleon decays to occur through effective four-fermion interactions mediated by exchanges of superheavy bosons (Ellis, 1982). By analogy with the expression for the Fermi weak interaction, $g^2/8m_w^2 = G_\mathrm{F}/\sqrt{2}$, m_w being the intermediate boson mass we can write for the corresponding grand unified coupling constant ($\mathrm{G_{GU}}$) as

$$g^2/8m_x^2 = \frac{G_{GU}}{\sqrt{2}} ,$$

where m_x is the mass of the superheavy X-boson mediating the baryon decay. The decay amplitude $A \propto 1/m_x^2$ and hence the decay rate $\Gamma \propto 1/m_x^4$ and as the decay rate has the dimensions of mass it must be scaled by the nucleon mass to the power of five, so that $\Gamma \propto m_N^5/m_x^4 \propto G_{GU}^2 m_N^5 \propto 1/t_N$ (t_N being the nucleon life time) in complete agreement with Equation (2). For $m_x \approx 10^{15}$ GeV (as in most unified theories),

$$G_{GU} \approx G_\mathrm{F} \left(\frac{m_w}{m_x}\right)^2 \simeq 2 \times 10^{-75}\,\mathrm{ergs\,cm^3} \quad (m_w \sim 100\,\mathrm{GeV}) .$$

Substituting G_{GU} and m_N instead of G_F and M_μ in Equation (2) gives the proton decay time into a barytino to be $\sim 10^{31}$ yr. Particles such as the barytino are not to be detectable as copiously as the neutrino since the interactions in which they participate are very weak (much weaker than neutrino weak interactions) at ordinary energies. Analogous to that of neutrino reaction cross-sections one can estimate the cross-sections of barytino processes for apart from the coupling constant G_{GU} being much weaker than the Fermi constant G_{F}, the interaction is of the same nature and form. The cross-section for the annihilation of a lepton-antilepton pair into neutrinos (i.e., $e^+ + e^- \to \nu + \bar{\nu}$) is of the form $\sigma \sim G_{\mathrm{F}}^2(E_{e^+} + E_{e^-})^2$, where E_{e^+} and E_{e^-} are the energies of the positrons and electrons, respectively. As is well known, these neutrino processes have cross-sections rising with the square of the energy and become far more important than corresponding processes involving photons if the temperatures of the stellar interiors approach a few billion degrees. Processes such as neutrino bremstrahlung, photoneutrino processes and neutrino pair production all of which have cross-sections rising with energy (unlike that of electromagnetic processes) can drastically influence the late stages in the evolution of a giant star. Again in the early stages of the big bang when the temperatures are $\sim 10^{11}$ K (i.e., the lepton era) the weak interactions involving neutrinos are strong enough to maintain thermal equilibrium among various particle species especially among neutrons and protons via $p + \bar{\nu} \rightleftarrows n + e^+$, $\nu + n \rightleftarrows p + e^-$, etc. It is because the weak interactions weaken when the temperature (and, hence, energy) falls as the Universe expands that the neutrinos decouple (weak interactions no longer strong enough to maintain equilibrium) from the rest of the matter and would now constitute a background with a temperature ~ 2 K. The fact that the weak interactions become stronger as the energy increases is related to the fact that the coupling constant G_{F} of the four-fermion theory of weak interactions is dimensional,

$$G_{\mathrm{F}} = 10^{-5}/m_N^2\,, \qquad m_N = \text{nucleon mass}\,.$$

As the barytino processes are also governed by a four-fermion theory, it follows that the cross-sections for two-particle processes must behave at high energies like $\sigma \sim G_{GU}^2 S$, where $S = 4\mathrm{E}^2$, E being the energy of the particles in the C.M. frame. The cross-sections of the elastic processes involving production of n particle pairs will go as $\sigma_n \sim G_{GU}^2 S(G_{GU}S)^{2n}$, implying that for energies of $S \sim 1/G_{GU} \sim 10^{14}$ GeV the interactions become effectively strong and the cross-sections have large values. Thus at a sufficiently early stage of the big bang with energies $\sim 10^{14}$ GeV, processes involving the production of barytinos, such as annihilation of particle pairs to barytinos, interactions like $p + \bar{p} \to \nu_B + \bar{\nu}_B$, would be as copious as neutrino interactions at a later stage, i.e., the lepton era. When energies drop below 10^{14} GeV, as the Universe expands, the barytinos would rapidly decouple as their interactions become superweak at lower energies. Thus barytinos, if they exist, would have decoupled much earlier in the evolution of the Universe than the neutrinos, which decouple at energies ~ 1 MeV.

Once they decouple, they do not benefit from any subsequent heating and their abundance relative to ordinary neutrinos is diluted. We shall elaborate this in the next section. What about low-energy signatures of the barytino? We have already said that proton decay can take place via decay into a positron, barytino and electron neutrino; through reaction (1), with a transion rate given by Equation (2) G_{GU} and m_N replacing

G_F and M_μ or into a positive muon, muon neutrino and a barytino (i.e., $p \rightarrow \mu^+ + \nu_\mu + \nu_B$) with a transition rate given by Equation (2) multiplied by a factor $(1 - 8\delta + 8\delta^3)$ where $\delta = (m_\mu/m_p) \approx 0.1$ (implying more or less same life-time). These proton decays with barytino production have the same life-time ($\sim 10^{31}$ yr) as the decays usually pictured in grand unified theories where pions and other mesons are produced. Only in these decays baryon number is not violated as the barytino has a baryon number. Owing to current interest in the large number of experiments being planned to detect proton decay (Florini, 1982) the distinct theoretical possibility of decays which involve the barytino must be kept in mind. In the usual decay modes envisaged most of the energy will go in gamma rays and positrons; if the barytino is a by product in some decays, the energies of the positrons and gamma rays might be reduced and may not all add up to 1 GeV (i.e., the proton rest mass). So far there is no unambigous signature of proton decay and hence decays such as (1) must be borne in mind as a possibility. The barytino can give rise to other interesting interactions; $e^+ + \nu_B \rightarrow p + \nu_e$, (conversion of lepton to a baryon, Equivalent of a charged current weak interaction where a neutrino is converted to a charged lepton) $e^- + \bar{\nu}_B \rightarrow \bar{p} + \nu_e$ ($\bar{p}$ is antiproton) or the reverse reaction

$$\bar{\nu}_e + p \rightarrow e^+ + \nu_B\,, \qquad \bar{\nu}_\mu + p \rightarrow \mu^+ + \nu_B\,,$$

$$\bar{\nu}_B + n \rightarrow p + \bar{p} \rightarrow e^+ + e^-\,, \qquad \text{etc.}$$

Of course the cross-sections for all these interactions would be very low at ordinary energies the reaction rates being of the same duration as the proton decay time. However while looking for proton decay in specially designed experiments the possibility of the above reactions must perhaps be taken into account. The 'Calorimetry' or a meticulous energy inventory of proton decay events may lead to a detection of these particles.

3. Long-Range Barytino Interactions

That there may be a long range field (mediated by a massless vector boson) associated with baryon number conservation analogous to the electromagnetic field was suggested long ago (Lee and Yang, 1955). As in the Lee–Yang analogue of the electric field, the force is proportional to the nucleon number of the atom, the null result of the Eötvös and Dicke experiments implies that if it exists the Lee–Yang interaction is only about 10^{-7} of the gravitational interaction, since the Eötvös experiment demonstrated with an accuracy of about 5 parts in 10^9 that gravitational accelerations are independent of the atomic weight of the falling body. While the great weakness in itself does not imply non-existense of the field, Dicke (1962) used a symmetry argument based on the isotropy of space to rule out existence of the field. From the isotropy of space (i.e., no preferred direction) the average vector field must vanish with all its components, i.e., $F^{ij} = 0$, and from the Maxwell-like equations of the Lee–Yang field, the nucleon-four current, $J^i = F^{ij}, j$, must also vanish implying equal numbers of nucleons and antinucleons (as nucleon number density of space is zero). This would be contradicted by observations as the observed photon density of space is far too small for equal numbers of nucleons and antinucleons. Thus the Lee–Yang field does not exist by isotropy arguments. However, apart from longrange coulomb forces (which neutralize due to equal numbers of positive and negative charges) there are second order effects in the electromagnetic interactions like the Van der Waals force due to the exchange of two photons with a potential of the form, $V \simeq (e^2/r)(r_B/r)^5$, r_B being the Bohr radius.

There is an analogue of similar origin for the weak interactions arising from the exchange of a neutrino-antineutrino pair, from interaction terms of the form $L \sim (e\bar{e})(\nu\bar{\nu})$ i.e., an electron current coupled to a $\nu\bar{\nu}$ pair. The calculation of such pair lepton forces was first carried out by Tamm and Ivanenko (1934) who found the potential for such an interaction as $V = -(2\pi)^3(\Lambda_F/R)^5 M_F c^2$, Λ_F being the beta decay length, $M_F = h/\Lambda_F c$. The difference from the electromagnetic interaction comes about as for the weak interaction one has in momentum space $G_F^2 p^2$ instead of $e^2\delta(p)$, G_F^2 having dimension of $(10^{-5})^2/m_p^4$. So averaging over the mass distribution one gets from phase space we get for the weak potential between two leptons due to this force as

$$V_w \simeq G_F^2/r^5 = 10^{-10} r^{-1} (\lambda_p/r)^4 , \tag{3}$$

where λ_p is the proton compton wavelength. Comparing this with the corresponding gravitational potential between two leptons i.e., $V_G = \alpha_G/r = 10^{-38}/r$, ($\alpha_G = Gm_p^2/hc = 10^{-38}$). We see that for distances $r > 10^7 \lambda_p \sim 10^{-7}$ cm, the gravitational force dominates over the long-range weak interaction forces (i.e., over distances larger than a typical molecular distance).

One can envisage a similar long-range force arising between two baryons as a result of exchange of a barytino-antibarytino pair. By analogy with the neutrino case, the potential between two baryons, can be written as

$$V \simeq G_{GU}^2/r^5 \simeq G_F^2 \left(\frac{m_w}{m_x}\right)^4 \frac{1}{r^5} . \tag{4}$$

Comparision with the gravitational potential shows that this force is overhelmed by gravitational forces even at subnuclear distances! Thus there is no contradiction with Eötvös–Dicke experiments unlike the case of the Coulomb-like Lee–Yang vector field (the $1/r^5$ dependence damping out the force very fast). The only situation when such a force might be of some significance is during the earliest phase of the big bang when the GUTS regime is dominant.

4. Astrophysical Consequences

As discussed in Section 2, in the very early stages of the big bang when the energies $\sim 10^{14}$ GeV, processes involving the production of the barytino were very efficient and barytino interactions would be as strong as neutrino interactions were at a later stage (i.e., lepton era) of the big bang. Once the energies dropped as the Universe expanded, the barytinos would have decoupled (like the neutrinos would after the lepton era) as their interactions would become superweak. In fact the possibility of superweakly interacting particles (such as right handed neutrinos, gravitinos, etc.) which decoupled very early in the big bang (long before nudeosynthesis at ~ 1 MeV) was considered by Steinman *et al.* (1979) and constraints were put on such particles. As noted before such particles would not be subsequently heated and their abundance (N^{sw}) relative to the ordinary neutrinos would be diluted according to (T_d being their decoupling temperature):

$$N^{sw}(T) = N_\nu(T)[N_\gamma(T_d)/N_\gamma(T)]\,,$$

and their contribution to the total density would also be reduced by the same factor raised to $\frac{4}{3}$*rd* power. Thus the earlier they decouple the less they contribute and more such particles can coexist without violating the nucleosynthetic constraint. However a significant aspect of these 'fossil' barytinos would be that each of them carries a unit baryon number. Of course fossil antibarytinos each having a negative unit baryon number would also be present. In the case of fossil neutrinos and antineutrinos (they carry lepton number) it is usually assumed that they are present in equal number; a difference in numbers of 1 part in say 10^8 or 10^9 would not make any difference either to nucleosynthesis or to the subsequent evolution of the universe. Similarly an excess of fossil barytinos over antibarytinos or vice versa would give the universe a net baryon number. As is well known the universe seems to have a net baryon number of $\sim 10^{80}$, there being far more nucleons (protons) than antinucleons, i.e., a universe with equal amounts of matter and antimatter is untenable with the oberved γ-ray photon background. But if there were more fossil antibarytinos than barytinos, this baryon number could be cancelled and we can still have a universe with zero baryon number. This would be one of the consequences of the existence of the barytino. The massless barytinos would not contribute significantly to the overall density (thus nucleosynthesis, photon background and dynamical features would be unaltered) but would have the effect of drastically altering the baryon number. Thus with barytinos we could have a zero baryon number universe which could be pleasing from symmetry considerations. A small asymmetry in the barytino background would give a Universe with net zero baryon number. The asymmetry could be produced by CP violation in particle decays analogous to that in neutral Kaon leptonic decay modes. (Sivaram, 1982a, b) Barytinos may also provide a possible solution to the problem of the violation of conservation of baryon number when a massive object collapses to form a blackhole. Baryon number is not an observable quantity (i.e. signature) for a black hole; only mass, charge (electric) and angular momentum are detectable quantities. Thus when an object of $N > 10^{58}$ nucleons collapses to form a black hole, we have apparently a drastic violation of baryon number conservation once the object is inside the event horizon. However as the gravitational binding energy approaches the rest energy of the particles, the effective mass of a baryon can tend to zero and one can have interactions favouring the production of barytinos. These being massless and travelling at light velocity can escape from the black hole into the surrounding space carrying the baryon number of the black hole with them. An analogous situation arises in the formation of neutron stars where an apparent violation of lepton number conservation appears to take place. Neutrons are formed by inverse beta decay (i.e., electron capture by nucleons). So we start out with a certain lepton number (associated with electrons) and a baryon number (associated with nucleons). All the electrons are captured and only neutrons remain; so that the baryon number is preserved whereas the lepton number appears destroyed. But each electron capture is accompanied by emission of a neutrino ($e^- + p \rightarrow n + \nu$) which escapes from the star. So the formation of a neutron star is accompanied by the emission of 10^{57} neutrinos which escape away from the star carrying away the lepton number. So although the neutron star has no measurable lepton number, there is no violation of lepton number globally as the neutrinos have been produced in an equal amount to that of the electrons captured and have carried away the lepton number while escaping away from the neutron star (Sivaram, 1982a). The barytino can be envisaged to play a similar role in carrying away the baryon number while escaping from the black hole. So we don't need to worry about baryon number being destroyed by a black hole any more than we worry about lepton number being destroyed in the formation of a neutron star (Sivaram, 1982b).

References

Curtright, T. L. and Freund, P. G. O.: 1979, in P. Van Nieuwenheuizen and D. Z. Freedman (eds.), *Supergravity*, North-Holland, Amsterdam.
Dicke, R. H.: 1962. *Phys. Rev.* **126**, 1580.
Ellis, J.: 1982, *Phil. Trans. Roy. Soc. London* **304**, 69.
Fayet, P.: 1977, *Phys. Letters* **70B**, 461.
Fayet, P.: 1979, *Phys. Letters* **84B**, 421.
Florini, E.: 1982, *Phil. Trans. Roy. Soc. London* **304**, 105.
Freedman, D. Z., Van Nieuwenheuizen, P., and Ferrara, D.: 1976, *Phys. Rev.* **D13**, 3214.
Harari, H. and Seiberg, R.: 1981, *Phys. Letters* **98B**, 269.
Lee, T. D. and Yang, C. N.: 1955, *Phys. Rev.* **98**, 1501.
Sivaram, C.: 1981, *Phys. Rev.* (to be published).
Sivaram, C.: 1982a, *Astrophys. Space Sci.* **82**, 485.
Sivaram, C.: 1982b, (in preparation).
Steigman, G., Olive, K. A., and Schramm, D. N.: 1979, *Phys. Rev. Letters* **43**, 239.
Tamm, I. E. and Ivanenko, D.: 1934, *Nature* **133**, 981.