Abstract

The mass of the axion and its decay rate are known to depend only on the scale of Peccei–Quinn symmetry breaking, which is constrained by astrophysics and cosmology to be between $10^9$ and $10^{12}$ GeV. We propose a new mechanism such that this effective scale is preserved and yet the fundamental breaking scale of $U(1)_{PQ}$ is very small (a kind of inverse seesaw) in the context of large extra dimensions with an anomalous $U(1)$ gauge symmetry in our brane. The production and decay of the associated $Z_A$ gauge boson, which ends up as two gluons and two axions, is a distinct collider signature of this scenario.

Although CP violation has been observed in weak interactions [1,2] and it is required for an explanation of the baryon asymmetry of the universe [3], it becomes a problem in strong interactions. The reason is that the multiple vacua of quantum chromodynamics (QCD) connected by instantons [4] require the existence of the CP violating $\theta$ term [5]

$$L_\theta = \theta_{\text{QCD}} \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu},$$

(1)

where $g_s$ is the strong coupling constant, $G_{\mu\nu}^a$ is the gluonic field strength and $\tilde{G}_{\mu\nu}^a$ is its dual. Nonobservation of the electric dipole moment of the neutron [6] implies that

$$\tilde{\theta} = \theta_{\text{QCD}} - \text{Arg Det} M_u M_d < 10^{-10},$$

(2)

instead of the theoretically expected order of unity. In the above, $M_u$ and $M_d$ are the respective mass matrices of the charge $2/3$ and $-1/3$ quarks of the standard model of particle interactions. This is commonly known as the strong CP problem.

The first and best motivated solution to the strong CP problem was proposed by Peccei and Quinn [7], in which the quarks acquire a dynamical phase from the spontaneous breaking of a new global symmetry $[U(1)_{PQ}]$ and relaxes $\theta$ to its natural minimum value of zero. As a result, there appears a Goldstone boson called the axion but it is not strictly massless [8] because it couples to two gluons (like the neutral pion) through the axial triangle anomaly [9].

The scale of $U(1)_{PQ}$ breaking (which is conventionally identified with the axion decay constant $f_a$) determines the axion coupling to gluons, which is proportional to $1/f_a$. If $f_a$ is the electroweak symmetry breaking scale as originally proposed [7], then the model is already ruled out by laboratory experiments [10]. In fact, $f_a$ is now known to be constrained by astrophysical and cosmological arguments [11] to be between $10^9$ and $10^{12}$ GeV. Hence the axion must