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Свидетельство против существования аксионов от реакторных экспериментов

Обсуждается вопрос о том, исключают ли уже проведенные эксперименты на ядерных реакторах существование аксионов.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Evidence Against Axions from Reactor Experiments

The question is being discussed as to whether the experiments already performed on nuclear reactors exclude the existence of axions.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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Recently there appeared two papers by S.Weinberg /1/ and F.Wilczek /2/ in which theoretical arguments, based on quantum chromodynamics and renormalizable gauge theory, were given in favour of the existence of a hypothetical particle, the axion a, having the following properties: the electrical charge equal to 0, $J^P=0^-$, the mass m_a in the range of 10 keV to 1 MeV. The arguments rely upon the work of Peccei and Quinn /3/, the existence of the axion being desirable /1-3/ to preserve the parity and time reversal invariance of strong interactions in spite of the instanton solution /4/ of quantum chromodynamics.

Possible experiments which might reveal low energy Higgs scalar particles are reviewed in refs. /5-7/, wherein many proposals are pointed out which would be valid also in the case of a search for axions. As far as we know, however, reactor experiments have not yet been considered. While it would be exciting to perform experiments especially designed to reveal the existence of the particle a, these are in general rather cumbersome, although perfectly feasible, and we wish to discuss here the question as to whether the experiments already performed would give some information on the a particle. In fact, we show that reactor experiments designed to investigate neutrinos have the required sensitivity to detect axions, the expected rate of axion events being at least comparable with that of neutrino events.

We discuss here two reactor experiments. In the first one [8] the process $\bar{\nu}_e + e \to \bar{\nu}_e + e$ has been observed while in the second one [9], designed to reveal the process $\bar{\nu}_e + D \to \bar{\nu}_e + n + p$, an upper limit for the corresponding cross section has been given.

The particle a is expected to be coupled [1,2] to a fundamental fermion (quark or lepton) as follows:

$$L_{int} = 2^{1/4}\sqrt{G}\, m_f \bar{f}\gamma_5 f a = g_f \bar{f}\gamma_5 f a , \qquad (1)$$

where m_f is the fermion mass, $G = 10^{-5}/M_p^2$ is the Fermi constant, a and f are, respectively, the axion and fermion fields, g_f^2 is the effective dimensionless squared coupling constant. As far as electrons (mass m_e) are concerned, g_e^2 is

$$g_e^2 = 2^{1/2} G m_e^2 \approx 4\cdot 10^{-12}. \qquad (2)$$

As far as quarks are concerned, it is not clear which value for the quark mass m_q should be used.

In the experiments which are considered below the typical momentum of axions which might be emitted by excited nuclei is $p_a \sim 3$ MeV/c. In refs. [1-2] reasons are given why at energies well above the pion threshold the squared dimensionless coupling constant g_q^2 should be expressed through the pion constant $F_\pi \sim m_\pi$:

$$g_q^2 \approx 2^{1/2} G F_\pi^2 .$$

At low energies, however, in the axion emission amplitude there should appear* explicitly the momentum of the emitted axion p_a. Thus, this amplitude would be proportional to $2^{1/4}\sqrt{G}\frac{p_a}{M_N}F_\pi$. Now the estimates of the axion emission intensity which are presented below are expressed in terms of the intensity of photons having momenta $p_\gamma \approx p_a$ (the corresponding strength being taken as $4\pi\alpha$) and here too, that is in the photon emission amplitude, a small coefficient of the order of the change in nucleon velocity $p_\gamma/M_N \approx p_a/M_N$ should be present. Thus, the effective dimensionless squared coupling constant g_{eff}^2, relative to the photon emission squared coupling constant taken as $4\pi\alpha$, is again equal to the preceding expression, that is:

$$g_{eff}^2 \approx 2^{1/2} G F_\pi^2 \approx 10^{-7} . \qquad (3)$$

Now this may be a too optimistic view on the reactor as an axion source, so that we shall consider in addition some pessimistic possibilities which on the physical ground are less reasonable. One may suppose that in the axion amplitude there is a quantity with the dimensions of a mass having a much smaller value than F_π, the smaller value one can think of being a few MeV and/or that in exp. (3) there should be a small dimensionless factor connected with the nuclear aspect of axion emission. For the sake of definiteness we shall then consider the following range of possible g_{eff}^2 values

$$g_{eff}^2 = 10^{-10} \div 10^{-7} , \qquad (3a)$$

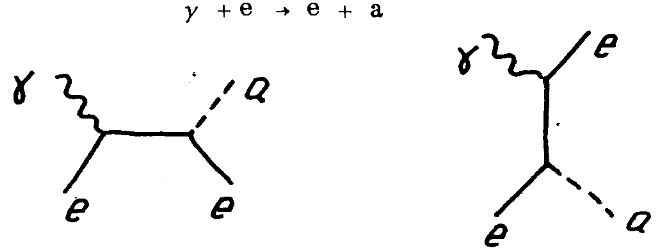
having in mind that the larger value is more reliable.

In reactors the emission of axions by both quarks and electrons should take place. Below we discuss various sources of axions from a reactor.

The most important electron source of axions is the quasi Compton effect, that is the process (see the Figure)

*This is the effect of the γ_5 coupling of pseudoscalar axions to fermions the importance of which has been stressed to us by L.B.Okun and M.I.Vysotsky.

$\gamma + e \to e + a$



Figure

There are many quark sources of axions, the most important being those which "compete" with gamma-ray emission, namely, the axion emission is a slow neutron capture

$n + (Z,A) \to (Z,A+1) + a$,

the axion emission by excited nuclei produced in beta-decay:

$(Z,A)^* \to (Z,A) + a$

and the direct production of axions in nuclear fission.

Since the reactor experiments /8,9/ we are interested in are neutrino experiments (involving neutrino energies higher than 1.5 MeV) it is natural to compare directly the axion and neutrino intensities Φ_a and $\Phi_{\bar\nu}$. Reactor data suggest a very rough rule of thumb; the number of photons $\Phi_{\gamma > 1.5\,MeV}$ with energies $E_\gamma > 1.5$ MeV in a reactor is a few times larger than the number of antineutrinos of comparable energies and is of the same order of magnitude as the total number $\Phi_{\bar\nu}$ of antineutrinos, i.e., $\Phi_{\gamma > 1.5\,MeV} \approx \Phi_{\bar\nu}$.

Let us estimate now the intensity of axions from electrons ${}^{e}\Phi_a$ and from quarks ${}^{q}\Phi_a$. As is seen from the Figure, equation (2) and from the fact that the total γ-cross section at the energies considered is equal to the Compton cross section, we obtain:

$$
{}^{e}\Phi_a \approx \Phi_{\gamma > 1.5\,MeV}\frac{\sigma_{\gamma e\to e a}}{\sigma_{\gamma}^{tot}} \approx \Phi_{\gamma > 1.5\,MeV}\frac{\sigma_{\gamma e\to e a}}{\sigma_{\gamma}^{Compton}} \approx \Phi_{\bar\nu}\frac{g_e^2}{4\pi a} \approx 4.10^{-11}\Phi_{\bar\nu} \,. \qquad (4)
$$

Using exp. (3a), we estimate now the intensity ${}^{q}\Phi_a$ of axions from quarks noting that, in the processes which are considered, axion emission competes with photon emission:

$$
{}^{q}\Phi_a \approx \Phi_{\bar\nu}\frac{g_{eff}^2}{4\pi a} \approx (10^{-9} \div 10^{-6})\,\Phi_{\bar\nu} \,.
$$

Although the intensity ${}^{e}\Phi_a$ is estimated much more accurately than ${}^{q}\Phi_a$, the latter is much larger so that below we shall take the total axion intensity Φ_a to be approximately equal to ${}^{q}\Phi_a$:

$$
\Phi_a \approx {}^{q}\Phi_a \approx (10^{-9} \div 10^{-6})\,\Phi_{\bar\nu} \,. \qquad (5)
$$

Obviously equation (5) gives also the relation between axion and neutrino fluxes at the detector location.

In one of the two neutrino experiments, which are being analysed here from the point of view of a possible detection of axions, scintillation detectors were used /8/. One may consider detecting axion decays in the scintillator as a method for observing axions. This in fact gives the most definite, if not the most significant, information and will be discussed at the end of the paper.

One should note that relatively low energy axions (of energy of a few MeV) can be detected also through the process $a + e \to e + \gamma$, for the observation of which a scintillation detector is adequate. The cross section expected for the process $a + e \to e + \gamma$ which is the reaction inverse to the quasi Compton process (see the Figure and eq. (2)) is:

$$\sigma_{a\,e\to e\gamma} \approx \sigma_{\gamma e\to\gamma e}\,\frac{g_e^2}{4\pi a} \approx 10^{-25}\cdot 4\cdot 10^{-11}\,\mathrm{cm}^2 \approx 4\cdot 10^{-36}\,\mathrm{cm}^2 . \qquad (6)$$

The effect searched for in ref. /8/ – the $\bar{\nu}_e + e \to \bar{\nu}_e + e$ process, was revealed in a 16 kg plastic scintillation counter. The plastic reactor associated rate was (7.1 ± 1.5)/day in the electron energy interval 1.5 – 4.5 MeV, the cross section in this interval $\sigma_{\bar{\nu} e}$ averaged over the neutrino spectrum being $(9.5 \pm 2.3).10^{-46}\mathrm{cm}^2$ /8,10/. In order to decrease the number of background events accompanied by photons a huge (300 kg) NaI veto scintillator was used. This unfortunately makes the plastic data practically unusable for the purpose of revealing the reaction $a + e \to e + \gamma$. Thus we used the upper limit of the reactor associated rate of the NaI scintillator, published in ref. /8/ $N = (-1.6 \pm 2.6).10^2$ /days. Knowing the rate in the plastic we can calculate the value of the rate $N_{\bar{\nu} e}$ due to the $\bar{\nu}_e + e \to \bar{\nu}_e + e$ process in the NaI scintillator:

$$N_{\bar{\nu} e} = 7.1 \times 300/16\ \mathrm{day}^{-1} = (1.3 \pm 0.3) \times 10^2\,\mathrm{day}^{-1} ,$$

which is perfectly compatible with the measured rate N. Thus, the number of events N_a in the NaI counter possibly due to axions is

$$N_a = N - N_{\bar{\nu} e} = (-2.9 \pm 2.7) \times 10^2\ \mathrm{day}^{-1} ,$$

the upper limit of the rate due to the process $a + e \to e + \gamma$ being at the two standard deviations level:

$$N_a < 250/\mathrm{day} . \qquad (7)$$

We express now $N_{\bar{\nu} e}$ through the corresponding cross section /8,10/ $\sigma_{\bar{\nu} e} = (9.5 \pm 2.3) \times 10^{-46}\mathrm{cm}^2$:

$$N_{\bar{\nu} e} = k\, \Phi_{\bar{\nu}}\, \sigma_{\bar{\nu} e} , \qquad (8)$$

where k is a coefficient connected with the overall apparatus efficiency. It follows that

$$k\Phi_{\bar{\nu}} = N_{\bar{\nu} e} / \sigma_{\bar{\nu} e} = \frac{(1.3 \pm 0.3) \times 10^2}{(9.5 \pm 2.3)} \times 10^{46}\,\mathrm{cm}^{-2}\,\mathrm{day}^{-1} \approx 1.4 \times 10^{47}\,\mathrm{cm}^{-2}\,\mathrm{day}^{-1} . \qquad (9)$$

Let us calculate now the number N_a of events expected from the process $a + e \to e + \gamma$. We shall assume that the coefficient k defined above is appropriate also for the reaction $a + e \to e + \gamma$ in the sense that

$$N_a = k\,\Phi_a\,\sigma_{a\,e\to e\gamma} . \qquad (10)$$

From equations (5), (6), (9), (10) we obtain

$$N_a = k\Phi_{\bar{\nu}}\,\frac{g_{eff}^2}{4\pi a}\,\sigma_{ae\to e\gamma} = 5.6\,(10^2 \div 10^5)/\mathrm{day} \qquad (11)$$

which must be compared with the experimental limit (7) $N_a < 250$/day. The most reasonable conclusion is that the experiment /8/ excludes the existence of axions. However, our feeling is that this conclusion is not definite because of the theoretical uncertainty in the expected axion intensity.

Few MeV axions could be detected also through the "axiodisintegration" of such nuclei with low photoneutron threshold as D and Be. Thus we analyse the experiment /9/, in which the reaction $\bar{\nu}_e + D \to \bar{\nu}_e + n + p$ was searched for. The detector was a $^3F_3$ proportional counter immersed in a D_2O tank, the neutron from the deuteron disintegration having the possibility of being detected after slowing down. In this experiment there was found an upper limit of the cross section $\sigma_{\bar{\nu}D\to\bar{\nu}np} < 3\mathrm{x}10^{-44}\,\mathrm{cm}^2$ at a 3 standard deviations level. This upper limit may be used also as an upper limit for the cross section $\sigma_{aD\to np}$ in the sense that (see eq. (5)):

$$\sigma_{aD\to np} < \frac{\Phi_{\bar{\nu}}}{\Phi_a}\, 3\times 10^{-44}\mathrm{cm}^2 \approx \begin{cases} 3\times 10^{-35}\,\mathrm{cm}^2 , \\ 3\times 10^{-38}\,\mathrm{cm}^2 , \end{cases} \qquad (12)$$

where the smaller value $3.10^{-38}\,cm^2$ corresponds to the more reliable axion flux estimate. On the other hand, we may estimate the expected value of $\sigma_{aD\to np}$ by expressing it through

$$\sigma_{\gamma D\to np} \approx 10^{-27}\ cm^2 \ ;$$

$$\sigma_{aD\to np} \approx \sigma_{\gamma D\to np}\ \frac{g^2_{eff}}{4\pi a} \approx \begin{cases} 10^{-36}\,cm^2\,, \\ 10^{-33}\ cm^2\,. \end{cases} \qquad (13)$$

From the values in (12) and (13) which correspond to the optimistic estimate of g^2_{eff} one would conclude from the experiment [9] that there are no axions. (The reactor associated rate [9] was less than 20/day at a 3 standard deviation level, whereas the expected axiodisintegration rate should have been $> 10^5$ /day. On the contrary from the smaller estimate (3a) of g^2_{eff} no conclusion can be reached on the existence of axions on the basis of the experiment [9].

Let us now consider the axion decay into two gammas, which could be perfectly well detected with high efficiency in the NaI scintillator [8]. The decay rate R in the volume $V = 8\times10^4\ cm^3$ of the scintillator is:

$$R = \frac{\Phi_a}{c}\ V\ \frac{1}{\tau\,\frac{E}{m_a}}\ 10^5\ /day\ , \qquad (14)$$

where $E \sim 3$ MeV is the axion energy, $c \simeq 3\times10^{10}$ cm/sec is its velocity, $\tau \approx 10^{-4}\ (m_a/MeV)^{-3}$ sec is the estimated [1,2] mean life of the axion at rest, Φ_a is the axion flux which according to eq.(5) is $\Phi_a \approx (10^{-9} \div 10^{-6})\,\Phi_{\bar\nu}$. Taking [8] $\Phi_{\bar\nu} = 2\times10^{13}\ cm^2\,sec^{-1}$ we obtain

$$R = (2\times10^7 \div 2\times10^{10})\ (m_a/MeV)^4/day^{-1}\ , \qquad (15)$$

the more reliable value of R being the larger one. This should be compared with the upper limit (7) of the NaI scintillation rate $N_a < 250$/day. From eq. (15) we see that axions with a mass larger than 11 keV are excluded when taking the more likely value of the axion flux, whereas axions with a mass larger than 60 keV are excluded from the more conservative low value of the axion flux. We recall that the expected [1,2] axion mass lies in the range of 10 keV to 1 MeV, and conclude that our analysis excludes, in any case, most of this range. Since very light axion masses are very unlikely on the astrophysical ground (light axions would be radiated by stars) our analysis in terms of axion decay gives strong evidence against the existence of axions. Note that the range of excluded masses is relatively insensitive to the uncertainty in the estimated axion flux Φ_a, because the rate R in (14) is proportional to m_a^4. This suggests that one should make use of the expected axion flux ${}^e\Phi_a = 4\times10^{-11}\,\Phi_{\bar\nu}$ (see expression (4)) from the reaction $\gamma + e \to e + a$. Such a flux, true, is much smaller than the expected flux from quarks; however, it is estimated much more reliably. Then one would obtain the following limit on the axion mass: $m_a < 140$ keV.

To summarize, one can say that both reactor experiments, when interpreted in terms of axion emission by quarks, give evidence against the existance of axions. However, the axion flux from quarks is estimated with large theoretical uncertainties. In this sense the analysis of decays of axions emitted by electrons has the advantage of not having such uncertainties and definitely excludes the existence of axions with the masses larger than 140 keV. Unfortunately, it is not possible to exclude the existence of axions with the mass $m_a > 2m_e$ since their decay path due to two electron decays becomes much smaller than the reactor-detector distance.

In conclusion we wish to thank L.B.Okun for having introduced us to the subject and for critical illuminating remarks, S.M.Bilenky, V.N.Gribov and V.A.Matveev for useful discussions.

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