ASTROPHYSICAL CONSEQUENCES OF NEUTRON-ANTINEUTRON OSCILLATIONS

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Abstract. Grand unified theories predict baryon number violating interactions and one of the implications of this is the possible existence of neutron-antineutron oscillations. The neutron-antineutron oscillations have been considered in the neutron rich astrophysical sources such as solar flares, supernovae explosions, neutron stars and the nucleosynthetic phase of the early universe in order to partly account for the antiproton flux of the cosmic rays at low energies and the γ-ray emission, at GeV energies. Low magnetic fields and high neutron concentrations provide the right environment for the production of antineutrons and hence antiprotons and GeV γ rays.

1. Introduction

The phenomenon of neutron-antineutron ($n - \bar{n}$) oscillations is one of the possible outcomes of the grand unified theories of strong, weak and electromagnetic interactions. These theories predict the violation of baryon number. The baryon nonconserving interactions are mediated by super heavy gauge bosons. The $n - \bar{n}$ transition is a first order process involving a baryon number change of 2. This is analogous to the well-known phenomenon of strangeness oscillation in the neutral K meson system i.e. $K_0 \leftrightarrow \bar{K}_0$, which involves a strangeness change of 2. A number of theoretical models have been proposed to estimate the average transition time for the oscillations $n - \bar{n}$, Kuzmin (1978), Glashow (1979), Mohapatra and Marshak (1980). The characteristic time of such oscillations is predicted to be between 10^5 to 10^7 s, and the associated transition energies (Δe) are of the order of 10^{-20} eV. The β decay of the antineutron so formed results into an antiproton, a positron and a neutrino. This mechanism has been recently considered (Sawada *et al.*, 1981) to generate the cosmic ray antiproton flux, however, the neutron flux produced during the spallation of cosmic ray nuclei in the interstellar space is low because of the low He^4/p ratio. The $n\bar{n}$ mechanism is expected to be important wherever large fluxes of low energy neutrons are produced or present. Therefore, in this paper, we consider the consequences of $n\bar{n}$ oscillations in several astrophysical situations like the Sun during flare stage, supernovae explosions, neutron stars and the nucleosynthetic stage of the big bang. We discuss these cases as follows:

2. Solar Flares

Fairly large fluxes of neutrons have been observed during solar flares. The highest value of the neutron flux of 30–70 neutrons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ has been noted by

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Lingenfelter *et al.* (1965) during the major cosmic ray flare of November 12, 1960. If one considers a free beam of neutrons travelling from the Sun to the Earth, one can calculate the number of antineutrons produced during their travel time (t) ($\sim 10^4$ s) from the relationship

$$\bar{n}(t) = n_0\left[\frac{(\Delta e)^2}{(\Delta e)^2 + (\Delta E)^2}\right] \sin^2[(\Delta e)^2 + (\Delta E)^2]^{1/2} t\,, \tag{1}$$

$$\Delta e = \hbar/\tau$$

where τ is the oscillation time, we find for $\Delta E = 0$, i.e. free neutrons and $t < \tau$:

$$\bar{n}/n \sim (t/\tau)^2 = 10^{-2} \quad \text{for} \quad \tau \sim 10^5\ \text{s}.$$

Evidently this antineutron flux is quite high and the inclusion of the magnetic field is warranted. In the presence of the magnetic field, the $n - \bar{n}$ oscillations are inhibited because of magnetic splitting of the neutron energy levels, given by $\Delta E = g\mu B$ where g is the anomalous gyromagnetic ratio of the neutron, $\mu = e\hbar/2M_n c$ and B is the magnetic field. Using Schrödinger equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\bar{n}(t) = H\bar{n}(t)\,,$$

with the Hamiltonian H in the presence of magnetic field given by

$$H = \begin{pmatrix} E_0 + \Delta E & \Delta e \\ \Delta e & E_0 - \Delta E \end{pmatrix},$$

one finds the transition rate $\bar{n}/n$ to be

$$\frac{\bar{n}}{n} \simeq \frac{1}{2}\left(\frac{\Delta e}{\Delta E}\right)^2, \tag{2}$$

where E_0 is the neutron rest energy (one can neglect the width Γ_n of the neutron decay)

$$\Delta e = \hbar/\tau \simeq 10^{-32}\ \text{ergs and}\ \Delta E = 9.6 \times 10^{-24} B\ \text{ergs}\,,$$

and B is in gauss. Assuming $B \sim 10^{-5}$ G at 1 AU and $n \sim 70\ \text{cm}^{-2}\,\text{s}^{-1}$ from Equation (2), we find that in 100 s (duration of the flare) and for a 1 m^2 detector, one can detect about 0.4 events which should manifest as one γ ray event in the GeV energy range ($n + \bar{n} = 2\gamma$) in addition to the lower energy ~ 100 MeV γ rays produced through $n\bar{n}$ annihilation into pions and subsequent emission into γ rays. In the past γ rays of few MeV have been detected during solar flares (Švestka, 1976). The present consideration would suggest that attempts should be made to detect GeV γ-ray events during outstandingly large solar flares.

It is interesting to note the effect of solar activity on the background cosmic ray intensity. It is well known that during flares the solar wind sweeps away the low energy cosmic rays resulting in Forbush decrease. On the other hand, the generation of antiprotons through $n-\bar{n}$ oscillations comes into play only during the solar flare at which time a large neutron flux is produced.

3. Supernovae Explosions

A supernova explosion is expected to release a very large number of neutrons. It is commonly accepted that prior to the explosion, most of the neutron rich isotopes are created so that the heavy nuclei in the expanding shell are bathed in a steady flux of neutrons. There are several ways in which the neutrons may be generated, for instance the supernova shell is sufficiently dense for the heavy nuclei to interact and produce neutrons by breakup or charge exchange. Nuclear statistical equilibrium distributions dominated by extremely neutron rich nuclei are expected for the large neutron to proton ratio which characterizes this matter. One expects total ratios of neutrons to protons reaching 2–8 (Truran, 1977). In effect every supernova explosion might shoot out 10^{57} free neutrons into interstellar space, the rest having been captured. Using Equation (2), one finds the value of the ratio $\bar{n}/n$ or alternately $\bar{p}/n$ to be

$$\frac{\bar{n}}{n} \simeq \left(\frac{10^{-32}}{9\times 10^{-24}}\right)^2 \left(\frac{1}{10^{-7}}\right)^2 \simeq 10^{-4} \tag{3}$$

for an interstellar magnetic field of $\sim 10^{-7}$ G. Taking n/p as ~ 10, one gets

$$\frac{\bar{p}}{p} \sim 10^{-3}\,. \tag{4}$$

It has recently been observed (Stephens, 1981a) that the ratio of $\bar{p}/p$ in cosmic rays increases with decrease in energy and is $\sim 10^{-4}$ at energies < 1 GeV, whereas it is $\sim 10^{-3}$ at 10 MeV, the latter energy being of the same order as the energy of most of the neutrons in the supernova explosion. Equation (4) would imply that out of the 10^{57} free neutrons, shot out of the supernova into interstellar space, 10^{54} of them would ultimately get converted into antiprotons. A cosmic ray density of 1 eV/c.c. and a galactic volume of 10^{68} c.c. would give a total of 10^{59} protons. The observed average $\bar{p}/p$ ratio would then require 10^{55} antiprotons to be present in the galaxy. We thus see that a few supernova explosions are fully capable of accounting for the background antiproton flux.

All previously proposed mechanisms (Stephens, 1981b) for the generation of antiprotons are at relativistic energies and require $\bar{p}/p$ to decrease with decreasing energy since the threshold for production of $\bar{p}$ from these mechanisms $(p+p\rightarrow p+p+p+\bar{p})$ is 2 GeV. This is in contradiction with the observations where $\bar{p}/p$ increases at lower energies (Stephens, 1981a). Thus, as pointed out above, the $n-\bar{n}$ oscillations may account for the antiproton populations at low energies in neutron-rich matter ejected in the supernova explosions. One may also note that the energies of the neutrons produced by solar flares are also in the range of a few MeV. Therefore, these neutrons, through neutron oscillations would contribute additionally to the cosmic ray antiproton flux, especially during large solar flares. We may also remark that during the earlier denser phase of the supernova shell expansion, a copious number of GeV γ-rays would be produced as a result of $n - \bar{n}$ annihilation. Various γ-ray lines have already been detected in supernova shells. Observations of the GeV γ-ray lines following a supernova explosion could provide confirmation of the $n - \bar{n}$ oscillation phenomenon. It may also be added that the DUMAND project is expected to be sensitive enough to register neutrons from supernova explosions.

4. Neutron Stars

Another rich astrophysical source of neutrons is of course the neutron star with an agglomeration of 10^{57} neutrons. However, because of the high magnetic fields (10^{12} gauss) believed to be present in such stars, the phenomenon of neutron oscillations is completely suppressed as shown by Equation (2). As the neutron star ages, the magnetic fields decay at a rate given (cf. Hewish, 1981) by

$$B = B_0 \exp\left[\frac{-t}{0.2 \times 10^6\ \text{yr}}\right], \tag{5}$$

one can rewrite Equation (2) as

$$\frac{\bar{n}}{n} = \left(\frac{10^{-32}}{9 \times 10^{-24}}\right)^2 \left(\frac{1}{B_0^2 \exp - t \times 2/0.2 \times 10^6\ \text{yr}}\right). \tag{6}$$

We thus find that after a time $t \sim 4 \times 10^6$ yr, there will be a comparable number of neutrons and antineutrons. At such times the neutron-antineutron annihilation will be very rapid (owing to the high densities) as compared to the antiproton production due to β decay. Thus at this stage of the neutron star, a large amount of energy could be explosively released in the form of GeV γ rays. One can probably associate some of the intense γ ray sources (radiating more than 10^{46} ergs s^{-1} in > 100 MeV γ rays) to this terminal evolutionary stage of the neutron stars.

The phenomenon of $n - \bar{n}$ oscillations can be of relevance even during the active phase of some neutron stars in which stochastic fluctuations in the period of the pulsar are observed. The phenomenon is attributed to glitches. These glitches are supposed to be the release of γ ray energy from the superfluid core to the crustal surface of the neutron star, Hewish (1981), Manchester and Taylor (1977), Bhat *et al.* (1981). Since the superfluid region is known to support quantized magnetic vortices, there will be regions of weak or no magnetic field in the core. This would be the right place for the neutrons to oscillate and thus produce antineutrons. The annihilation $n\bar{n}$ can give rise to an energy release of 10^{41} ergs if there are 10^{44} pairs of $n\bar{n}$ formed, which is a very small fraction of the total number of neutrons in the core. The formation time of these pairs lies between 10^5 to 10^7 s which is of the order of the observed recurrence time of the glitches.

5. Nucleosynthetic Stage of the Early Universe

The nucleosynthetic stage of the big bang, i.e. the epoch during which deuterium and helium were synthesized provides another possible scenario where the phenomenon of neutron oscillations can manifest itself. Neutrons were present in great abundance during the first 100 s of the big bang. The fusion of neutrons and protons through $n + p \rightarrow D + \gamma$ led to the (irreversible) synthesis of D, as a first step in the formation of helium. During these 100 s, if the phenomenon of $n - \bar{n}$ oscillations does occur, then from Equation (1), it follows that about 0.1% of the neutrons would have been converted into $\bar{n}$ (with $\tau \sim 10^5$ s) and owing to the high density, these $\bar{n}$ would have annihilated with the neutrons. If we now put the constraint that there should not be too many high energy γ rays to photodisintegrate the deuterium formed, then it follows that the energy of the annihilation (10^3 times the fusion energy) should not exceed the energy released in the formation of D and this restricts the number of antineutrons produced in 100 s to 0.1% of the total number of neutrons. Thus it follows that the oscillation time could not be less than 10^5 s. This oscillation time is also consistent with consequences of $\bar{n}$ production in other situations as discussed in Sections 2, 3, 4.

Another constraint can come from the fact that the rate of conversion of neutrons to protons (via $\nu + n \rightarrow p + \bar{e}$) cannot be exceeded by the rate of $\bar{n} - n$ annihilation. Using the crosssection σ for $n \rightarrow p$ as 10^{-42} cm^2 and that for $n - \bar{n}$ annihilation as 10^{-26} cm^2, one finds the number density of neutrinos as 10^{28} cm^{-3} (αT^3, $T \sim 10^9$ K) and that of neutrons as 10^{19} cm^{-3} (photons to nucleons ratio $\simeq 10^9$). This implies that $\bar{n}/n$ should be less than 10^{-7} (as the cross-sections are in ratio of 10^{16} and the densities are in the ratio of 10^9). However, the helium production would be affected if the n/p ratio changes. The standard model allows production of about 25% helium. The allowed fluctuations are at most a few per cent. If the helium production is not to be affected, then $\bar{n}/n \leq 10^{-9}$. For this ratio $\bar{n}/n$, Equation (2) would give a magnetic field of $\sim 10^{-4}$ gauss, which would be the lower limit for the strength of the primordial magnetic field. It may be mentioned that once the $\bar{n}$ is formed, the annihilation ($n + \bar{n} \rightarrow 2\gamma$) time $\sim 10^{-23}$ s is much shorter than the oscillation time ($\tau \sim 10^5$ s). So, there is no possibility of $\bar{n} \rightarrow n$. The γ rays from the annihilation ($n\bar{n}$) are produced in a medium of temperature ~ 0.1 MeV, which further forbids the reverse reaction because the pairs will not be in equilibrium with the background radiation field which is anyway sharing the general expansion at that time.

6. Conclusions

The phenomenon of neutron-antineutron oscillations has been studied in several neutron rich sources like solar flares, supernova explosions, neutron stars and the nucleosynthetic stage of the early universe. The two main consequences are: (1) a mechanism for the production of antiprotons which can account for large $\bar{p}/p \sim 10^{-3}$ at energies much less than GeV. and (2) emission of γ rays at GeV energies from these sources. The glitches from the neutron stars may also be attributed to the $n - \bar{n}$ annihilation occurring at the magnetic field free regions lying in between the quantized vortices in the superfluid core. The mechanism of $n - \bar{n}$ oscillation also predicts the neutron star to explosively emit γ rays during its dying stage (the low magnetic field stage). Finally this phenomenon constrains the primordial magnetic field to be $\sim 10^{-4}$ gauss from considerations of helium production.

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