New constraints on a light spinless particle coupled to photons

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We obtain new stringent constraints on a light spinless particle ϕ coupled only to photons at low energies, considering its effects on the extragalactic photon background, the black-body spectrum of the cosmic microwave background radiation and the cosmological abundance of deuterium. [S0556-2821(97)00312-3]

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I. INTRODUCTION

Light pseudoscalar (or scalar) particles appear as fundamental ingredients of several extensions of the standard model. Examples are axions [1] and Majorons [2] which arise, respectively, from the spontaneous breaking of a Peccei-Quinn symmetry and of a global lepton symmetry. Other examples are omions [3], arions [4], and light bosons from extra-dimensional gauge theories [5]. Pseudoscalar particles normally couple to photons by means of the Lagrangian

$$\mathcal{L}=\frac{1}{8}g\phi\varepsilon_{\mu\nu\alpha\beta}F^{\mu\nu}F^{\alpha\beta}. \tag{1}$$

Axions may be the most famous of them. Their existence would solve the CP violation problem of QCD and could help to explain the composition of the cosmological dark matter. Several experiments have been or will be performed trying to detect axions. Many of them are based on the coupling of axions to photons (1). Hence, there is the possibility that these experiments detect some sort of light bosons different from axions, coupled at low energies only to photons.

In Ref. [6] the latter possibility was thoroughly explored. Using laboratory experiments, and several astrophysical and cosmological observations a set of constraints was found on the parameter space coupling constant g and mass m of this hypothetical light ($m<1$ GeV) boson ϕ coupled at low energy only to photons. Its role as a dark matter component was also studied.

Afterwards, further bounds have been published by several authors [7–10]. In particular, using the conversion of the particles ϕ produced in the core of SN 1987A to photons, on its way to the Earth, by the galactic magnetic field, one sets the most stringent bound (for $m<10^{-9}$ eV) [9]:

$$g\leqslant 3\times 10^{-12}\,\mathrm{GeV}^{-1}. \tag{2}$$

This bound relies on data taken by the Gamma-Ray Spectrometer on board the Solar Maximum Mission (SMM) satellite, which was on duty when the supernova neutrino burst was observed on the Earth. Modern spaceborne detectors such as the Energetic Gamma Ray Experiment and Telescope (EGRET) on the Compton Gamma Ray Observatory (GRO) or the project GLAST would allow a positive signal, or being pessimistic would set a bound more stringent than Eq. (2), provided that a type-II supernova exploded and was observed in our galaxy.

The purpose of this paper is to show that one can also place very restrictive constraints on ϕ for masses higher than $m\sim 10$ eV, using three cosmological issues: the extragalactic photon background, the cosmic microwave background radiation (CMBR), and the cosmological abundances of light elements. For certain large regions in the ϕ space parameter, the photons produced by the decay $\phi\rightarrow\gamma\gamma$ would render a measurable contribution to the extragalactic photon background, would induce departures of the CMBR spectrum from that of a black body, and would fission the deuterium synthesized during the first minutes of the Universe. Using experimental data these three facts allow us to set new bounds on ϕ. The present work complements the work presented in [6].

II. NEW CONSTRAINTS ON ϕ

Light bosons ϕ are thermally produced in the early Universe via processes like $e\gamma\rightarrow e\phi$. Its relic cosmic abundance depends on the freeze-out temperature T_F, the temperature of the primordial plasma when the rates of production and destruction of ϕ became smaller than the Universe expansion rate. Its number density, relative to the number of photons, at time t after freeze-out, is given by

$$\frac{n_\phi}{n_\gamma}=\frac{1}{g_*(T_F)}, \tag{3}$$

as long as $\tau>t$, being τ the ϕ lifetime. The smaller the coupling g, the higher the temperature T_F and the larger the effective degrees of freedom $g_*(T_F)$ coupled to γ (more annihilations to photons have heated the photons relative to the decoupled ϕ). We are interested in the region $g<10^{-10}$ GeV^{-1} allowed by astrophysical arguments (energy loss in He burning stars and SN 1987A). This small value of g corresponds to $T_F\gg 200$ GeV. However, we do not know the effective degrees of freedom at such high temperature. Clearly, some hypothesis must be made to cope with this problem. Since our final goal is to constrain the ϕ parameters, we adopt a conservative hypothesis. Assuming the so-called standard model desert one obtains $g_*(T_F)\approx 110$, i.e., no more particles appear with masses larger than 200 GeV [until grand unified theory (GUT) scales]. The prediction of the supersymmetric standard model desert is $g_*(T_F)\sim 200$. We will be conservative and assume $g_*(T_F)\sim 500$, which is the value obtained at $T_F\sim 10^8$ GeV if one extrapolates by means of an approximate power law the growth rate of the degrees of freedom below 200 GeV. Nevertheless, the limits we will find are not much sensitive to the precise value of $g_*(T_F)$.

The particle ϕ is unstable, it decays into two photons with a lifetime given by

$$\tau=\frac{64\pi}{g^2m^3}. \tag{4}$$

These decay-produced photons may have different measurable consequences for the present state of the Universe depending on z_τ, the redshift at which the boson ϕ decays $[1+z=R(t=t_0)/R(t=\tau)$ being t_0 the age of the Universe and $R(t)$ the cosmological scale factor]. One has to consider four important decay epochs.

(1) Lifetimes either $\tau>t_0$ or such that $1<z_\tau<z_{\rm dec}\approx 1100$, where $z_{\rm dec}$ is the redshift at which photons last scattered with matter. If ϕ decays after matter-radiation decoupling, the decay-produced photons stream away freely, redshifting due to the expansion of the Universe (if $\tau<t_0$), and reach the Earth contributing to the photon extragalactic background. One can compute the present energy flux of photons per energy and solid angle interval coming from ϕ decay (we assume that ϕ is unclustered, which is the least restrictive case):

$$\frac{dF_E}{dEd\Omega}=\frac{n_0}{2\pi\tau H_0}\left(\frac{E}{m/2}\right)^{3/2}\exp\left[\frac{t_0}{\tau}\left(\frac{E}{m/2}\right)^{3/2}\right], \tag{5}$$

where H_0 is the Hubble constant and n_0 is the number density that ϕ would have nowadays if it did not decay. The measured energy flux can be in general approximated by a power law $\propto E^{-\alpha}$ with $\alpha\sim 1$ (α and the normalization factor depend not very strongly on E) [11]. The region of interest falls in the UV part of the spectrum, therefore using the normalization in the UV region given by [12] one obtains the upper limit

$$\frac{dF_E}{dEd\Omega}<10^5\left(\frac{10\ \text{eV}}{E}\right)\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}. \tag{6}$$

This experimental upper limit constrains the allowed region for the parameters of ϕ as depicted in Fig. 1 (for $\tau>t_0$ see also [7]). We should point out that this constraint excludes ϕ as a component of the cosmological dark matter and almost excludes ϕ as an important component of the galactic dark matter

(2) $z_{\rm rec}<z_\tau<z_c\approx 10^5$, z_c being the redshift at which the rate of Compton scattering $e\gamma\rightarrow e\gamma$ becomes too slow to keep kinetic equilibrium between photons and electrons. The energy dumped by ϕ decay heats the electrons compared to the cosmic background photons. Scattering of these hot electrons with the cosmic background photons distorts the photon spectrum. The departure from a black-body spectrum is parametrized by the Sunyaev-Zeldovich parameter y. Using the Kompaneets equation [13] one can calculate the relation between y and the energy dumped by ϕ decay ΔE:

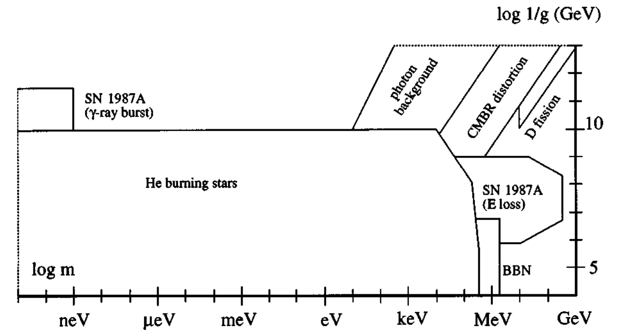

FIG. 1. Forbidden regions for the mass m and coupling constant g of ϕ. The new bounds stemming from the extragalactic photon background, distortion of the CMBR spectrum, and deuterium photofission are shown. The excluded region labeled ''CMBR distortion'' includes the two regions ruled out by the smallness of the distortion parameters y and μ. The constraints from stellar energy loss arguments, He burning stars and SN 1987A, and from big bang nucleosynthesis (BBN) are borrowed from [6] and references therein (see also [6] for further constraints). The small region forbidden only by BBN is present as long as the BBN effective number of additional neutrinos is $\Delta N_\nu<0.5$, which might be overly restrictive. The absence of a γ-ray burst from SN 1987A occurring at the same time as the detected neutrino burst gives the stringent bound for masses $m<10^{-9}$ eV [9]. The logarithm is to base 10.

$$\frac{\Delta E}{E}=e^{4y}-1\approx 4y, \tag{7}$$

where we have advanced that y must be small. Using Eqs. (3) and (4), energy conservation, and considering an instantaneous energy release by ϕ decay, we obtain

$$\frac{\Delta E}{E}=6.6\left(\frac{500}{g_*(T_F)}\right)\left(\frac{10^{-10}\ \text{GeV}^{-1}}{g}\right)\left(\frac{100\ \text{keV}}{m}\right)^{1/2}. \tag{8}$$

The Cosmic Background Explorer Far Infrared Absolute Spectrometer (COBE) (FIRAS) showed that the CMBR spectrum agrees with a black-body spectrum to high accuracy [14]. The parameter y is constrained to be very small, $|y|<1.5\times 10^{-5}$. Thus, FIRAS data exclude another region on the plane (m,g) plotted in Fig. 1.

(3) $z_c<z_\tau<z_{\rm th}\approx 3\times 10^6$, where at $z_{\rm th}$ the nonconserving $(e\gamma\rightarrow e\gamma\gamma)$ photon number processes decouple. At this epoch Compton scattering is fast enough so that decay-produced photons can be thermalized. However, since the photon number cannot be changed, one obtains for the CMBR a Bose-Einstein spectrum, $f=[\exp(E/T+\mu)-1]^{-1}$, characterized by a nonvanishing photon chemical potential μ, rather than a black-body spectrum. Using photon number and energy conservation (and assuming that all particles ϕ decay at once at time τ) one gets the following expression for the photon chemical potential:

$$\left[\frac{4}{3}\frac{\zeta(2)}{\zeta(3)}-\frac{\zeta(3)}{\zeta(4)}\right]\mu=\frac{\Delta E}{E}-\frac{8}{3}\frac{1}{g_*(T_F)}, \tag{9}$$

for small μ [$\zeta(n)$ is Riemann's zeta function]. FIRAS data constrain the photon chemical potential to be $|\mu|<0.9\times10^{-4}$. Making use of Eqs. (8) and (9), and taking into account that the contribution to μ proportional to $1/g_*(T_F)$ is negligible in the interesting region, we obtain the forbidden zone plotted in Fig. 1.

(4) At earlier times, the high energy photons coming from ϕ decay create electromagnetic showers that may photofission the deuterium produced during the first minutes of the Universe. Using the detailed analysis of these showers made in [15], we rule out the region depicted in Fig. 1, which would imply a cosmological deuterium abundance D/H $<10^{-5}$, smaller than the experimental value. Only for masses $m>10$ MeV, the photon cascades have enough energy to fission the deuterium nuclei. For masses $m\gtrsim100$ MeV, there are also helium photofission and hadronic showers that may modify the primordial abundances of light elements, but we are not interested in such high masses.

III. CONCLUSIONS

A light scalar or pseudoscalar ϕ coupled at low energies only to photons could contribute to the extragalactic photon background, could distort the spectrum of the CMBR and could destroy the primordial deuterium. The observed extragalactic photon background, the stringent limits on the CMBR distortion parameters y and μ found by FIRAS, and the measured cosmological abundance of deuterium allow us to obtain new stringent constraints on ϕ, extending the former study carried out in [6].

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