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Particle physics bounds from the Hulse-Taylor binary

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The orbital period of the binary pulsar PSR 1913+16 has been observed to decrease at the rate of 2.40×10^{-12} s/s which agrees with the prediction of the quadropole formula for gravitational radiation to within one percent. The decrease in orbital period may also occur by radiation of other massless particles such as scalars and pseudoscalar Nambu-Goldstone bosons. Assuming that this energy loss is less than one percent of the gravitational radiation, we can establish bounds on couplings of these particles to nucleons. For a scalar nucleon coupling of the form $g_s\phi\bar{\psi}\psi$ we find that $g_s<3\times10^{-19}$. From the radiation loss of massless Goldstone bosons we establish the upper bound $\theta g_p<10^{-16}$ on the QCD vacuum angle θ and the pseudoscalar nucleon coupling constant g_p.

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The Hulse-Taylor (HT) binary consisting of the pulsar PSR 1913+16 orbiting around an unseen companion star provides firm evidence for the existence of gravitational waves [1]. The observed loss of orbital period agrees with the prediction from the quadropole formula of gravitation radiation [2] to within one percent. In this paper we compute the orbital energy loss due to radiation of other massless particles like scalars and pseudoscalar Nambu-Goldstone bosons. Massless scalars which couple to nucleons arise in scalar-tensor theories of gravity [3], as dilatons in theories with spontaneously broken conformal symmetry [4], and in string theories [5]. For a generic scalar-nucleon coupling $\mathscr{L}_s=g_s\phi_s\bar{\psi}\psi$ we find that the energy loss by the radiation of ϕ_s particles from the HT binary is less than 1% of the gravitational radiation loss if $g_s<3\times10^{-19}$. This gives an upper bound $\alpha_B=g_s^2/4\pi G m_n^2\leqslant1$ on the ratio of a long-range scalar-mediated fifth force to the gravitational force between two nucleons. This bound is much less stringent than the bounds obtained from terrestrial fifth force search experiments [6,7] which give $\alpha_B\leqslant10^{-6}$ (which corresponds to $g_s\leqslant10^{-21}$) and from the analysis of planetary orbits of Mercury and Mars [8] which give $\alpha_B\leqslant10^{-9}$ (i.e., $g_s\leqslant10^{-23}$).

In theories with a spontaneously broken global symmetry like the baryon number or the lepton number we have massless pseudoscalar Nambu-Goldstone bosons (NGB's) which have a generic coupling $\mathscr{L}_p=g_p\phi_p\bar{\psi}i\gamma_5\psi$ with nucleons. The pseudoscalar field of a macroscopic source adds up coherently only if the spins of the constituents are polarized. It was observed by Chang *et al.* [9] and Barbieri *et al.* [10] that the CP-violating operator $\theta G\tilde{G}$ in the QCD sector induces a coupling $\mathscr{L}=(\theta g_p/m_n)[m_u m_d/(m_u+m_d)]\phi_p\bar{\psi}\psi$ between the NGB ϕ_p and nucleons. This coupling gives rise to a $1/r$-type long-range force and the NGB field of the constituent nucleons of a macroscopic test body add up coherently even when their spins are randomly aligned. From the constraints on the energy carried away by the radiation of NGB's from the HT binary we obtain the upper bound $(\theta g_p)<10^{-16}$. This can be compared with the separately established bounds $\theta<10^{-9}$ (from the measurement of the neutron electric dipole moment [11,12]) and $g_p<10^{-8}$ GeV (from the cooling rate of helium stars [13]). The rate of energy loss by scalar particle emission is $\propto\Omega^4$ (where Ω is the orbital frequency). Observations of binary systems with faster orbital frequencies can be used to put more stringent bounds on couplings considered in this paper.

Finally we compute the energy loss by the radiation of neutrino pairs from the constituent neutrons of the HT binary. We find that for the standard-model neutral current coupling $\mathscr{L}_\nu=(1/\sqrt{2})G_F n(x)\overline{\nu\nu}$, the energy radiated by neutrino pair emission is suppressed by the phase factor and is negligibly smaller than the gravitational radiation. Therefore if experimentally one observes a discrepancy between the observed period loss of the binary orbit and the prediction from gravitational radiation formula, it would be a signal of a new kind of massless particle radiation and a signal of new physics beyond the standard model.

Massless scalar radiation. We assume a coupling between massless scalar fields ϕ_s and the baryons of the form

$$\mathscr{L}_s=g_s\phi_s\bar{\psi}\psi, \tag{1}$$

which for a macroscopic baryon source can be written as

$$\mathscr{L}_s=g_s\phi_s n(x), \tag{2}$$

where $n(x)$ is the baryon number density. A neutron star with radius ~10 km can be regarded as a point source since the Compton wavelength of the radiation $\sim\Omega^{-1}=10^9$ km is much larger than the dimension of the source. The baryon number density $n(x)$ for the binary stars (denoted by $a=1,2$) may be written as

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$$n(x)=\sum_{a=1,2} N_a \delta^3(\vec{x}-\vec{x}_a(t)), \tag{3}$$

where $N_a \sim 10^{57}$ is the total number of baryons in the neutron star and $\vec{x}_a(t)$ represents the Keplerian orbit of the binary stars. For the coupling (2) and the source (3) the rate of scalar particles emitted from the neutron star in a binary orbit is

$$d\Gamma = g_s^2 |n(\omega)|^2 (2\pi)\delta(\omega-\omega')\frac{d^3\omega'}{(2\pi)^3 2\omega'}, \tag{4}$$

and the rate of energy loss by massless scalar radiation is

$$\frac{dE}{dt}=g_s^2\int |n(\omega)|^2\omega'(2\pi)\delta(\omega-\omega')\frac{d^3\omega'}{(2\pi)^3 2\omega'}, \tag{5}$$

where $n(\omega)$ is the fourier expansion of the source density (3)

$$n(\omega)=\frac{1}{2\pi}\int e^{i\vec{k}\cdot\vec{x}}e^{-i\omega t}\sum_{a=1,2} N_a\delta^3(\vec{x}-\vec{x}_a(t))d^3x\ dt, \tag{6}$$

where $\omega = n\Omega$ is the nth harmonic of the fundamental frequency $\Omega=[G(m_1+m_2)a^{-3}]^{1/2}$ of the Keplerian orbit. Going over to the c.m. coordinates $\vec{r}=(x,y)$ by substituting $\vec{x}_1=m_2\vec{r}/(m_1+m_2)$, $\vec{x}_2=-m_1\vec{r}/(m_1+m_2)$ we have

$$n(\omega)=(N_1+N_2)\delta(\omega)+\left(\frac{N_1}{m_1}-\frac{N_2}{m_2}\right)M[ik_x x(\omega)+ik_y y(\omega)] + O(\vec{k},\vec{r})^2, \tag{7}$$

where $[x(\omega),y(\omega)]$ are the Fourier components of the Kepler orbit of the reduced mass in the c.m. frame $\vec{r}=(x,y)=(r\cos\theta, r\sin\theta)$ given by

$$r=\frac{a(1-e^2)}{1+e\cos\theta}, \tag{8}$$

$$\dot{\theta}=\left[\frac{G(m_1+m_2)a(1-e^2)}{r^2}\right]^{1/2}, \tag{9}$$

where a is the semimajor axis and e the eccentricity of the eliptical orbit. The expressions for $(x(\omega),y(\omega))$ obtained from (8,9) [14] are given by

$$x(\omega)=\frac{2a}{n}J_n'(ne), \quad y(\omega)=\frac{2ia\sqrt{1-e}}{ne}J_n(ne). \tag{10}$$

The first term in (7) is a delta function which has vanishing contribution to (5). The leading nonzero contribution comes from the second term in (7). Substituting (10) in (7) we obtain the expression for $|n(\omega)|^2$ given by

$$|n(\omega)|^2=\frac{4}{3}\left[\left(\frac{N_1}{m_1}-\frac{N_2}{m_2}\right)M\right]^2 a^2\Omega^2\left[J'^2_n(ne) + \frac{(1-e^2)}{e^2}J_n^2(ne)\right], \tag{11}$$

where we have used the dispersion relation $k_x^2=k_y^2=\frac{1}{3}(n\Omega)^2$. Substituting (11) in (5) we have the rate of energy loss by massless scalars given by

$$\frac{dE}{dt}=\frac{2}{3\pi}\left[\left(\frac{N_1}{m_1}-\frac{N_2}{m_2}\right)Mg_s\right]^2 a^2\Omega^4\sum_n n^2\left[J'^2_n(ne) + \frac{(1-e^2)}{e^2}J_n^2(ne)\right]. \tag{12}$$

The mode sum can be carried out using the Bessels function series formula $\sum_n n^2[J'^2_n(ne)+(1-e^2)e^{-2}J_n^2(ne)] = (1/4)(2+e^2)(1-e^2)^{-5/2}$ given in Ref. [2]. The energy loss (12) in terms of the orbital parameters Ω, a and e is given by

$$\frac{dE}{dt}=\frac{1}{3\pi}\left[\left(\frac{N_1}{m_1}-\frac{N_2}{m_2}\right)Mg_s\right]^2\Omega^4 a^2\frac{(1+e^2/2)}{(1-e^2)^{5/2}}. \tag{13}$$

Since $N_a m_n = m_a-\epsilon_a$ where $\epsilon_a = Gm_a^2/R_a$ is the gravitational binding energy and m_n the neutron mass, the factor $(N_1/m_1-N_2/m_2)=G/m_n[(m_1/R_1)-(m_2/R_2)]$. For the HT binary $m_1-m_2\simeq 0.02M_\odot$ and $R_a\sim 10$ km; therefore, $(N_1/m_1-N_2/m_2)\simeq 3\times 10^{-3}$ GeV^{-1}. Substituting the numerical values $\Omega=0.2251\times 10^{-3}$ sec^{-1}, $m_1=1.42M_\odot$, $m_2=1.4M_\odot$, $a=3.0813815$ lsec, and $e=0.617127$ for the parameters of the HT binary in (13) the rate of energy loss by massless scalar particle radiation by the HT binary turns out to be

$$\frac{dE}{dt}=g_s^2\times 9.62\times 10^{67}\ \text{ergs/sec}. \tag{14}$$

The time period of the elliptical orbit depends upon the energy E, so energy loss leads to a change of the time period of the orbit at the rate

$$\frac{dP_b}{dt}=-6\pi G^{-3/2}(m_1m_2)^{-1}(m_1+m_2)^{-1/2}a^{5/2}\left(\frac{dE}{dt}\right). \tag{15}$$

For the Hulse-Taylor binary, the energy radiated due to gravitational radiation [1,2] is given by

$$\frac{dE}{dt}=\frac{32}{5}G\Omega^6\left(\frac{m_1m_2}{m_1+m_2}\right)^2 a^4(1-e^2)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) = 3.2\times 10^{33}\ \text{erg/sec}. \tag{16}$$

Using (16) in (15) yields the orbital period deceleration due to the gravitational radiation $\dot{P}_b=-2.403\pm 0.002 \times 10^{-12}$ which agrees with the observed value from the Hulse–Taylor binary [1] $\dot{P}_b(\text{observed})=-2.40\pm 0.09 \times 10^{-12}$ to within 1%. Energy loss by emission of other massless particles should be within 1% of energy loss by gravitational radiation, and that can be used to put bounds on the couplings of the various massless scalar and pseudoscalar particles that arise in particle physics models.

Assuming that the energy loss by massless scalar radiation (14) is less than 1% of the gravitational energy loss i.e., $dE/dt \leqslant 10^{31}$ ergs/sec, we obtain an upper bound on scalar nucleon coupling given by

$$g_s < 3\times 10^{-19}. \tag{17}$$

Exchange of massless scalar between two nucleons gives rise to spin-independent fifth force with the static potential $V_{ss}(\vec{r}) = -g_s^2/4\pi r$, which shows that the ratio of the fifth force to the gravitational force between two nucleons is $\alpha_B = g_s^2/4\pi G m_n^2 \leqslant 1$. This is less stringent than the bound $\alpha_B \leqslant 10^{-6}$ for intermediate-range fifth force (with range $\sim 10^2$ cm) from terrestrial experiments [6,7] and $\alpha_B \leqslant -10^{-9}$ for long-range forces from solar system orbitals [8].

Nambu-Goldstone boson radiation. Massless pseudoscalar particles arise as Nambu-Goldstone bosons (NGB) when some global symmetry is broken spontaneously [15–17]. The generic coupling of massless NGB's ϕ_p to (on shell) nucleons can be written in the form

$$\mathscr{L}_p = g_p \phi_p (\overline{\psi i} \gamma_5 \psi). \tag{18}$$

For models [19] where the quarks carry the global charges whose spontaneous breaking gives rise the NGB's , the coupling (18) is present at the tree level and the coupling constant g_p is given by

$$g_p = \frac{C m_n}{f}, \tag{19}$$

where f is the symmetry breaking scale and C is a model-dependent constant of order 1. In some models where the neutrino masses are generated via a spontaneously broken lepton number [15–17] there is no tree level coupling between the NGB's (called Majorons) and the quarks. Such couplings can arise from radiative corrections and the coupling constant g_p is of the form

$$g_p \simeq \frac{G_F m_n m_\nu^2}{f}. \tag{20}$$

The coupling (18) gives rise to a spin-dependent long-range force [18] $V(r) \sim (g_p/m_n)^2 (1/r^3)[\sigma_1 \cdot \sigma_2 - 3(\sigma_1 \hat{r})(\sigma_2 \hat{r})]$. The pseudoscalar coupling in the first order in g_p is spin dependent and the field of a macroscopic body with randomly oriented constituents averages to zero. The radiation of NGB by the N constituent particles of the macroscopic system will be incoherent, which means that the energy radiated by N particles will be N times the single-particle energy loss. This is different from scalar radiation, which being coherent scales as N^2 times the single particle radiation.

It was observed by Chang *et al.* [9]. and Barbieri *et al.* [10] that if there is CP violation in the theory then ϕ_p can have both pseudoscalar coupling as in (18) and scalar coupling of the form (1). For example the CP-violating QCD term $\theta G\tilde{G}$ will induce an interaction between ϕ_p and nucleons of the form

$$\mathscr{L}_p = \frac{\theta g_p}{m_n}\left(\frac{m_u m_d}{m_u + m_d}\right)\phi_p \overline{\psi}\psi. \tag{21}$$

This scalar coupling gives rise to a long-range $[V(r) \sim 1/r]$ potential which is spin independent so that ϕ_p field outside a macroscopic object adds up coherently. The form of the interaction term (21) is the same as in Eq. (1) so the same bound (17) holds for the dimensionless coupling

$$\frac{\theta g_p}{m_n}\left(\frac{m_u m_d}{m_u + m_d}\right) < 3\times 10^{-19}, \tag{22}$$

which means that for $m_u = 5$ MeV, $m_d = 9$ MeV we have $\theta g_p < 7.5\times 10^{-16}$. This can be compared with the separate bounds $\theta < 10^{-9}$ (obtained from neutron electric dipole moment [11,12]) and $g_p < 10^{-8}$ (obtained from the cooling rate of helium stars [13]). The bound (22) holds for models [15–17] where the mass of the Nambu-Goldstone boson is smaller than the frequency $\Omega \simeq 10^{-19}$ eV of the binary orbit.

Neutrino radiation. The coupling of neutrinos to neutrons in the standard model is via the weak neutral current and is given by

$$\mathscr{L}_\nu = \sqrt{2} G_F \frac{n(x)}{2} \overline{\nu_L} \gamma^0 \nu_L, \tag{23}$$

where $n(x)$ is the number density of the neutrons which are the source of the neutrino field. The radiation of neutrinos from the HT binary with $n(x) = N\delta^3(x - x(t))$ carries away energy at the rate

$$\frac{dE}{dt} \simeq \left(\frac{G_F^2 N^2}{4}\right)\Omega^6 = 10^{-43} \text{ ergs/sec}. \tag{24}$$

The weak coupling of neutrinos to neutrons is much larger than the coupling of the gravitons to matter; however, since the emission of neutrinos occurs in pairs, the phase-space suppression makes the energy radiated by neutrino emission negligible compared to graviational radiation.

The period loss in the HT system has been determined by measuring the time of periastron over a period of almost 19 years. The accuracy of the measured value of period loss increases quadratically with time. If in the course of observation one finds a significant discrepancy between the observed value of period loss and the prediction of the gravitational quadropole formula, it would be a compelling signal of physics beyond standard model.

Note added. Astrophysical bounds from the Hulse-Taylor binary have been considered in Refs. [20] and [21]. In [20] the energy loss in Brans-Dicke gravity is derived and in [21] effect of scalar couplings on orbital parameters of the HT binary is studied.

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