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Results from a search for cosmic axions

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A search experiment has been carried out to look for relic cosmic axions trapped in the halo of our Galaxy and limits on their coupling $g_{a\gamma\gamma}$ and galactic abundance are presented for the axion mass range of $m_a = (5.4$–$5.9) \times 10^{-6}$ eV. The detector consisted of a tunable high-Q microwave cavity immersed in liquid helium and permeated by a strong magnetic field. A low-noise microwave receiver with a cryogenic HEMT amplifier as its first stage was coupled to the cavity. The noise power within successive cavity bandwidths was spectrum analyzed and searched for narrow peaks resulting from axion-to-photon conversions in the cavity.

The axion[1,2] is generally thought to be the most attractive solution to the strong CP problem. However, no positive indication of its existence has been obtained so far. At present, the axion is constrained by laboratory searches[2] and by astrophysical[3,4] and cosmological[5] considerations. The main axion "window" still allowed at present is 10^{-3} eV $\gtrsim m_a \gtrsim 10^{-6}$ eV, where the upper limit is obtained from an analysis of the SN 1987A and the lower limit is from an estimate[5] of the present cosmological energy density due to axions that were produced during the QCD phase transition. We refer the reader to Ref. 6 for a detailed discussion of the astrophysical and cosmological constraints. If m_a is of order 10^{-5} eV, axions may constitute the dark matter in the Universe. Such axions would be cold dark matter.[5,7] Cold dark matter with a flat (Zel'dovich-Harrison) spectrum of primordial density perturbations and some "biasing," in the extent to which light traces matter, yields at present a popular and apparently viable scenario of galaxy formation. It is thus conceivable that axions constitute the dark halos that appear to surround galaxies such as our own.

If the halo of our own galaxy is made up exclusively of axions, their local density[8] would be $\rho_{\text{halo}} \simeq 5 \times 10^{-25}$ g/cm^3. Galactic halo axions have velocities of order 10^{-3}. This paper describes an experiment to detect these axions through their conversion to photons in a microwave cavity subjected to a large static magnetic field.[9] A previous axion search experiment has been reported by DePanfilis et al.[10] Our experiment searches in a similar mass range but we have improved the sensitivity of the detector by slightly more than a factor of 10, allowing an improved limit on the axion coupling $g_{a\gamma\gamma}^2$ by the same amount.

For the cavity detector, the relevant coupling is

$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{4\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}, \quad (1)$$

where $g_{a\gamma\gamma} \equiv g_\gamma \alpha / \pi f_a$. The axion mass is given in terms of the axion decay constant f_a by

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 0.6 \times 10^{-5} \text{ eV} \left[\frac{10^{12} \text{ GeV}}{f_a} \right], \quad (2)$$

g_γ is given in terms of the axion model parameters[11] by

$$g_\gamma = \frac{1}{2} \left[\frac{N_e}{N} - \frac{5}{3} - \frac{m_d - m_u}{m_d + m_u} \right], \quad (3)$$

where $N = \text{Tr}(Q_{\text{PQ}} Q_{\text{color}}^2)$ and $N_e = \text{Tr}(Q_{\text{PQ}} Q_{\text{em}}^2)$. Tr represents the sum over all left-handed Weyl fermions. Q_{PQ}, Q_{em}, and Q_{color} are respectively the Peccei-Quinn charge [the generator of the $U_{\text{PQ}}(1)$ quasisymmetry], the electric charge, and one of the generators of $SU_c(3)$. In all grand unified axion models which obtain the (almost) successful Georgi-Quinn-Weinberg prediction of $\sin^2\theta_W$, one has $N_e = \frac{8}{3} N$ and hence $g_\gamma = m_u/(m_u + m_d) \simeq 0.36$. This is the case in particular of the Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model.[12] In other models, one may have different values for g_γ however. In particular, in the Kim-Shifman-Vainstein-Zakharov model,[13] one has $N_e = 0$ and hence $g_\gamma \simeq -0.97$.

Axion-to-photon conversion is greatly enhanced in a microwave cavity with resonant frequency equal to the axion energy $\omega = m_a [1 + O(10^{-6})]$, where the $O(10^{-6})$ spread comes from the kinetic-energy distribution of virialized galactic axions. With a static background field $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$, the power delivered into TM mode nlp is given in the
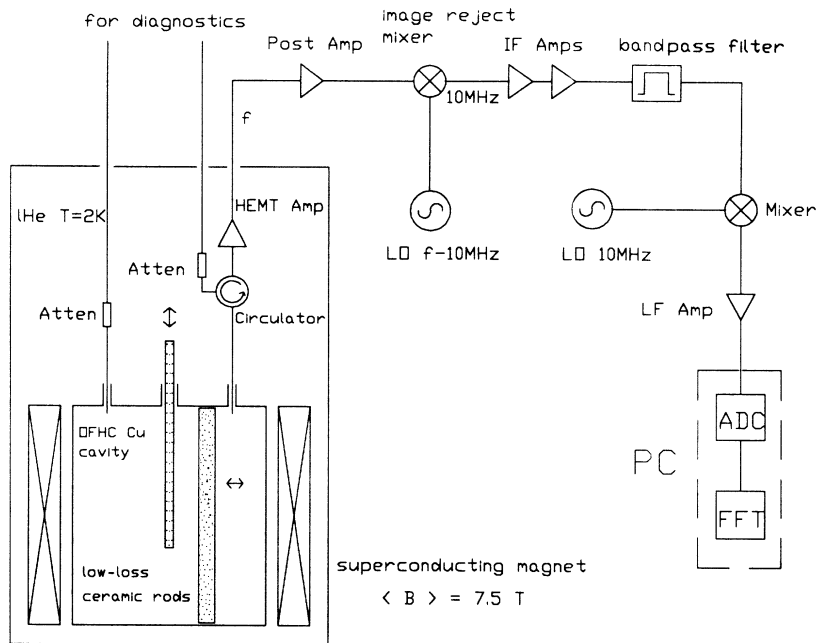
FIG. 1. Block diagram of data-acquisition system.

DFSZ model by[11]

$$P_{nlp} = 4 \times 10^{-22} \text{ W} \left[\frac{V}{10\,l} \right] \left[\frac{B_0}{8\,T} \right]^2 C_{nlp} \left[\frac{\rho_a}{5 \times 10^{-25} \text{ g/cm}^3} \right] \left[\frac{m_a}{2\pi(3\text{ GHz})} \right] \frac{Q_{nlp}}{Q_a} , \tag{4}$$

where V is the cavity volume, Q_{nlp} is the loaded quality factor of the cavity, and $Q_a \equiv 10^6$ is the quality factor of the axion line. In addition, ρ_a is the local axion energy density and C_{nlp} is a dimensionless form factor given by

$$C_{nlp} = \frac{\left[\int_V \hat{z} \cdot \mathbf{E}_{nlp}(\mathbf{x}) d^3x \right]^2}{V \int_V \epsilon(\mathbf{x}) \mathbf{E}_{nlp}^2(\mathbf{x}) d^3x} , \tag{5}$$

where $\mathbf{E}_{nlp}(\mathbf{x})$ is the electric field of the cavity mode and $\epsilon(\mathbf{x})$ is the dielectric constant at position $\mathbf{x}$ in the cavity.

During the fall of 1989, we conducted a search for galactic halo axions using a detector of the kind described above. A sketch of the detector is shown in Fig. 1. The detector uses a superconducting solenoid magnet with $\simeq 17$-cm inner bore and an average field of 7.5 T. The oxygen-free high-conductivity (OFHC) copper cavity of 7-l volume was operated in the TM_{010} mode with an unloaded Q of $\simeq 1.5 \times 10^5$ at $T = 2$ K and was tuned by two low-loss ceramic rods, giving a tuning range of 1.32 GHz $\leq f \leq 1.44$ GHz. The minimum value of C over this frequency range was $\simeq 0.50$, as determined by computer simulations. As shown in Fig. 1, the bigger rod was moved sideways (radially) and was manually adjusted for coarse tuning of the cavity frequency. The smaller one was inserted through the top plate and was controlled by a stepper motor. This arrangement was used to avoid the degradation of C due to longitudinal mode localization.[14] The output of the overcoupled cavity ($Q_{\text{wall}} = 2Q_{\text{hole}}$) was

amplified by a commercially available cryogenic HEMT amplifier[15] with a noise temperature of about 3 K (see Fig. 2). Its noise temperature was carefully measured using a variable-temperature technique. The room-temperature part of the detector consisted of a double-conversion superheterodyne receiver, whose audio signal (30 kHz in width) was fed to a real-time fast-Fourier-
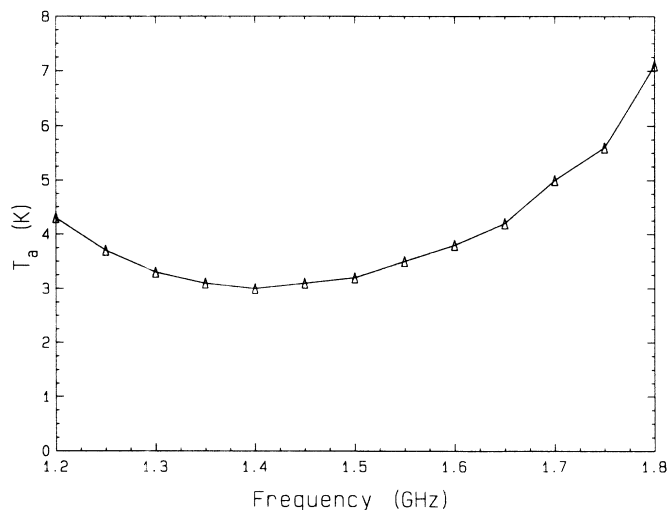

FIG. 2. Noise temperature vs frequency of the HEMT amplifier at $T_{\text{phys}} = 2$ K.
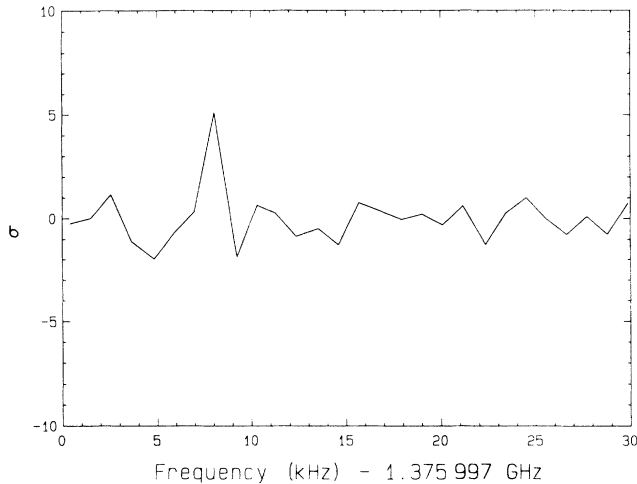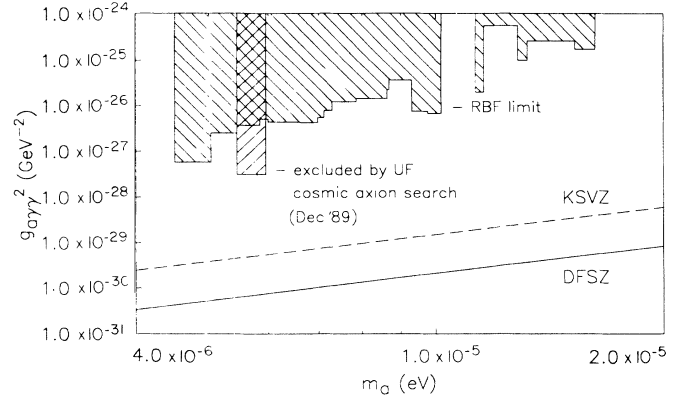
FIG. 3. Power spectrum with candidate peak.

FIG. 4. Experimental limits on axion coupling $g_{a\gamma\gamma}^2$ assuming $\rho_a = \rho_{\text{halo}}$.

transform (FFT) spectrum analyzer. This analyzer consisted of a 16-bit analog-to-digital converter (ADC) combined with a TMS320C25 digital signal processor, which was integrated with the PC which served as the main controller of the data-acquisition system.

The power emitted from the cavity, which had an $\approx$ 30-kHz bandwidth, was measured with roughly 1-kHz resolution at each tuning rod setting. 10^5 power spectra were averaged giving a total measurement time of 90 sec. Each average spectrum was searched for 2σ peaks in single bins and combinations of two neighboring bins. If a peak was found, another set of 10^5 spectra was taken and averaged with the first. If the peak remained statistically significant, this process was repeated up to five times, after which the peak was flagged for later investigation and the scan continued. Figure 3 shows one of several peaks which survived these tests. However, when reexamined with the magnetic field B_0 off, all of these maxima persisted and, therefore, were not signals coming from axion conversion.

The sensitivity of the detector is set by thermal noise.

The noise power fluctuation is given by

$$\Delta P_n = k_B T_n B / \sqrt{N} , \tag{6}$$

where

$$T_n = T_{\text{amp}} + T_{\text{bath}} \tag{7}$$

is the system noise temperature, B is the 1-kHz bin width, and N is the number of averages. Two separate runs were made at bath temperature $T = 2.2$ K and $T = 4.2$ K, and their statistics combined. These fluctuations set the minimum detectable signal power (at the 95% C.L.) to be

$$P_{\text{signal}} \simeq 7 \times 10^{-22} \text{ W} \tag{8}$$

for $B = 1100$ Hz (1 bin) and $\sqrt{2}$ times that for a signal falling into two bins. This power is still a factor of ~ 500 too large for the signal expected from axion conversions $P_{a \to \gamma} \simeq 1.3 \times 10^{-24}$ W in the DFSZ model assuming $\rho_a = \rho_{\text{halo}}$. Our experiment[16] is thus able to set the upper limit on $g_{a\gamma\gamma}^2$ (for $\rho_a = \rho_{\text{halo}}$) plotted in Fig. 4. Also shown is the limit obtained by DePanfilis et al.[10]

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D. Harari and P. Sikivie, *ibid.* **195B**, 361 (1987). Davis concludes that the contribution from cosmic axion strings is about one hundred times more important than the contribution from initial θ misalignment, whereas Harari and Sikivie conclude that the two contributions are roughly of the same order of magnitude. Recent computer simulations by two of the authors (C.H. and P.S.) support the latter conclusion (unpublished).

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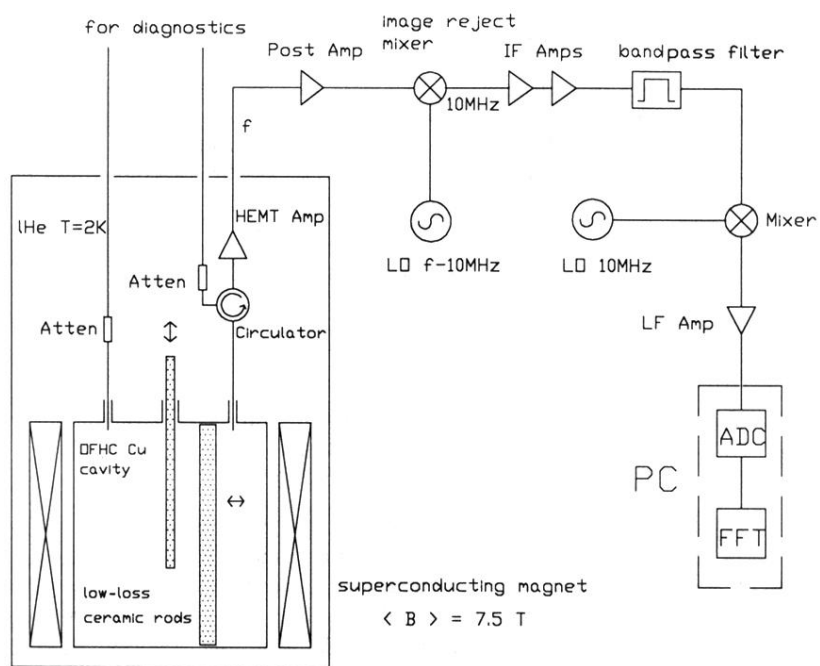[16]Our limit is not valid in the narrow window 1.346 096–1.346 382 GHz, where a mode crossing occurred and where no data could be obtained.

FIG. 1. Block diagram of data-acquisition system.