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PRODUCTION AND DECAY OF SAXION IN e^+e^- COLLISIONS

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The production of saxion in e^+e^- collider and the saxion decay into two photons were calculated in detail. Based on results it shows that the saxion is stable in our universe and can play the role of the late decaying particle (LDP) in a dark matter. At the low bound of the saxion mass it can be a new candidate for the cold dark matter (CDM).

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1 Introduction

The most attractive candidate for the solusion of the strong CP problem is Peccei and Quinn (PQ) mechanism [1], where the CP-violating phase θ ($\theta \leq 10^{-9}$) is explained by the existence of a new pseudo-scalar field, called the axion. Based on the recent laboratory researches and astrophysical and cosmological considerations [2] the value of the axion mass was estimated in range between 10^{-6} eV and 10^{-3} eV [3]. The axion appears in different models. In particular, it appears as a new phase of Higgs fields in the electroweak theories, or appears as a term of chiral superfields in the low - energy supersymmetry (SUSY) theories [3, 4].

The nature of the dark matter in the Universe remains one of the most challenging problems in cosmology. Numerous candidates for dark matter have been proposed in the literature. One of the most popular candidates in the context of supersymmetric theories with R - parity conservation is the lightest supersymmetric particle (LPS), namely the lightest neutralino. The interactions of the neutralino are weak, and its number density at decoupling is therefore often of the required order of magnitude, which makes it an excellent candidate for the weakly interacting massive particle (WIMP) [5].

In the SUSY extension of the axion model, the axion supermultiplet ($\Phi = 1/\sqrt{2}$(s + ia + $\sqrt{2}\tilde{a}\theta$ + $F_\Phi\theta\theta$) consists of the axion, its real scalar superpartner saxion (s), and the fermionic superpartner axino ($\tilde{a}$). Like axions, the coupling of the axino to ordinary matter is very weak [6], thus it is a good candidate for WIMP. The stable relic axino shows that the axino can be an attractive candidate for CDM [7]. Important properties of the axino have been studied [8–10]. In SUSY axion models, The saxion mass depends on the specific forms of the axion sector superpotential, which is predicted in range between 1 keV and 100 MeV [11]. The decay of saxion into two axions with high values of the Hubble constant is presented in [12]. The saxion properties and its

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contribution on the dark matter were studied recently [13–15]. The direct detection of supersymmetric dark matter via scattering on nuclei in deep-underground, low-background experiments has been discussed many times [16–18].

The possible consequences of the presence of saxions are the subject of this study. In this paper we evaluate the production of saxion in the e^+e^- collision and the saxion decay into two photons. The results showed that the saxion is stable in our unverse and it can play the role of LDP in the dark matter. This paper is organized as follows: In Sec.II we give constraints on the saxion mass in the SUSY axion model. In Sec. III and Sec. IV, we evaluate the production and decay of the saxion in the e^+e^- collisions. Finally, our conclusions are summarized in the last section.

2 Constraint on the saxion mass

In the framework of gauge mediated SUSY breaking theories, an interesting possibility to dynamically generate the PQ symmetry breaking scale in the hadronic axion model(KSVZ model) was proposed in [12]. In this model, a gauge singlet PQ multiplet X and new PQ quarks Q_P and $\overline{Q}_P$ (**3** and **3*** in $SU(3)_C$) are introduced. Their $U(1)_{PQ}$ charges are assigned as $\mathcal{Q}[X] = +1$, $\mathcal{Q}[Q_P] = -1/2$ and $\mathcal{Q}[\overline{Q}_P] = 1/2$. The superpotential of the PQ sector takes the following simple form

$$W = \lambda_P X Q_P \overline{Q}_P, \tag{1}$$

where λ_P is a coupling constant and here the mass parameter was not introduced. Due to the supersymmetric limit the $U(1)_{PQ}$ symmetry is enhanced to its complex extension, there appears a flat direction Q_P = $\overline{Q}_P$ = 0 with X undermined in the same limit. The balance of the SUSY breaking effects between the gravity mediation and the gauge mediation stabilizes X and gives the nonzero vacuum expectation value (VEV) $<$ X $>$ = F_a approximately as

$$F_a = \frac{f^2}{m_s}, \tag{2}$$

where m_s denotes the mass of a saxion field, the real part of the scalar component of X. The mass of saxion is estimated as m_s = $\xi m_{3/2}$ with a parameter ξ of order unity, and f is a mass scale, with a current scalar lepton mass limit, suggests that $f \gtrsim 10^4\ GeV$. The axion arises when the X field develops the non-vanishing VEV. The decay constant of the axion (the PQ scale) F_a is constrained by various astrophysical and cosmological consideration, the allowed region for the PQ scale is discussed [9, 12]

$$10^9\ \text{GeV} \lesssim F_a \lesssim 10^{12}\ \text{GeV}. \tag{3}$$

From Eqs. (2) and (3) we can deduce the allowed region for the saxion mass, with the minimum value f = 10^4 GeV as

$$100\ \text{MeV} \gtrsim m_s \simeq m_{3/2} \gtrsim 1\ \text{keV}. \tag{4}$$

Thus the model gives a very simple description of the PQ breaking mechanism solely governed by the physics of the SUSY breaking. In this model it makes sense to consider the possibility of the very small saxino mass, which is comparable to the gravitino mass.

3 The production of saxion in e^+e^- collisions

For the saxino - photon system, a suitable Lagrangian density is given by [14]

$$\mathcal{L}_{(s,\gamma,\gamma)} = \frac{\alpha_c}{8\pi F_a} s F_{\mu\nu} F^{\mu\nu}, \tag{5}$$

where α_c is the colour constant, $F_{\mu\nu}$ = $\partial_\mu A_\nu$ - $\partial_\nu A_\mu$ is the field strength tensor.
From (5) we get a saxion - photon- photon vertex

$$V_\alpha^\beta(s,\gamma,\gamma) = \frac{-i\alpha_c}{4\pi F_a}[2(q.k)g_\alpha^\beta - q^\beta k_\alpha - q_\alpha k^\beta]. \tag{6}$$

Considering the collider process in which the initial state contains the electron and the positron and the final state, are the photon and the saxino: $e^-(k_1)$ + $e^+(k_2) \rightarrow \gamma(q_1)$ + s(q_2), where k_1, k_2, q_1 and q_2 stand for four-momenta of particles, respectively. This process proceeds through the s - channel photon exchange. We work in the center-of-mass frame, and denote the scattering angle by θ (the angle between momenta of the initial electron and the final photon), and $s = p^2 = (q_1 + q_2)^2 = (k_1 + k_2)^2$ is the square of the collision energy.

Supposing that the production of the photon - saxino pairs at high energies i.e., $m_s \ll \sqrt{s}$, then the amplitude for this process is given by

$$\langle f\,|M|\,i\rangle = \frac{-ie\alpha_c}{4\pi F_a}\frac{1}{p^2}\overline{v}(k_2)\gamma^\nu u(k_1)[2(p.q_1)g_\nu^\alpha - p^\alpha q_{1\nu} - p_\nu q_1^\alpha]\epsilon_\alpha(q_1). \tag{7}$$

The straightforward calculations yields the following differential cross-section (DCS) as

$$\frac{d\sigma(e^+e^- \rightarrow \gamma s)}{d\Omega} = 4.9 \times 10^{-4}\frac{\alpha\alpha_c^2}{\pi^3 F_a^2}(7 + cos^2\theta), \tag{8}$$

where α = $e^2/4\pi$ is the structure constant. After integration over the θ angle, we obtain the total cross-section (σ) as

$$\sigma(e^+e^- \rightarrow \gamma s) = 1.4 \times 10^{-2}\frac{\alpha\alpha_c^2}{\pi^2 F_a^2}. \tag{9}$$

From (9) it shows that at high energies the cross section only depends quadratically on PQ scale F_a and α_c. For $\alpha_c = 0.1$, F_a = 10^{11} GeV [14, 15], $\alpha^{-1} = 137.0359895$, and in system of units [GeV]$^{-2}(\hbar c)^2 = 0.389379323$ mb [20], we get the σ ($e^+e^- \rightarrow \gamma s$) = 8.3 $\times$ 10^{-24} nb.

In Fig.1 the DCS was plotted by $\cos\theta$, as we can see from the figure, the DCS is peaked in backward and forward direction, $\frac{d\sigma(e^+e^- \rightarrow \gamma s)}{d\Omega} = 3.6 \times 10^{-25}$ nb.

The axino production in e^+e^- and $\gamma\gamma$ collisions is presented in [19]. From our results, it shows that cross - sections for the saxion and axino production at high energies are very small, much below neutrino production cross sections, so that the direct production of CDM particles is in general not expected to lead to easily observable signals in e^+e^- annihilation. Note that the experimental upper limit on the dark matter scattering cross section recently provided by the DAMA experiment [21] and the CDMS [22], in which CDMS II experiment is substantially more stringent than previous experiments.

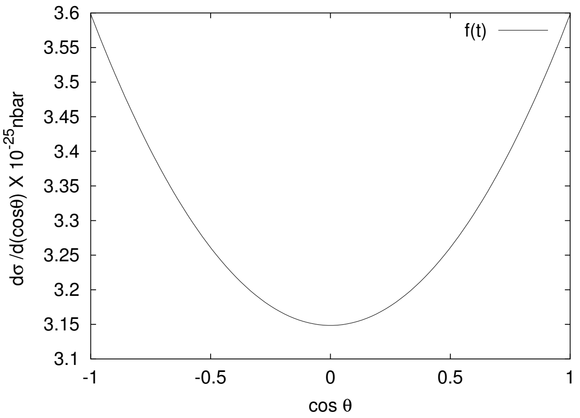

Fig. 1. The DCS for $e^+e^- \to \gamma s$ as a function of $\cos\theta$

4 The decay of saxion into two photons

If the saxino is light enough in which it's mass is comparable to gravitino mass, then the saxino can not decay into two gluons but decays into two photons. In this section we calculate the decay of saxion into two photons. The amplitude for this process is

$$\langle f\,|M|\,i\rangle = \frac{i\alpha_c}{4\pi F_a}[2(q.k)g_{\alpha\beta} - k_\alpha q_\beta - q_\alpha k_\beta]\epsilon^\alpha(q)\epsilon^\beta(k). \tag{10}$$

After some calculations, we obtain the decay rate

$$\Gamma(s\to\gamma\gamma) = 4.9\times 10^{-3}\frac{\alpha_c^2}{\pi^3 F_a^2}m_s^3. \tag{11}$$

With $\alpha_c = 0.1$, $F_a = 10^{11}$ GeV and note that $[\mathrm{GeV}]^1 = \frac{1}{6.6\times 10^{-25}}$ sec^{-1} [20], then we can rewrite (11) as

$$\Gamma(s\to\gamma\gamma) = 2.3\times 10^{-4}\left(\frac{\alpha_c}{0.1}\right)^2\left(\frac{10^{11}\ \mathrm{GeV}}{F_a}\right)^2 m_s^3(\mathrm{GeV})\ \mathrm{sec}^{-1}. \tag{12}$$

Therfore the lifetime of saxion is

$$\tau(s\to\gamma\gamma) = \frac{1}{\Gamma(s\to\gamma\gamma)} = 4.3\times 10^6\ \mathrm{sec}\left(\frac{\alpha_c}{0.1}\right)^{-2}\left(\frac{F_a}{10^{11}\ \mathrm{GeV}}\right)^2\left(\frac{100\ \mathrm{MeV}}{m_s}\right)^3. \tag{13}$$

For the saxion mass in region 100 MeV $\le m_s \le$ 1 keV, the dependence of the decay rate and the lifetime of the saxion on its mass is shown in Table 1

m_s (MeV)	100	10	1	0.1	0.01	0.001
Γ (sec^{-1})	2.3×10^{-7}	2.4×10^{-10}	2.3×10^{-13}	2.3×10^{-16}	2.3×10^{-19}	2.3×10^{-22}
τ (sec)	4.3×10^{6}	4.3×10^{9}	4.3×10^{12}	4.3×10^{15}	4.3×10^{18}	4.3×10^{21}

From the Table 1, we can see that the saxion can play the role of a long lived constituent of dark matter. When $m_s \leq 10$ MeV, then the lifetime of saxion is very long, therefore the saxion can be a good candidate for LDP. If the saxion mass is smaller than 10 keV , it becomes stable within the age of universe ($\sim 10^{17}$ sec), when the saxion lifetime is larger than the age of the universe then saxion oscillation still exists now. Note that the value τ varies very widely because of the strong dependence on the saxion mass.

Now we estimate the cosmic temperature at the saxion decay (T_D) [12]

$$T_D = 0.6 \times A\left(\frac{M_G}{A^2\tau_\sigma}\right)^{2/3}, \tag{14}$$

where A is the saxion abundance: $A \leq 3.6 \times 10^{-9}h^2$, $M_G = 2,4.10^{18}$ is the Planck scale, $h = 0.7$ is the Hubble parameter. For $m_s = 10$ keV we have $T_D \sim 726,94$ GeV.

5 Conclusion

In our work, we evaluated the production and decay of saxion in e^+e^- collisions. From our results, it shows that cross - sections for the saxion production at high energies are very small, so that the direct production of saxions is not expected to lead to easily observable signals in e^+e^- annihilation.

The decay of saxion into two photons was also calculated in detail. Based on the results it shows that the saxion can play a role of the late decaying massive particle. We point out that in all possible modes the decay of saxion strongly depends on it's mass. If the mass of saxion is smaller than 10 keV (correspond to the low bound of PQ scale), then the saxion becomes stable and can be a new candidate for CDM of our universe.

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