CATALYZED NUCLEON DECAY IN NEUTRON STARS

Savas DIMOPOULOS [1,2] and John PRESKILL [1]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

and

Frank WILCZEK
Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

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We consider the effect in neutron stars of nucleon decay catalyzed by grand unified monopoles. Invoking observational limits on the diffuse ultraviolet and X-ray background, we obtain a bound on the product of the cross section σ for the catalysis process and the interstellar monopole flux Φ, $\langle\sigma\beta\rangle\Phi \lesssim 10^{-27}\ \mathrm{cm}^2 \times 10^{-25}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$. If, as Rubakov and Callan have recently suggested, $\langle\sigma\beta\rangle$ is a typical strong interaction cross section, then this bound is stronger by nine orders of magnitude than previous limits on the monopole flux.

Since grand unified theories [1] were first proposed, it has been recognized that baryon number is not a symmetry of these theories, and that they predict that the proton will decay at a calculable rate [2]. More recently, it has been noticed that the dynamics of a grand unified monopole [3] coupled to fermions is quite intricate [4–7], and that the monopole has a complex and subtle fermionic structure. Their developments have led Rubakov [8] and, independently, Callan [9], to a striking prediction, viz. that the cross section for baryon number violating scattering of fermions off monopoles is independent of the size of the monopole core. They conclude that monopoles catalyze nucleon decay at rates typical of the strong interactions. While we are not certain the analysis of Rubakov and Callan is correct (for a different view, see refs. [5,6]), we have nevertheless investigated some consequences of their claims.

The most interesting astrophysical implication concerns the effects of monopoles in neutron stars. Surrounded by matter at nuclear density, monopoles behaving as suggested by Rubakov and Callan catalyze nucleon decay at a furious rate. A modest number of monopoles in a neutron star could raise the luminosity of the star to the point where it emits a substantial flux of UV or X-ray photons. From observational limits on the diffuse UV and X-ray spectrum, we thus obtain an upper bound on σN, where σ is the cross section for monopole-catalyzed nucleon decay and N is the number of monopoles in a typical neutron star. Because neutron stars capture any monopoles incident on them, N is proportional to Φ, the interstellar monopole flux, if a neutron star contains a negligible number of monopoles when it forms. Hence we obtain a bound on $\sigma\Phi$,

$$(\langle\sigma\beta\rangle/10^{-27}\ \mathrm{cm}^{-2})\Phi \lesssim 10^{-25}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ , \qquad (1)$$

where $\beta c \approx 0.3\ c$ is the Fermi velocity of a neutron in the star. Eq. (1) is our main result.

We first derive the dependence of the luminosity and temperature of a neutron star on $N\sigma$. If the neutron number density is $n \approx 2 \times 10^{38}\ \mathrm{cm}^{-3}$, and the star contains N monopoles, the energy released per unit time by monopole-catalyzed neutron decay is

$$L = N\langle\sigma\beta\rangle cnm_\mathrm{n}$$
$$= N(\langle\sigma\beta\rangle/10^{-27}\ \mathrm{cm}^2) \times 9 \times 10^{18}\ \mathrm{erg/s}\ . \qquad (2)$$

[1] Alfred P. Sloan Fellow.
[2] On leave from the Institute of Theoretical Physics, Stanford University, Stanford, CA 94305, USA.

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Eq. (2) is actually valid only for $\langle\sigma\beta\rangle \lesssim 10^{-27}\ \mathrm{cm}^2$. For larger values of the cross section, the nucleon decay rate is controlled by the requirement that the pressure exerted on the surrounding neutron fluid by the outgoing decay products not exceed the neutron degeneracy pressure. Thus L becomes independent of σ.

Let us first suppose that a fraction of order one of the energy released by the catalyzed nucleon decay process is emitted as thermal photons. (The effect of neutrino emission will be considered below.) Then the surface temperature of the star is determined by $L = 4\pi r^2 a T^4$, where a is the Stefan–Boltzmann constant, and $r \approx 10^6$ cm is the radius of the star. From eq. (2) we obtain

$$T = N^{1/4}(\langle\sigma\beta\rangle/10^{-27}\ \mathrm{cm}^2)^{1/4} \times 0.03\ \mathrm{eV}\,. \tag{3}$$

Next, we wish to estimate N. Because heavy slow-moving grand unified monopoles are essentially dissipationless, we do not expect them to clump gravitationally as stars condense; instead they remain in interstellar or intergalactic space. The typical velocity of monopoles in a galaxy is determined by either the galactic magnetic field, from which they acquire a kinetic energy of order 10^{11} GeV, or, if they are sufficiently heavy, by the galactic gravitational field, which accelerates them to velocities of order $10^{-3}\,c$. These monopoles are not likely to be captured inside normal stars, although they may be captured into bound orbits about such stars [10]. Moreover, it is possible that the monopoles inside a normal star would be ejected when the star becomes a supernova and undergoes collapse to a neutron star. Let us therefore suppose that neutron stars are born containing a negligible number of monopoles.

Monopoles which strike the surface of a neutron star are captured inside the star. There are three important contributions to the energy loss of a monopole passing through a neutron star: hadronic collisions between monopoles and neutrons, collisions with neutrons due to the interaction of the monopole with the neutron magnetic moment, and electron encounters. When the monopole velocity is large, $v \approx c$, all three effects are of comparable importance, but for $v \lesssim v_{\mathrm{n}} \approx 0.3\,c$, the electron encounters dominate, and we have [11]

$$\frac{\mathrm{d}E}{\mathrm{d}x} \approx 4\pi^2 n_{\mathrm{e}} \frac{(eg)^2}{p_{\mathrm{e}}c}\,\frac{v}{c} \approx \frac{v}{c} \times 10^{11}\ \mathrm{GeV/cm}\,, \tag{4}$$

where $p_{\mathrm{e}}c \approx 70$ MeV is the Fermi momentum of the electrons and $n_{\mathrm{e}} \approx 1.5 \times 10^{36}\ \mathrm{cm}^{-3}$ is the electron density.

Monopoles will strike the surface of the star with a velocity equal to the escape velocity $v_{\mathrm{es}} \approx 0.5\,c$. (The 10^{12} G surface magnetic field of the star has a negligible effect on the monopole trajectory.) Monopoles with masses larger than 10^{17} GeV might pass through the star without stopping, but will have lost enough energy to become gravitationally bound. They will continue to make passes through the star until they have lost enough energy to remain inside. Only monopoles heavier than about 10^{23} GeV might be able to pass through the star and escape to infinity. Slow monopoles inside the star lose energy less efficiently, but they remain gravitationally confined to the interior of the star.

The capture cross section of the star is enhanced relative to its geometrical area by a factor $1 + v_{\mathrm{es}}^2/v_0^2$ (in the newtonian approximation), where v_0 is the typical initial velocity of a monopole. Therefore, if the ambient interstellar monopole flux is Φ, the number of monopoles which have been captured by a neutron star of age τ is

$$N = 4\pi^2 r^2 \frac{v_{\mathrm{es}}^2}{v_0^2}\Phi\tau = 3 \times 10^{20}\left(\frac{10^{-3}c}{v_0}\right)^2 \frac{\Phi}{\Phi_0}\,\frac{\tau}{10^{10}\ \mathrm{yr}}\,, \tag{5}$$

where $\Phi_0 = 10^{-16}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ is the Parker limit on the monopole flux derived by considering the energetics of the galactic magnetic field [12,13].

Now we can use observational limits on the X-ray luminosity of our galaxy, combined with eqs. (2), (3), and (5) to derive a bound on $\langle\sigma\beta\rangle\Phi$. Let us assume that the approximately 10^9 neutron stars have a roughly uniform age distribution, that new neutron stars have been produced at the rate of one every 10 yr for 10^{10} yr. If the luminosity of a neutron star is proportional to its age, as in eq. (5), then the total neutron star luminosity as a function of temperature behaves like

$$\mathrm{d}L_{\mathrm{total}}/\mathrm{d}T \propto T^7\,. \tag{6}$$

This luminosity distribution is sharply peaked at the maximum allowed T, corresponding to the oldest neutron stars, and we will therefore obtain the best bound by considering the oldest stars. For these stars we have, combining eqs. (2) and (5),

$$T\frac{\mathrm{d}L_{\text{total}}}{\mathrm{d}T} \simeq 4(10^9)(3\times 10^{20})(9\times 10^{18}) \times \left(\frac{10^{-3}\,c}{v_0}\right)^2 \frac{\Phi}{\Phi_0}\,\frac{\langle\sigma\beta\rangle}{10^{-27}\,\mathrm{cm}^2}\ \mathrm{erg/s}$$

$$= 10^{49}\ \mathrm{erg/s}\times\left(\frac{10^{-3}\,c}{v_0}\right)^2 \frac{\Phi}{\Phi_0}\,\frac{\langle\sigma\beta\rangle}{10^{-27}\,\mathrm{cm}^2}\,, \tag{7}$$

where, from eqs. (3) and (5),

$$T = 4\ \mathrm{keV}\left(\frac{10^{-3}\,c}{v_0}\right)^{1/2}\left(\frac{\Phi}{\Phi_0}\right)^{1/4}\left(\frac{\langle\sigma\beta\rangle}{10^{-27}}\right)^{1/4}. \tag{8}$$

This galactic luminosity corresponds to an X-ray or UV flux F incident on the earth of order

$$T\frac{\mathrm{d}F}{\mathrm{d}T} \approx 10^3\ \mathrm{erg\ s^{-1}\,cm^{-2}\,sr^{-1}} \times\left(\frac{10^{-3}\,c}{v_0}\right)^2 \frac{\Phi}{\Phi_0}\,\frac{\langle\sigma\beta\rangle}{10^{-27}\,\mathrm{cm}^2}\,, \tag{9}$$

at the temperature T given by eq. (8). UV or X-ray emission from neutron stars in other galaxies provides a contribution to the flux which is of the same order as eq. (9). Observational limits [14] on the UV and X-ray flux are consistent with eqs. (8) and (9) only if

$$\frac{\Phi}{\Phi_0}\,\frac{\langle\sigma\beta\rangle}{10^{-27}\,\mathrm{cm}^2} \lesssim 10^{-9}\,, \tag{10}$$

assuming $v_0 \approx 10^{-3}\,c$. If (10) is satisfied, the neutron stars are cooler than 20 eV and have a luminosity smaller than 3×10^{30} erg/s.

In very hot neutron stars, it is expected that the luminosity is dominated by neutrino emission, and that photon emission accounts for only a small fraction of the total luminosity. However, according to the best estimates [15] the neutrino luminosity is not substantial if the total luminosity is less than 3×10^{30} erg/s. Therefore, the bound (10) is not significantly modified if neutrino emission is properly taken into account.

From (10) we infer that, if the ΔB catalysis cross section really is strong, then the interstellar monopole flux must be smaller than the Parker limit by at least nine orders of magnitude. This result casts serious doubt on the candidate monopole event recently reported by Cabrera [16]. Even if the sun acts as a local source of monopoles [10], roughly a Parker flux incident on the sun is required to sustain the monopole cloud. If the catalysis cross section is as large as Rubakov and Callan claim, monopoles must be so rare that there is little hope of observing them directly. The best way of obtaining evidence for the existence of monopoles is then by observing their effect on the luminosity distribution of neutron stars.

If the Parker bound is saturated, we infer from (10) that the cross section $\langle\sigma\beta\rangle$ for monopole-catalyzed nucleon decay is smaller than estimated by Rubakov and Callan by nine orders of magnitude. This may be because their analysis of grand unified monopoles is incorrect, or because the correct unified theory is one in which there is no microscopic baryon number violation at all.

Results very similar to ours have been obtained by Kolb et al. [17].

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