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BRIEF REPORTS

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Astrophysical bounds on millicharged particles in models with a paraphoton

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The upper bound on the number of relativistic species present at nucleosynthesis has been used to constrain particles with electric charge ϵe ($10^{-8} < \epsilon < 1$). We correct the bound previously calculated for millicharged particles that interact with a shadow photon. We also discuss the additional constraints from the properties of red giants and of Supernova 1987A.

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A problem of continuing interest in elementary particle physics is the possible existence of particles with an electric charge very small compared to the electron charge. We will refer to such particles as "millicharged" and will denote the small charge as ϵe. Traditionally, these particles have been considered as new ingredients added to the standard model, reflecting the mystery of the electric charge quantization observed in nature. In this context, many authors have pointed out astrophysical constraints on the mass and charge of millicharged particles [1–7]. In addition, a very persuasive argument against the existence of such particles is the fact that they would be forbidden in models with a grand unification.

However, in 1986, Holdom [8] showed that, by adding a second, unobserved, photon (the "paraphoton" or "shadow photon"), one could construct grand unified models which contained millicharged particles in a natural way. Holdom's scheme for millicharged particles is genuinely persuasive, and has stimulated new experimental tests [9]. It also requires a rethinking of the astrophysical constraints on millicharged particles [6, 10, 11]. In this paper, we will improve on previous treatments of these constraints, correcting an error in a previously claimed nucleosynthesis bound and discussing possible additional bounds from stars and from Supernova 1987A.

Our conclusions are presented in Fig. 1. This figure is based on Fig. 2 of Ref. [6]. It includes the limits from direct accelerator experiments [12], the Lamb shift, $\Omega < 1$, and other sources derived in Ref. [6], and the supernova bound from Ref. [5], and adds the new limits from nucleosynthesis and from helium-burning stars described below.

Holdom showed that particles with small electric charge would appear naturally in grand unified models if the model contained *two* unbroken U(1) symmetries. Conventional grand unification leads to one unbroken U(1) symmetry; at low energies, this is the gauge symmetry of electromagnetism. Holdom suggested that it could

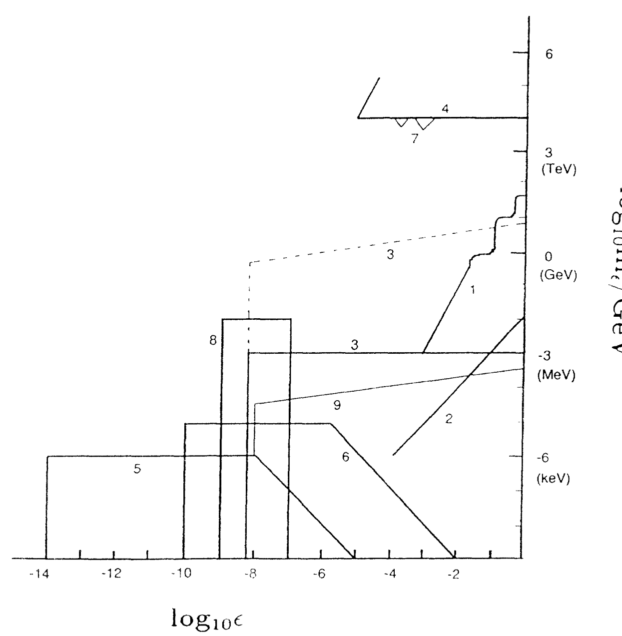

FIG. 1. Regions of mass-charge space ruled out for millicharged particles in the model with a paraphoton. The bounds arise from the following constraints: 1—accelerator experiments; 2—the Lamb shift; 3—nucleosynthesis; 4—$\Omega < 1$; 5—plasmon decay in red giants; 6—plasmon decay in white dwarfs; 7—dark matter searches; 8—Supernova 1987A; 9—γ' emission by red giants. The bounds 1,2 and 4–7 are from Ref. [6], 8 is from Ref. [5], and 3 and 9 are from this paper.

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easily contain another unbroken U(1) which lives completely outside the standard model gauge group. At the most fundamental level, the model would contain as light fermions ordinary quarks and leptons, which are neutral under the shadow U(1), and new shadow fermions which are neutral under the ordinary U(1). However, any small mixing of the two U(1) gauge bosons, even if it is induced by loop diagrams involving particles at the grand unification scale, will cause observable millicharges with ϵ proportional to the mixing angle. A natural size of this mixing angle is $\alpha/\pi \sim 10^{-3}$. In the resulting field space, the original U(1) directions are not orthogonal by the amount ϵ. We will define the conventional photon (γ) to be that linear combination of the two gauge bosons which couples to ordinary quarks and leptons, and define the paraphoton (γ') to be the orthogonal combination of gauge fields. Then the conventional photon has couplings of size ϵ to shadow matter, but the shadow photon has zero coupling to conventional matter. The opposite convention is also possible, by taking a different choice of basis in the field space, but it is less convenient. The value of the basic U(1) charge could well be different between the ordinary and shadow U(1)'s (α' could differ from α), but, for simplicity, we will ignore this distinction below.

One of the strongest constraints on models of millicharged particles both with and without a paraphoton is the bound from primordial nucleosynthesis. If the mass of the millicharged particle is sufficiently small, this particle will provide extra light degrees of freedom at the era of nucleosynthesis and will thus contradict the limit usually quoted as the bound on the number of light neutrinos. The principal uncertainty in this bound comes from the estimation of the primordial mass fraction Y_p of ^{4}He. In a recent paper, Walker *et al.* [13] have argued for the relation

$$N_\nu = 2.00 \pm 0.15 + 83.3(Y_p - 0.228) \tag{1}$$

and for the value $Y_p = 0.23\pm0.01$. However, the standard error given here should be used with care in citing confidence limits, since it is mainly systematic. We believe it is correct, in citing limits on new particles, to consider a scenario with $N_\nu = 4.2$ as acceptable, and we will argue below in this spirit. A much stronger conclusion would follow if we took the error on Y_p literally as the width of a Gaussian distribution and claimed $N_\nu < 3.3$ (95% confidence); we will also discuss the bound in this case below.

A millicharged fermion with a small mass counts as two neutrinos, to be added to the three light neutrinos of the standard model. Thus, millicharged particles with $m_\epsilon \lesssim 1$ MeV can be ruled out (for $\epsilon \gtrsim 10^{-8}$). This bound applies to models both with and without a paraphoton. However, it was incorrectly claimed in [6] that the nucleosynthesis bound in the model with a paraphoton was much stronger, ruling out $m \lesssim 200$ MeV. Since this is a region of parameter space in which a direct experiment test of the model is possible [9], we should correct this conclusion.

The upper bound on the number of light neutrinos at nucleosynthesis is, more correctly, a bound on the energy density at this epoch. Since the paraphoton is necessarily massless, it always contributes to this energy density. A paraphoton in thermal equilibrium with ordinary photons has a contribution equal to 8/7 of a neutrino, and so is excluded only by the strongest claimed bounds on N_ν. However, the authors of [6] argued that the contribution of the paraphoton was considerably larger. They assumed that, if millicharged particles were heavier than 1 MeV, these particles would annihilate before the era of nucleosynthesis and transfer their entropy to the paraphotons. This would raise the paraphoton temperature with respect to the photon temperature and increase the paraphoton energy density. They concluded that the millicharged particles had to annihilate before the QCD phase transition, where substantial entropy production increases the temperature of ordinary photons.

However, this is unneccessary. We will now show that the paraphotons remain in thermal equilibrium with the photons as the millicharged particles annihilate, so that $T_{\gamma'}$ will never be significantly larger than T_γ.

Photons can turn into paraphotons by Compton scattering from a millicharge (or antimillicharge) to produce a paraphoton. For a given photon, the rate of this process is given by $\Gamma(\epsilon\gamma \to \epsilon\gamma') \simeq n_\epsilon \sigma(\epsilon\gamma \to \epsilon\gamma')$, which we can estimate for $m_\epsilon > T$ by

$$\Gamma(\epsilon\gamma \to \epsilon\gamma') \simeq 4\left(\frac{m_\epsilon T}{2\pi}\right)^{3/2} e^{-m/T}\,\frac{8\pi\epsilon^2\alpha^2}{3m_\epsilon^2}, \tag{2}$$

where we have used the low-energy limit of the Compton cross section and assumed that $\alpha' = \alpha$. The rate for converting a paraphoton to a photon is identical. To estimate quantitatively the temperature at which the millicharges have transferred their entropy to the paraphotons, we define $T_\epsilon(m_\epsilon)$ to be the temperature at which the equilibrium density of millicharges has fallen to 1/10 the number density of a relativistic species:

$$\left(\frac{m_\epsilon T_\epsilon}{2\pi}\right)^{3/2} e^{-m_\epsilon/T_\epsilon} = \frac{1}{10}\,\frac{7\zeta(3)}{8\pi^2}T_\epsilon^3 \ . \tag{3}$$

Then the paraphotons will equilibrate this entropy with ordinary photons if the rate $\Gamma(\epsilon\gamma \to \epsilon\gamma')$, evaluated at T_ϵ, is large compared to the expansion rate of the Universe at T_ϵ:

$$\Gamma(\epsilon\gamma \to \epsilon\gamma') > H(T_\epsilon) \simeq \frac{1.7\sqrt{g_{\rm eff}(T_\epsilon)}\,T_\epsilon^2}{m_{\rm PL}} \ , \tag{4}$$

where H is the Hubble expansion rate, $m_{\rm PL}$ is the Plank mass and $g_{\rm eff}(T)$ is the total effective number of relativistic degrees of freedom. The inequality (4) is satisfied for $\epsilon > 10^{-8}$.

Thus, for $\epsilon > 10^{-8}$, nucleosynthesis gives a lower limit to the millicharge mass of 1 MeV, as before. This revised nucleosynthesis bound is plotted in Fig. 1.

If we accept the strong nucleosynthesis bound of Ref. [13], and neglect the possibility of a heavy (unstable?) τ neutrino [14, 15], the bound on the millicharge mass becomes much stronger. If one cannot have more that 3.3 effective neutrinos at the era of nucleosynthesis, the paraphotons cannot be in thermal equilibrium with the ordinary photons; rather, they must be cooler in such a way that

$$\frac{8}{7}T_{\gamma'}^4 \leq 0.3T_\gamma^4 \ . \tag{5}$$

The photons must therefore be heated by annihilations after the paraphotons decouple. This implies [6] that the photons and paraphotons must be out of equilibrium at the temperature of the QCD phase transition, $T_c \approx 200$ MeV. The dominant equilibration process is still Compton scattering, and so we can use the estimates above, with T_ϵ replaced by T_c, to find the limit

$$m_\epsilon > 7 + 0.4 \ln \epsilon \ \text{ GeV} \ . \tag{6}$$

We plot this bound as a dotted line in Fig. 1. We emphasize to the reader that the difference between this limit and the qualitatively weaker limit above corresponds to a 1σ shift in the ^{4}He abundance constraint.

Previous discussions of the astrophysical bounds on millicharged particles made use of physical arguments which were independent of the existence of the paraphoton. In particular, when ϵ is small, millicharges made in the center of a helium-burning star (or of Supernova 1987A) can escape freely, adding substantially to the cooling rate. This leads to a bound for small masses and $\epsilon < 10^{-7}$. However, in models with a paraphoton, there is another physical picture which leads to constraints at larger values of ϵ.

The new bound arises when we consider the radiation of paraphotons from the star. It is not difficult to see that this radiation can be substantial: Under circumstances that we will specify below, the core of a star can contain millicharges and paraphotons in thermal equilibrium with the ordinary matter. The cross section for paraphoton-millicharge scattering is the full Compton cross section, without a factor ϵ^2. Thus, the mean free path for paraphotons will be much shorter than the size of the stellar core. However, in outer regions of the star, the temperature drops, the density of millicharges decreases, and the star becomes transparent to paraphotons. Thus, the star will have a photosphere for paraphotons and will radiate from this "paraphotosphere" approximately like a blackbody. For millicharged masses greater than 100 eV, the paraphoton mean free path in the outer regions of the star will be longer than that of the photon, so the the "paraphotosphere" will occur at a smaller radius, and thus a higher temperature, than the sphere from which ordinary photons are radiated [16]. Thus, the stellar luminosity in paraphotons should be greater than the stellar luminosity in ordinary photons. However, the Sun is too young to have been losing energy at twice the photon luminosity, and the observed lifetimes of helium-burning stars also disfavor such a large addition to the rate of energy loss [17]. We get a better bound from the hotter star, but a more dependable one from the Sun. We will therefore outline the calculation for a helium-burning star, but quote the bound also for the analogous argument applied to the Sun.

Since millicharges are produced from ordinary matter by the pair production process $e^-N \to e^-N\epsilon\bar{\epsilon}$, there is no difficulty in creating a thermal population of millicharges. The weak link in the argument is the bottleneck in converting ordinary photons to paraphotons if the thermal density of millicharges is small. We can make a rough estimate of this rate by assuming that paraphotons are only created in a helium core of radius $R_c \sim 10^9$ cm in thermal equilibrium at the temperature $T_c \sim 10$ keV. The production rate of paraphotons in the sphere by Compton scattering $\epsilon\gamma \to \epsilon\gamma'$ is given by

$$\frac{4\pi R_c^3}{3} n_\gamma n_\epsilon \sigma_{\epsilon\gamma\to\epsilon\gamma'} \sim \alpha\alpha'\epsilon^2 R_c^3 T_c^4 \sqrt{\frac{T_c}{m_\epsilon}} e^{-m_\epsilon/T_c}. \tag{7}$$

If we require that this be less than $\mathcal{L}_\gamma/T_s$, where $\mathcal{L}_\gamma$ is the luminosity of the sphere in ordinary photons, and T_s is the surface temperature, we find the limit

$$m_\epsilon \gtrsim 0.4 + 0.02 \ln \epsilon \text{ MeV} \quad \text{(He)} \tag{8}$$

for helium-burning stars, and

$$m_\epsilon \gtrsim 40 + 2 \ln \epsilon \text{ keV} \quad \text{(Sun)} \tag{9}$$

from the Sun. We have plotted (8) as a thin line in Fig. 1. Our new bound is obviously very rough, but, fortunately, it is unimportant, because it applies only to a region of parameter space already ruled out by nucleosynthesis.

A similar argument could in principle give a stronger bound from the properties of Supernova 1987A. However, the protoneutron star cools by emitting neutrinos, not photons. If ϵ is sufficiently large that the millicharged particles do not escape from the core, the paraphoton mean free path is shorter than that of the neutrinos, so the "paraphotosphere" would be at a larger radius (and lower temperature) than the "neutrinosphere," and the paraphoton luminosity would be lower than that of neutrinos. Thus, SN 1987A gives no additional constraint in models with a paraphoton beyond the limit found in Ref. [5] in the model without a γ'.

In this paper, we have presented new evaluations of the bounds on millicharged particles in models with a paraphoton, as advocated by Holdom. Our main conclusion is that, with a conservative estimate of the nucleosynthesis constraint, there is no astrophysical restriction on the existence of millicharges with $m_\epsilon > 1$ MeV and $\epsilon < 10^{-2}$. We look forward to new direct experiments which will explore this interesting region.

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