Problem set 11

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Problem 24: Hidden photons

Consider the Lagrangian of a hidden photon A' that kinetically mixes with the Standard Model photon:

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} - \frac{m_{A'}^2}{2}A'^{\mu}A'_{\mu} \; , \tag{1}$$

where $F^{\mu\nu}$ and $F'^{\mu\nu}$ denote the field-strength tensor for the photon field A^μ and the hidden photon field A'^μ, respectively. Because of the mixing term, the physical fields γ^μ and γ'^μ will be different from the fundamental fields A^μ and A'^μ. Indeed, we can write the fundamental fields as a general linear combination of the physical fields:

$$\begin{pmatrix} A^\mu \\ A'^\mu \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ \gamma'^\mu \end{pmatrix} \; . \tag{2}$$

a) Determine the mixing matrix such that the physical fields have canonical kinetic terms (i.e. standard normalisation and no kinetic mixing) and that there is no mass term for the physical photon field γ.

b) What is the mass $m_{\gamma'}$ of the physical hidden photon field γ'?

Photons couple to charged particles (such as leptons ℓ) via an interaction of the form

$$\mathcal{L} = eA^\mu \bar{\ell}\gamma_\mu \ell \; , \tag{3}$$

where e denotes the electric charge.

c) Show that the physical photon field γ has the same coupling to charged particles as the fundamental photon field A.

d) Show that the physical hidden photon field γ' picks up a coupling to charged particles. Determine this coupling to linear order in ϵ.

The electron-photon scattering cross section is approximately given by the Thompson cross section

$$\sigma_\mathrm{T} = \frac{8\pi}{3}\frac{\alpha^2}{m_e^2} \; . \tag{4}$$

e) Estimate the corresponding cross section σ_conv for the process $\gamma e^- \to \gamma' e^-$ as a function of ϵ.

f) By comparing the conversion rate $\Gamma_\mathrm{conv} = \langle \sigma_\mathrm{conv} v \rangle \, n_e$ to the Hubble rate $H(T)$ for $T = 1\,\mathrm{MeV}$, find an upper bound on ϵ from the requirement that hidden photons do not thermalize with the Standard Model.

Hidden photons can be searched for in LSW experiments. In contrast to axions, conversion between photons and hidden photons is possible even in the absence of a magnetic field. The conversion probability can be estimated by replacing $g_{a\gamma}\, eB \to \epsilon q$, where $q = m_{\gamma'}^2/(2\, E_{\gamma'})$.

g) Use the expected sensitivity of the ALPS-II experiment ($g_{a\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$ using a laser with $\lambda \sim 1\,\mu\mathrm{m}$ and a magnetic field with $B \sim 5\,\mathrm{T}$ applied over a length of $l \sim 5\,\mathrm{m}$) to estimate the sensitivity of this experiment to hidden photons.

h) As for axions, hidden photon conversion is efficient only as long as $q\, l \lesssim 1$. What is the largest hidden photon mass that can be probed?

i) Can ALPS-II reach the relevant parameter space for non-thermal hidden photons?