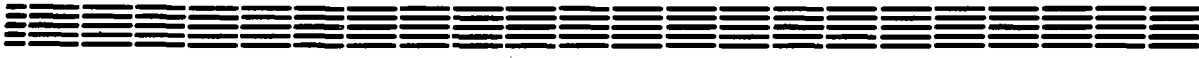


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YEREVAN PHYSICS INSTITUTE



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RELATIVISTIC EFFECTS IN THE QUARKONIA  
RADIATIVE DECAYS WITH AXION PRODUCTION

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ԱԿԱԻՈՆԻ ԾՆԱՄԱԲ ՔՎԱՐԿԻՈՆՈՒՄՆԵՐԻ ՌԱԴԻԱՑԻՈՆ ՏՐՈՂՈՒՄ-  
ՆԵՐՈՒՄ ԴԻՏՎՈՂ ՌԵԼՅԱՏԻՎԻՍԱԿԱՆ ԷՓԵԿՏՆԵՐԸ

Ցույց է արված, որ ռելյատիվիստական էֆեկտները հանգեցնում են ոչ ռելյատիվիստական քվարկային մոդելով կանխագուշակված  $Bz(\Psi \rightarrow \alpha\gamma) / Bz(\Psi \rightarrow \mu^+\mu^-)$  և  $Bz(\gamma \rightarrow \alpha\gamma) / Bz(\gamma \rightarrow \mu^+\mu^-)$  առնչությունների արժեքների զգալի նվազեցման, որն արդեն թույլ չի տալիս այս տրոհումների վերաբերյալ զոյություն ունեցող փորձարարական սվյալների հիման վրա միարժեքորեն բացատել երկարակյաց ակսիոնի զոյությունը:

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М.Г.АЗНАУРЯН, С.Г.ГРИГОРЯН, С.Г.МАТИНЯН

РЕЛЯТИВИСТСКИЕ ЭФФЕКТЫ В РАДИАЦИОННЫХ РАСПАДАХ  
КВАРКОНИЕВ С РОЖДЕНИЕМ АКСИОНА

Показано, что релятивистские эффекты приводят к сильному уменьшению предсказываемых нерелятивистской кварковой моделью значений отношений  $\Gamma(\Psi \rightarrow \alpha\gamma) / \Gamma(\Psi \rightarrow \mu^+\mu^-)$  и  $\Gamma(\gamma \rightarrow \alpha\gamma) / \Gamma(\gamma \rightarrow \mu^+\mu^-)$ , что уже не позволяет на основании имеющихся экспериментальных данных по этим распадам однозначно исключить существование долгоживущего аксиона.

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I.G. AZNAURYAN, S.G. GRIGORYAN, S.G. MATINYAN

RELATIVISTIC EFFECTS IN THE QUARKONIA RADIATIVE  
DECAYS WITH AXION PRODUCTION

It is shown that relativistic effects lead to a strong decrease in the values of ratios  $Bz(\Psi \rightarrow \alpha\gamma)/Bz(\Psi \rightarrow \mu^+\mu^-)$  and  $Bz(\gamma \rightarrow \alpha\gamma) / Bz(\gamma \rightarrow \mu^+\mu^-)$ , predicted by the nonrelativistic quark model. This does not already allow to unambiguously exclude, on the basis of available experimental data on these decays, the existence of a long-lived axion.

Yerevan Physics Institute

Yerevan 1987

It is known that in connection with the solution of the CP-invariance breaking problem in strong interactions, Peccei and Quinn [1] have proposed to introduce an additional chiral U(1)-symmetry into total Lagrangian. Later on, Weinberg [2] and Wilczek [3] have shown that this gives rise to a light neutral pseudoscalar particle - the axion.

The axion was searched for in different experiments. So, experiments on the axion search in nuclear transitions [4,5], in the  $K^+ \rightarrow \pi^+ \alpha$  decay [6], experiments of the "beam-dump" type [7] as well as the radiative decays  $J/\psi \rightarrow \alpha \gamma$  [8] and  $\gamma \rightarrow \alpha \gamma$  [9,10] bring to a conclusion about the absence of axion with standard properties. The report [11] on the observation of narrow peak in electron and positron spectra in heavy ion collisions and the interpretation of this fact as a production of neutral particle with a mass  $\approx 1.8 \text{ MeV}/c^2$  have stimulated a number of experiments [12,13] in order to check whether this particle is an axion. However, these experiments, too, exclude the existence of short-lived axion with a mass  $m_\alpha > 2m_e$ .

Note that the main experiments excluding the existence of axion are considered those on vector quarkonia radiative decays  $J/\psi \rightarrow \alpha \gamma$  [8]

and  $\gamma \rightarrow \alpha\gamma$  [9,10], since for these decays the theoretical estimates are less model-dependent.

In this work we have studied the influence of relativistic effects on the radiative decay widths of the heavy vector quarkonia with the axion production and have shown that the account of these effects leads to a strong decrease in theoretical estimates for the widths of these decays made in the nonrelativistic quark model [3] (this statement becomes stronger when taking account of the radiative corrections studied in Refs. [14,15]). This already does not allow us to exclude the axion with standard properties on the basis of only these decays which imposed an experimentally better grounded veto upon the axion.

In Ref. [3] the following formulae were obtained for the studied decays:

$$R_V \equiv \frac{Bz(V \rightarrow \alpha\gamma)}{Bz(V \rightarrow \mu^+\mu^-)} = \frac{G_F M_V^2 y_V^2}{4\sqrt{2}\pi\alpha}, \quad (1)$$

where  $V$  denotes the vector quarkonia  $\Psi$  and  $\gamma$ ;  $M_V$  is these quarkonia mass;  $y_\Psi = \alpha$ ,  $y_\gamma = \frac{1}{\alpha}$ ;  $\alpha$  is the only model-dependent theory parameter equal to the ratio of the vacuum averages of two Higgs fields. In the product of the branching ratios of the decays  $\Psi \rightarrow \alpha\gamma$  and  $\gamma \rightarrow \alpha\gamma$  the quantity  $\alpha$  drops out, and using the values

$Bz(\Psi \rightarrow \mu^+\mu^-) = 0.069 \pm 0.009$ ,  $B(\gamma \rightarrow \mu^+\mu^-) = 0.028 \pm 0.002$  we obtain

$$Bz(\Psi \rightarrow \alpha\gamma) \cdot Bz(\gamma \rightarrow \alpha\gamma) = (13.4 \pm 2.7) \cdot 10^{-9}. \quad (2)$$

At the same time, from the experiments [8-10] on the search for long-lived axion ( $m_a < 2m_e$ ) we have:

$$Bz(\Psi \rightarrow \alpha\gamma) \cdot Bz(\gamma \rightarrow \alpha\gamma) < 4.2 \cdot 10^{-9}. \quad (3)$$

From (2) and (3) one concludes that the existence of long-lived axion with standard properties is excluded by the experiments on the vector quarkonia radiative decays. Note, that the existence of short-lived axion is rejected by the experiments of [12,13].

If using the data on  $Bz(\Psi \rightarrow \alpha\gamma)$  and  $Bz(\gamma \rightarrow \alpha\gamma)$  separately, then the available experiments exclude the following values of the parameter  $\alpha$  :  $\alpha > 0.48 \pm 0.03$  from the data of [8],  $0.07 < \alpha < 0.87 \pm \pm 0.03$  from [9,10] and  $\alpha < 0.07$  from [12,13], thus rejecting all the values of  $\alpha$ .

We have studied relativistic effects in the mentioned decays and obtained estimates for the  $R_\Psi$  and  $R_\gamma$  ratios (see formula (1)) already with the account of these effects. In our calculations we based on the results obtained in Refs. [16,17], where we studied thoroughly the relativistic effects in the vector quarkonia radiative decays with the production of the scalar and pseudoscalar Higgs bosons. Therefore, we present here only the final results.

The account of the relativistic motion of quarks in the  $\Psi$  and  $\gamma$  quarkonia brings to the following expressions for the widths:

$$\Gamma(V \rightarrow \alpha\gamma) = \frac{2\sqrt{2}}{\pi} \alpha G_F M_V Q_q^2 y_V^2 \left( \frac{M_V}{2m_q} \right)^2 A_V^2, \quad (4)$$

$$\Gamma(V \rightarrow \mu^+\mu^-) = 16\alpha^2 \frac{Q_q^2}{M_V} B_V^2, \quad (5)$$

where we have neglected the axion mass and

$$A_V = \int \left[ 1 + \frac{m_q(2\varepsilon + m_q)}{2\varepsilon p} \ln \frac{\varepsilon + p}{\varepsilon - p} \right] \frac{m_q^2}{2(\varepsilon + m_q)\varepsilon^{3/2}} \Psi_V(p) p^2 dp, \quad (6)$$

$$B_V = \int \left[ 1 - \frac{p^2}{3\varepsilon(\varepsilon + m_q)} \right] \varepsilon^{-\frac{1}{2}} \Psi_V(p) p^2 dp, \quad (7)$$

$\varepsilon = (m_q^2 + p^2)^{1/2}$ ,  $q$ , denotes the c- or b-quark,  $\Psi_V(p)$  is the radial part of the quark wave function in the momentum representation, normalized by the condition:

$$\int \Psi_V^2(p) d\vec{p} = 1. \quad (8)$$

To clarify formulae (6), (7), let us give the first two terms of the  $A_V/B_V$  ratio expansion in powers of  $p^2/m_q^2$ :

$$\frac{A_V}{B_V} = 1 - \frac{5}{6} \Delta, \quad \Delta = \int \frac{p^2}{m_q^2} \Psi_V(p) d\vec{p} / \int \Psi_V(p) d\vec{p}. \quad (9)$$

One can see from (4), (5) and (9) that the account of relativistic effects leads to a decrease in the ratios  $R_V$ . This effect is accentuated by the circumstance that the numerical value of  $\Delta$  is greater than the mean value of  $\frac{p^2}{m_q^2}$  (or  $\frac{v^2}{c^2}$ ) in  $\Psi$  and  $\gamma$ , which is quite large in these systems. The numerical calculations for  $R_\Psi$  and  $R_\gamma$  by formulae (4)-(7) with the values of the c- and b-quark masses and the wave functions  $\Psi_V(p)$  from Ref. [18] result in a decrease in  $R_\Psi$  by a factor of 1.82, and in  $R_\gamma$  by a factor of 1.45. Note, that the wave function  $\Psi_V(p)$  is connected with the wave function  $R(z)$  of Ref. [18] by the relation:

$$p \Psi_V(p) = \frac{1}{\sqrt{2}\pi} \int R(z) \sin pz dz. \quad (10)$$

If one considers the product of the branching ratios of the studied decays, then the account of relativistic effects using the results of Ref. [18]

reduces the right-hand side of relation (2) by a factor of 2.6. The use of the results of Refs. [19-21] brings to a still stronger (nearly 4 times) reduction of this product. For Refs. [22,23] this suppression is weaker, being approximately 2.3 times. If taking into account that the radiative corrections to the  $\Psi \rightarrow \alpha\gamma$  and  $\gamma' \rightarrow \alpha\gamma$  processes also reduce the product (2), then it is clear that the given in formula (2) theoretical estimate for the product of the branching ratios of the studied processes must be at least a factor of 3.5 - 4 lower. Then one must not reject, on the basis of experimental restriction (3), the existence of long-lived axion from experiments with production of this particle in vector quarkonia radiative decays. If we do not use the  $\alpha$  independent product of the branchings but take them separately, then from the obtained result we may conclude that the long-lived axion with standard properties is not vetoed so far for  $\alpha$  near 0.7 in the considered experiments. As for the short-lived axion, its existence is rejected by the experiments [12,13] even with the account of relativistic effects and radiative corrections.

In conclusion, one of the authors (S.G.G.) would like to express his sincere gratitude to M.I.Vysotsky for his interest to the work and useful discussions.

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