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ASYMMETRIC LEPTON PRODUCTION IN A UNIVERSE WITH NON-ZERO BARYON NUMBER

(Letter to the Editor)

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Abstract. It is pointed out that as a result of processes during different stages of stellar evolution a universe with a net baryon number develops during a Hubble age an excess of neutrinos over antineutrinos of the same order as the observed relative strength of CP violation. The same processes also favour excess positron production.

1. Introduction

In a recent paper, Okeke *et al.* (1981) attribute the inequality of the electron-positron component of cosmic rays to CP-violating processes operating in various sources such as supernova remnants, black holes etc., and also conclude that the implications of this would be less neutrinos than antineutrinos in the universe.

However, the only known case where CP violation definitely occurs is in the decay of the longlived neutral K-meson (Christenson *et al.*, 1964). In fact, the more abundant leptonic decay mode of the long-lived neutral K – i.e., K_L – is that associated with the positron and the neutrino rather than the electron and antineutrino. In other words,

$$\frac{(K_L \rightarrow \pi^{-1} e^+ \nu)}{(K_L \rightarrow \pi^+ e^- \nu)} > 1. \tag{1}$$

This asymmetry in the decay of the same particle into charge-conjugated final states is a clear indication of CP-violation and is sufficiently well established for positive charge to be now defined as that of the lepton associated with the more abundant leptonic decay mode of the K_L meson – i.e., the positron. The fact that neutrinos are simultaneously produced with the positron enables one to uniquely define 'left-handed' as the 'helicity of the massless fermion produced in the more abundant decay of the long lived neutral kaon'. The relative strength of the CP-violating component is 10^{-9}, i.e. of superweak order (Wolfenstein, 1966). This ratio is of the same order as the baryon to photon ratio in the universe. This has led many authors (Yoshimura, 1978; Toussaint *et al.*, 1979) recently to propose baryon violating as well as CP-violating interactions in the early big-bang to generate the baryon excess of $N = 10^{78}$ in the present universe. Most theories of grand unification of fundamental interactions do predict baryon number violating interactions which are very weak at ordinary energies but significant at energies of 10^{15} Gev in the early universe. The important point is that baryon non-

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conserving processes alone are not enough, but CP-violating interactions with their characteristic asymmetric decay into charge conjugated states are essential for generating a net baryon number. The fact, however, remains that irrespective of the mode of generation of a baryon excess, the universe has a net baryon number of $N = 10^{78}$, and that the only known case of CP-violation in particle physics favours more production of positrons and neutrinos rather than electrons and antineutrinos.

It is also usually assumed that a net baryon excess would also be balanced by a corresponding excess of electrons over positrons to maintain charge neutrality. Again equal numbers of neutrinos and antineutrinos are assumed to be produced during the big-bang, as any excess of one over the other would affect primordial helium abundance.

In the following sections we shall indicate that once a universe forms with a net baryon number, subsequent processes chiefly as a result of various stages of stellar evolution would favour production of an excess of neutrinos and positrons.

2. Main-Sequence Stellar Evolution

A universe with a positive baryon number of $N = 10^{78}$ would, during subsequent evolution, form stars which owing to well-known reasons (such as requirements of igniting thermonuclear reactions and stability against radiation pressure) contain on an average 10^{57} baryons each. Each of these stars would undergo thermonuclear processes during a Main-Sequence lifetime of 10^{10} years on the average. The thermonuclear processes which occur in these stars, whether involving the proton-proton chain, the CNO cycle or the nucleosynthesis of heavier elements, systematically convert protons into neutrons, and this takes place through the weak interaction process of positron decay when positrons as well as neutrinos are emitted. For instance, in each set of reactions of the p-p chain as well as the CNO cycle, converting hydrogen into helium, two positrons and two neutrinos are emitted. Every second 10^{38} of these sets of reactions (the p-p cycle) generate the Sun's energy. This implies that, every second, the Sun produces 2×10^5 tons of positrons as well as 2×10^{38} neutrinos. The positrons of course get annihilated producing in the process about 10% of the Sun's energy while the neutrinos escape. For anti-matter stars, which would exist in a universe with a negative baryon number, exactly the same processes will take place – except that the nuclear-fusion processes will convert antiprotons to antineutrons, thus producing antipositrons – i.e., electrons and correspondingly antineutrinos. Therefore, we see that a universe containing 10^{21} stars would produce over a Hubble age ($\sim 10^{18}$ s) about 10^{78} neutrinos. These neutrinos would freely escape from the stellar interiors and would fill the universe. We shall see in the next two sections that other stellar processes also favour positron and neutrino production.

3. Supernova Explosions

It is now generally believed that nuclear fusion processes in a massive star terminate with the production of a large quantity (about one solar mass) of the isotope ^{56}Ni at the peak of the binding energy curve. The ^{56}Ni decays by electron capture and positron decay to ^{56}Co which further decays again by positron emission to ^{56}Fe. Both these decays are accompanied by neutrinos. A large fraction of the energy released after a supernova explosion is ascribed to this decay sequence. Thus the decay of a solar mass of ^{56}Ni would result in the production of at least 10^{57} neutrinos. With a conservative estimate of one supernova per galaxy every 50 yr, this would result in a production of about 10^{76} neutrinos during a Hubble age as a consequence of supernova explosions.

4. Neutron Stars and Black Holes

Neutron stars are formed by inverse beta-decay, such as the capture of electrons by protons and heavier nuclei. Each such capture is accompanied by emission of a neutrino. So the formation of a neutron star of about 10^{57} neutrons results simultaneously in the emission of 10^{57} neutrinos. If we assume a billion neutron stars to form in a galaxy during a Hubble age, this would result in 10^{77} neutrinos averaged over the universe. In all the above cases, we did not invoke CP violation to produce an asymmetry of neutrinos over anti-neutrinos.

One case where it would be important is in the evaporation of black holes (Hawking, 1974). To see this, consider the hottest black holes in the universe at the present epoch. They would be the ones with lifetimes of the Hubble age ($1/H$) which means their mass would be given by

$$\frac{1}{H}=\frac{G^2M^3}{hc^4}, \quad \text{or} \quad M=\left(\frac{hc^4}{G^2H}\right)^{1/3}. \tag{2}$$

The corresponding temperature would be

$$T=\frac{hc^3}{8\pi GK\left(\frac{hc^4}{G^2H}\right)^{1/3}}\simeq 10^{12}\,\mathrm{K}, \tag{3}$$

or 100 MeV in energy units

Most part of the emission from these hottest black holes would be in the form of π-mesons. The K-mesons would be suppressed by a Boltzmann factor of about e^{-3} (as $m_K = 3m_\pi$). Such black holes would emit about 10^{22} kaons every second. Since CP-violation is definitely known to exist in the neutral kaon system, in say about one leptonic decay per 500, this would definitely result in more positrons and neutrinos being produced. Again neutral kaons are also produced in high energy proton collisions and their subsequent decay would again lead to the same result.

5. Conclusions

As in generally assumed, if during the big-bang equal numbers of neutrinos and antineutrinos are produced, this number being about 10^9 per baryon (i.e., the same as the number of photons per baryon), it is seen that a universe with a positive baryon number develops during a Hubble age an excess of neutrinos over antineutrinos of about one part in 10^9 (as seen in Section 2, 10^{78} neutrinos were produced) as a result of the processes of stellar evolution. This is remarkably of the same order as the relative strength of CP-violation. Since the neutrinos have a 'left-handed' helicity, an initially symmetric universe would become weakly left-handed after a period of about 10^{10} yr.

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