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AXION IN PQWW MODEL AND AXION PRODUCTION IN e^+e^- COLLISION

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Abstract. *Properties of the axion in PQWW model is considered. In this model, axion appears as a new phase of the Higgs field. From a general Higgs potential which is renormalizable and invariant under $U_{PQ}(1)$ transformation, we consider the interaction of the axion with leptons and quarks. Based on these results, axion production in e^+e^- collision is calculated in detail. The numerical evaluation shows that the axion can be detected in experimental conditions.*

I. INTRODUCTION

For a long time, we have known CP violation created from weak interaction. In 1976, Callan *et al.*, [1] studied CP violation in strong interaction, called *strong-CP*. This effect happens because there is vacuum structure degenerate θ in QCD. This is equivalent to the addition of a new term in the QCD Lagrangian

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} G_{\mu\nu} G_{\alpha\beta},$$

where $G_{\mu\nu}$ is an asymmetry covariant gluon field. Under the action of CP transformation, $\mathcal{L}_\theta$ changes its sign, so that CP invariant is violated and the electric moment of neutron is $d_n \approx |\theta|(2.7 \div 5.2) \times 10^{-15}$ e.cm. In experimental calculations, $d_n < 5 \times 10^{-25}$e.cm, this shows that $|\theta| < 10^{-9}$, i.e. CP violation effect is very small. The question is why θ is very small in nature?

In 1977, Peccei and Quinn [2] showed that strong-CP problem can be solved if we accept the existence of a pseudo-scalar particle, called axion. Morever, the axion must be a pseudo-Nambu-Goldstone boson and its mass is a free parameter. Recent cosmological studies show that resonable mass of axion is in the range $10^{-6} \div 10^{-3}$ eV [3] (the main axion window). If the axion has a mass near the lower limit, it can play a very important role in the universe and could be (part of) the universe's cold dark matter.

In 1978, Bardeen *et al.*, [4] used techniques of current algebra to study properties of axion. Using the same techniques, in 1985, Kaplan [5] derived expression for the mass and electromagnetic coupling of the axion. In 1990, Sikivie [6] studied the transformation of the axion to electromagnetic energy and considered that as a new method to detect axion's signals from the space. So far almost all experiments designed to search for the light axions make use of the coupling of the axion to photons [7]. Following this direction, some new results have obtained [8-11]. Besides, the axion can be produced from collisions of charged particles [12-14] or other interaction with matter. Futher searches in this direction must be continued.

In this paper, we consider properties of the axion in Peccei-Quinn-Weinberg-Wilczek (PQWW) model. Using the Feynman diagram method, we present a study of axion production in e^+e^- collision.

II. AXION IN PQWW MODEL

The axion can be appeared in different models. It can play the role of a Goldstone boson of $U_{PQ}(1)$ group, or it can also be appeared as a component of the Chiral superfield in a supersymmetry (SUSY) theory. In this section, we consider properties of the axion in PQWW model, in which the axion appears as a phase of two Higgs doublet (ϕ_1, ϕ_2). The most general renormalizable Higgs potential with the reflection symmetry, $\phi_i \to -\phi_i$ is [10]

$$\begin{aligned} V(\phi_1,\phi_2) = & - \mu_1^2\phi_1^\dagger\phi_1 - \mu_2^2\phi_2^\dagger\phi_2 + \sum_{i,j} a_{ij}\phi_i^\dagger\phi_i\phi_j^\dagger\phi_j \\ & + \sum_{i,j} b_{ij}\phi_i^\dagger\tilde{\phi}_i\tilde{\phi}_j^\dagger\phi_j + \sum_{i\neq j} c_{ij}\phi_i^\dagger\tilde{\phi}_j\phi_i^\dagger\tilde{\phi}_j + h.c., \end{aligned} \tag{1}$$

where $Y(\phi_1) = \frac{1}{2}, Y(\phi_2) = -\frac{1}{2}; a_{ij}, b_{ij}$ are real; c_{ij} are hermitic and $\tilde{\phi} = i\sigma_2\phi^*$. The potential (1) has a $U(1)$ symmetry

$$\phi_1 \to e^{i\beta}\phi_1; \quad \phi_2 \to e^{i\beta}\phi_2. \tag{2}$$

However, this $U(1)$ symmetry is similar to $U_Y(1)$ gauge symmetry of the Standard Model (SM), therefore it is not useful for an independent global symmetry. Peccei and Quinn imposed the condition $c_{ij} = 0$, and this leads to the introduction of a $U_{PQ}(1)$ global symmetry

$$\phi_1 \to e^{i\alpha\Gamma_1}\phi_1; \quad \phi_2 \to e^{i\alpha\Gamma_2}\phi_2, \tag{3}$$

where Γ_1 and Γ_2 are the PQ charges of ϕ_1 and ϕ_2, respectively. The Yukawa interaction must satisfy the condition that the global symmetry (3) is not spoiled. This is assured by the coupling between ϕ_1 to d_R (or u_R) and ϕ_2 to u_R (or d_R). A special way to conserve PQ symmetry is the obtaining of quarks' mass from vacuum expectation values (VEV) of ϕ_1 and ϕ_2. Here, ϕ_1 gives mass for quark which has $Q_{em} = -\frac{1}{3}$, ϕ_2 gives mass for quark which has $Q_{em} = \frac{2}{3}$.

The Yukawa interaction of quarks is

$$\mathcal{L}_Y^q = -f_{ij}^{(u)}\bar{q}_{Lj}\phi_2 u_{Ri} - f_{ij}^{(u)}\phi_2^\dagger\bar{u}_{Ri}q_{Lj} - f_{ij}^{(d)}\bar{q}_{Lj}\phi_1 d_{Ri} - f_{ij}^{(d)}\phi_1^\dagger\bar{d}_{Ri}q_{Lj}, \tag{4}$$

where i and j are summed over the flavours. The couplings (1) and (4) expect PQ symmetry for fermions as follows

$$u_L \to e^{\frac{i}{2}\alpha\Gamma_2}u_L; \;\; d_L \to e^{\frac{i}{2}\alpha\Gamma_2}d_L; \;\; u_R \to e^{\frac{i}{2}\alpha\Gamma_2}u_R; \;\; d_R \to e^{\frac{i}{2}\alpha\Gamma_2}d_R. \tag{5}$$

Yukawa coupling (4) leads to the interaction between the axion and quarks. There are two models of Yukawa coupling of leptons as follows

Model I:

$$\mathcal{L}_Y^l = -f_{ij}^{(l)}\bar{l}_{Li}\phi_1 e_{Rj} - f_{ij}^{(l)^*}\phi_1^\dagger\bar{e}_{Rj}l_{Li}, \tag{6.1}$$

Model II:

$$\mathcal{L}_Y^l = -f_{ij}^{(l)}\bar{l}_{Li}\tilde{\phi}_2 e_{Rj} - f_{ij}^{(l)*}\phi_2\bar{e}_{Rj}l_{Li}, \quad (6.2)$$

where l_{Li} is left-handed lepton doublet of the i^{th} family, e_{Ri} is right-handed lepton singlet of the i^{th} family, $(e_1 = e, e_2 = \mu, e_3 = \tau)$. Under the action of $U_{PQ}(1)$ transformation

$$l_L \to e^{\frac{i}{2}\alpha\Gamma_1} l_L; \quad e_R \to e^{-\frac{i}{2}\alpha\Gamma_1} e_R \quad \text{for model I,} \quad (7.1)$$

and

$$l_L \to e^{-\frac{i}{2}\alpha\Gamma_2} l_L; \quad e_R \to e^{-\frac{i}{2}\alpha\Gamma_2} e_R \quad \text{for model II.} \quad (7.2)$$

Expressing ϕ_1^0 and ϕ_2^0 as

$$\phi_1^0 = \frac{\nu_1 + \rho_1}{\sqrt{2}} e^{\frac{ip_1}{\nu_1}}; \qquad \phi_2^0 = \frac{\nu_2 + \rho_2}{\sqrt{2}} e^{\frac{ip_2}{\nu_2}}, \quad (8)$$

where $< \phi_1^0 >= \nu_1/\sqrt{2}$, $< \phi_2^0 >= \nu_2/\sqrt{2}$, and ρ_1, ρ_2 are real Higgs fields. One linear combination of p_1 and p_2 phases is absorbed to Z boson and the other combination becomes the axion,

$$h \equiv -sin\theta \times p_1 + cos\theta \times p_2; \quad a \equiv -cos\theta \times p_1 + sin\theta \times p_2, \quad (9)$$

so that

$$p_1 = cos\theta \times a - sin\theta \times h; \quad p_2 = sin\theta \times a + cos\theta \times h,$$
$$tg\theta = \frac{\nu_1}{\nu_2}; \quad \chi = \frac{\nu_2}{\nu_1}; \quad \nu = \sqrt{\nu_1^2 + \nu_2^2} = 247 \text{ GeV}. \quad (10)$$

Higgs fields are expanded as

$$\phi_1^0 = \frac{\nu_1 + \rho_1}{\sqrt{2}} + \frac{i\nu_2}{\sqrt{2}\nu} a + .., \qquad \phi_2^0 = \frac{\nu_2 + \rho_2}{\sqrt{2}} + \frac{i\nu_1}{\sqrt{2}\nu} a + ... \quad (11)$$

Substituting (11) into (4) we obtain interactions between the axion and quarks

$$\mathcal{L}_Y^{a-q} = i\frac{a}{\nu}\{m_u(\frac{1}{\chi} - N_g\frac{(\chi+\chi^{-1})}{1+Z})\bar{u}\gamma_5 u + m_d(\chi - N_g\frac{(\chi+\chi^{-1})Z}{1+Z})\bar{d}\gamma_5 d + ...\}, \quad (12)$$

where $Z = m_u/m_d$, $N_g = 3$.

Interactions between the axion and leptons are obtained by substituting (11) into (6.1) and (6.2)

$$\mathcal{L}_Y^{a-l} = i\frac{a}{\nu}(\chi m_e e\gamma_5 e + \chi m_\mu \mu\gamma_5\mu + \chi m_\tau \tau\gamma_5\tau) \quad \text{for model I,} \quad (13.1)$$

and

$$\mathcal{L}_Y^{a-l} = i\frac{a}{\nu}(-\frac{m_e}{\chi}e\gamma_5 e - \frac{m_\mu}{\chi}\mu\gamma_5\mu - \frac{m_\tau}{\chi}\tau\gamma_5\tau) \quad \text{for model II.} \quad (13.2)$$

Notice that model I is defined by coupling ϕ_1 to right-handed lepton singlets and model II is defined by coupling ϕ_2 to right-handed lepton singlets.

III. AXION PRODUCTION IN e^+e^- COLLISION

Axion can be produced during the entering of photon in an external electromagnetic field [13]. It can also be created together photons in collisions of charged particles [14]. In this section, we focus on axion-photon production in e^+e^- collision

$$e^-(p_1) + e^+(p_2) \rightarrow \gamma(k_1) + a(k_2).$$

Using the Feynman rules we get the following expression for the matrix element

$$< P_f|M|P_i >= -i\frac{\alpha e N}{\pi F q^2}\epsilon_\lambda(k_1) q_\alpha k_{1\mu}\epsilon^{\alpha\sigma\mu\lambda}\bar{v}(p_2)\gamma_5 u(p_1), \quad (14)$$

F/N is Peccei-Quinn scale, $F/N = 10^9$ GeV $\div 10^{13}$ GeV [12], $\epsilon_\mu(k_1)$ is the polarization vector of the photon, and $s = q^2 = (p_1 + p_2)^2$ is the square of the collision energy. After some calculations, we obtain the differential cross-section at the high energy limit $(s \gg m_a^2, m_e^2)$

$$\frac{d\sigma}{dcos\theta} = \frac{\alpha^2 N^2}{64\pi^2 F^2}(1 + cos^2\theta), \quad (15)$$

where $\alpha = \frac{e^2}{4\pi} = 1/137.036$.

Fig. 1 shows that the axion is created mostly at $\theta \approx (0; \pi)$ direction. From (15), by calculating the integral over $cos\theta$ variable, we obtain the total cross-section as

$$\sigma = \frac{\alpha^2 N^2}{24\pi^2 F^2}. \quad (16)$$

Some values of the total cross-section in $\frac{F}{N}$ are shown in Table 1.

Table 1. *The cross-section values in* $\frac{F}{N}$.

F/N	10^9	10^{10}	10^{11}	10^{12}	10^{13}
$\sigma(cm^2)$	2.25×10^{-25}	2.25×10^{-27}	2.25×10^{-29}	2.25×10^{-31}	2.25×10^{-33}

IV. CONCLUSION

It is possible to consider the above-mentioned method as the second method to receive axion (the first method is the photon - axion transformation in electromagnetic field [8,11]). From Fig. 1 we can conclude that the differential cross-section of the process has maximum values 1.2×10^{-29} cm^2 at $cos\theta = -1$ and $cos\theta = 1$ (or $\theta = 0$ and $\theta = \pi$). However, the value of the differential cross-section in this case is much less than that of photon - axion conversion in the external electromagnetic field at $q = q_z$, $\theta = \frac{\pi}{2}$; $\phi = \frac{\pi}{2}$ [11]. With the total cross-sections given in the Table 1 and the intergrated luminosity $L = 10^5$ pb^{-1} [15] one expects several thousand events. Finally, if the axion exists, we will have new powerful tools to study the Galaxy and the Sun.

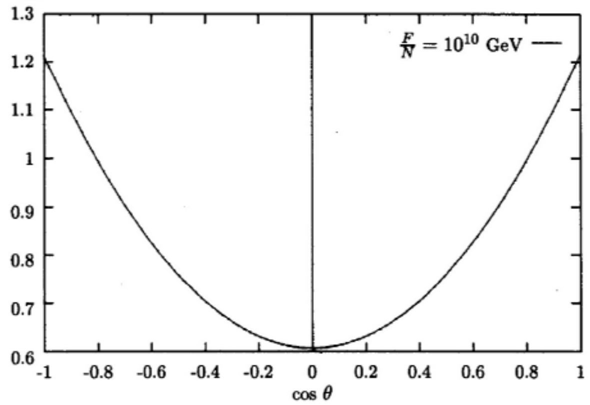

Fig. 1. The differential cross-section as a function of $cos\theta$, with $\frac{F}{N} = 10^{10}$ GeV.

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