Possible experiments to search for axions

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Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 1, 51–53 (5 January 1983)

The possibility of searching for "light" axions in the resonant excitation of nuclear isomer states and in optical transitions is discussed.

PACS numbers: 14.80.Gt

Several recent papers have predicted the existence of light pseudoscalar particles or "axions." The "standard" axion,[1] chronologically the first to be predicted, has not been found.[2–6] Some more recent models[7–10] predict axions which interact much more weakly with matter and have a very small or zero mass, so that their experimental detection would be problematical in principle. Regardless of the predictions of the specific models, however, it would not be totally pointless to substantially improve the sensitivity of experiments in the search for axions (or for other light, neutral particles which have not yet been observed).

Axions can be detected by detecting the products of their decay $a \rightarrow 2\gamma$, the products of the Compton effect $a + e\gamma + e$, and the nuclear reactions caused by axions.

The most sensitive experiments—reactor experiments—are designed to detect the decay pair. If the experimental data are interpreted in terms of an axion emission

 0021-3640/83/010060-03$01.00

probability, the "standard model" predicts a limit $< 10^{-6}$ on the ratio of the probability for the emission of an axion from a nucleus to the probability for the emission of a γ ray (the theoretical prediction is $\sim 10^4$), and this prediction is made for the most sensitive experiment, for a mass $m_a \geqslant 150$ keV and a lifetime $\tau_a \leqslant 0.1$ s. At a lower axion mass, the decay probability would drop sharply, and an experiment designed to detect the decay would become insensitive.

1. Let us examine the possibility of detecting axions in the resonant excitation (without recoil of the nucleus) of low-lying nuclear levels by axions emitted from the same states in a source.[1] This process is analogous to the Mössbauer effect with a resonant detector. Of the various methods for obtaining low-lying isomer states—after β and α decay; as a result of excitation by x radiation, synchrotron radiation, or charged particles; and, finally, after the radiative capture of a neutron—the latter seems the most promising. An axion can be emitted from a nucleus $(Z, N+1)$ formed after the capture of a neutron in a nucleus (Z, N) near the active zone of a reactor. A detector which contains $(Z, N+1)$ inside a resonant absorber is positioned behind a shield; it detects γ rays and the conversion electrons emitted after the excitation of the absorber nucleus by the axion. The detector count rate is

$$N(\mathrm{s}^{-1}) = \phi \sigma_{n\gamma} n_A I_\gamma f_1 \beta_1 f_2 \beta_2 n_{A+1} \sigma_r \epsilon (4\pi R^2)^{-1}, \tag{1}$$

where ϕ is the thermal-neutron flux density at the position of the axion source, $\sigma_{n\gamma}$ is the neutron capture cross section, n_A is the number of (Z, N) isotope nuclei, I_γ is the probability for the excitation of an isomer state after the neutron capture, f_1 and f_2 are respectively the probabilities for recoiless emission and absorption in the source and absorber, β_1 is the axion emission probability with respect to the γ emission probability, β_2 is the axion absorption probability with respect to the γ absorption probability, n_{A+1} is the number of $(Z, N+1)$ nuclei in the detector, ϵ is the probability for the detection of the γ ray or the conversion electron in the detector, R is the distance from the source to the detector, and σ_r is the cross section for the resonant absorption of a γ ray.

The choice of the isotopes (Z, N) and $(Z, N+1)$ is determined by the large quantity $\sigma_{n\gamma}$, I_γ, f_1, f_2, and the natural abundances of the isotopes. Resonances with a large level width are convenient, since with a small width it is difficult to satisfy the resonance condition, especially in view of the strong effect of the radiative violations on the shift and splitting of the resonances. Unfortunately, we currently have little in the way of experimental data on I_γ, which approaches 100% in some cases. Of the roughly 20 suitable isotope pairs those which appear to be the most convenient $(Z, N+1)$ nuclei are as follows: Fe^{57}, Ni^{61}, Te^{125}, W^{183}, and Hg^{201} (we are restricting the discussion to $M1$ transitions).

What is the sensitivity of the method? With $(\phi \sigma_{n\gamma} n_A) = 5 \times 10^{17}\ \mathrm{s}^{-1}$ (10% of the neutrons are absorbed in a 100-MW reactor), $R = 3M$, $I_\gamma = f_1 = f_2 = \epsilon = 0.5$, $\sigma_r = 10^{-18}\ \mathrm{cm}^2$, $n_{A+1} = 10^{24}$ (100 g of Fe^{57}), and $\beta_1 = \beta_2 = 10^{-9}$ the count rate is $N = 3 \times 10^3$ 1/day. For the "standard" axion, we might note, β_1 is on the order of[2] 10^{-4}.

For a detector resolution of 10–15%, the entire effect lies in a narrow energy interval, 1–5 keV. There are two possible detection methods:

1) The use of a proportional counter. In this case the working medium is enclosed by thin layers, to provide good detection of the conversion electrons and the soft γ rays. The limitation on the mass of the resonant detector is important here.

2) For the radiators Te^{1235}, Hg^{203}, and W^{183}, the detecting (and emitting) media could be CdTe, HgI_2, and $Ca(Cd)WO_4$, respectively. Because of the volume nature of the detection, the detector mass could be increased substantially.

There is the possibility in principle of using standard NaI, CsI, and Ge detectors, for which there is no severe restriction on the mass of the detecting medium. In this case we would use transitions in I^{127} (58.5 keV), Cs^{133} (81 keV), and Ge^{73} (67.4 keV), excited (for example) by fast neutrons in an (n, n') reaction. The 13.5-keV transition in Ge^{73} is too narrow for reliable observations of the resonant effect.

2. If the axion mass is $m_a \lesssim 1$ eV, then axions could in principle be emitted in optical transitions in atoms and in solids. A compact experiment, permitting the use of a well-shielded, low-background apparatus, might be arranged as follows: The source would be an electroluminescent material with a high quantum yield. The detector would be a photoluminescent material, monitored by a system of photomultipliers. The photon count rate in such an experiment can be written by analogy with (1):

$$N(s^{-1}) = WK_1\beta_1\sigma_0\beta_2 nK_2\epsilon(E4\pi R^2)^{-1}, \qquad (2)$$

where W is the electric power delivered to the electroluminescent material, E is the transition energy, K_1 is the quantum yield of the electroluminescent material, β_1 is the probability for axion emission from the excited state, σ_0 is the excitation cross section of the photoluminescent material (per outer-shell electron), β_2 is the ratio of the cross sections for the excitation of the luminescent material by an axion and by a photon, n is the number of electrons in the detector, K_2 is the quantum yield of the photoluminescent material, and ϵ is the photon detection efficiency. A numerical estimate with $W = 10$ kW, $E = 3$ eV, $K_1 = 0.1$, $n = 10^{27}$, $\sigma_0 = 10^{-16}$ cm^2, $K_2 = 0.5$, $\epsilon = 0.1$, $\beta_1 = \beta_2 = 10^{-15}$, and $R = 30$ cm yields $N = 10^{-3}$ s^{-1}.

I wish to thank Yu. A. Aleksandrov, G. V. Mitsel'makher, Yu. M. Ostanevich, and D. M. Khazins for discussions and comments.

[1)]The possibility of making use of a recoiless process to detect neutrinos was discussed in Ref. 11.

[2)]Extrapolation of the "standard" model[1] in accordance with $\tau_a \sim m_a^{-5}$ yields the limit $\beta_1 < 0.1$ for the experiment of Ref. 4 at $m_a = 15$ keV. As m_a is reduced, the limit worsens in proportion to m_a^{-6}.

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Translated by Dave Parsons
Edited by S. J. Amoretty