Limits on the Abundance and Coupling of Cosmic Axions at $4.5 < m_a < 5.0\ \mu eV$

S. DePanfilis, A. C. Melissinos, B. E. Moskowitz, J. T. Rogers, Y. K. Semertzidis, and W. U. Wuensch
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

H. J. Halama and A. G. Prodell
Brookhaven National Laboratory, Upton, New York 11973

and

W. B. Fowler and F. A. Nezrick
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
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We report preliminary results from a search for galactic axions in the frequency range $1.09 < f_a < 1.22$ GHz. For an axion linewidth $\Gamma_a \leq 200$ Hz we obtain the experimental limit $(g_{a\gamma\gamma}/m_a)^2\rho_a < 1.4\times10^{-41}$. The theoretical prediction is $(g_{a\gamma\gamma}/m_a)^2\rho_a = 3.9\times10^{-44}$ with $\rho_a = 300$ MeV/cm^3. We have also searched for the presence of a continuous spectrum of light pseudoscalar particles; if we assume that the above ρ_a is contained between the upper and lower frequencies of our search, then we find that $g_{a\gamma\gamma} < 2\times10^{-30}$ MeV$^{1/2}$ cm$^{3/2} \simeq 10^{-11}$ GeV^{-1}.

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On the basis of rotation curves of galaxies and galactic clusters, it is widely believed today that the total mass in the Universe greatly exceeds the observable luminous matter. Also, arguments concerning primordial nucleosynthesis of the light elements limit the total baryonic matter to less than 0.2 times the critical density required to close the Universe. Little is known about the missing or "dark" matter but many candidate constituent particles have been proposed, some of them exotic.[1] A leading candidate is a very light pseudoscalar particle, the so-called "invisible axion."[2]

In 1977 Peccei and Quinn[3] (PQ) introduced a new global symmetry which is spontaneously broken in such a way as to cancel the *CP*-nonconserving terms that are present in the QCD Lagrangean but not observed. Weinberg[4] and Wilczek[4] pointed out that the breaking of the PQ symmetry must give rise to a pseudoscalar Goldstone boson named the axion. Accelerator searches[5] have failed to detect axions with mass greater than 200 keV, but models with light, weakly interacting axions have been proposed.[2] In these models, the mass of the axion and its coupling to fermions are inversely proportional to the vacuum expectation energy f_a at which the PQ symmetry is broken. Specifically,

$$m_a = \frac{\sqrt{2}f_\pi m_\pi}{f_a} \approx \frac{10^{12}\,\text{GeV}}{f_a} \times 2\times10^{-5}\,\text{eV}, \qquad (1)$$

where $f_\pi = 93$ MeV and $m_\pi = 135$ MeV.

While m_a is not predicted by theory, observations on the cooling rate of ordinary stars[6] imply that $m_a < 1$ eV, while neutron stars[7] imply that $m_a < 4\times10^{-2}$ eV; the best upper limit of $m_a < 1\times10^{-2}$ eV comes from red-giant evolution.[8] At the same time cosmological considerations[9] place a lower limit of $m_a > 10^{-5}$ eV. In this window $m_a \sim 10^{-5}$ eV is preferred if the axions are to close the Universe. Axions should have been produced in the early stages of the Universe and later condensed into the galaxies with their present velocity being equal to the virial galactic velocity. Turner has calculated the expected axion density near the Earth on the assumption that galactic halos are due primarily to the presence of axions.[10] He finds that $\langle\rho_a\rangle = 5\times10^{-25}$ g/cm$^3 \approx 300$ MeV/cm^3.

The axion couples to fermions and, through a triangle graph, to two photons [see Fig. 1(a)]. Sikivie[11] proposed that, in spite of the extremely weak coupling, axions could be converted to photons in the presence of an intense electromagnetic field via the Primakoff effect[12] [Fig. 1(b)]. The interaction Lagrangean is given by $L_{\text{int}} = -(g_{a\gamma\gamma}/4\pi)\mathbf{E}\cdot\mathbf{B}\phi_a$, where **E** and **B** are the electric and magnetic fields, respectively, ϕ_a is the axion field, and the coupling constant $g_{a\gamma\gamma}$ is given by

$$g_{a\gamma\gamma} = m_a \frac{e^2}{\hbar c}\frac{(\hbar c)^{3/2}}{f_\pi m_\pi}(\sqrt{2}\pi)^{-1} \qquad (2)$$
$$= (1.1\times10^{-34}\,\text{MeV}^{1/2}\,\text{cm}^{3/2})\frac{m_a}{10^{-5}\,\text{eV}}.$$

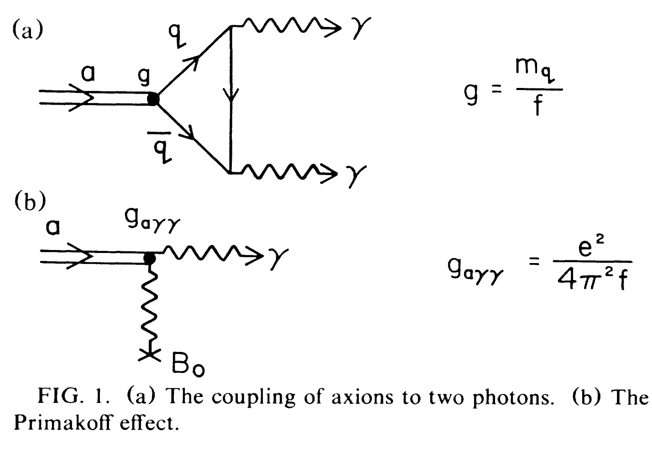

FIG. 1. (a) The coupling of axions to two photons. (b) The Primakoff effect.

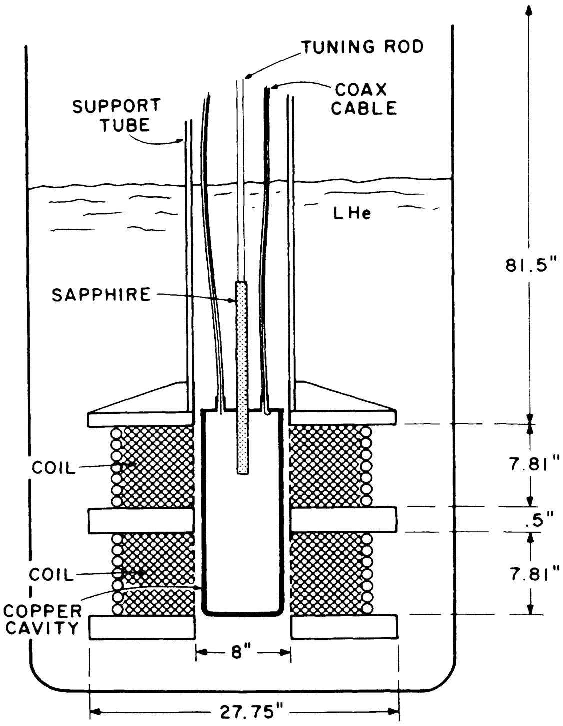

FIG. 2. Schematic diagram of the apparatus.

Since the relic axions that condensed in the galaxy move with the nonrelativistic virial velocity $\beta \approx 10^{-3}$, the converted photons will have an energy distribution characterized by $E_\gamma = m_a(1+\beta^2/2)$. A more detailed calculation[13] predicts a full width for the converted photon line of $\Gamma_a \approx 3\times 10^{-7} m_a$. It is the narrowness of this line that makes the detection of galactic axions possible.

If the conversion takes place in an electromagnetic cavity of quality factor Q in the presence of an externally applied magnetic field B_0, the conversion rate in mks units is

$$R_{a\to\gamma} = (\epsilon_0 c^2/\hbar^2) g_{a\gamma\gamma}^2 \omega^{-1} Q B_0^2 G_j^2. \tag{3}$$

Here ω is the frequency of the converted photon and G_j^2 is a geometric form factor measuring $\int \mathbf{E}\cdot\mathbf{B}_0 d^3x$ for the cavity mode j: The mode is chosen so as to keep G_j^2 of order unity. For our experimental parameters, Eqs. (2) and (3) predict that the transition rate per axion is $R_{a\to\gamma} = 1\times 10^{-17}$ sec^{-1}. For a given axion density $\langle\rho_a\rangle$ and cavity volume V, the power detected by a *critically coupled receiver* is[11]

$$P_a = \tfrac{1}{2}(g_{a\gamma\gamma}/m_a)^2 \langle\rho_a\rangle \omega Q[\epsilon_0(cB_0)^2] V G_j^2. \tag{4}$$

Theory predicts that $(g_{a\gamma\gamma}/m_a)^2 = 1.3\times 10^{-46}$ cm^3 MeV^{-1}.

We have initiated a program to search for galactic axions in the mass range $4.5 < m_a < 25$ μeV, which corresponds to the frequency range $1 < f_a < 6$ GHz; preliminary results are reported here for the mass range $4.5 < m_a < 5.0$ μeV. The experiment used a 6-T superconducting solenoid with a 20-cm bore that was located at Brookhaven National Laboratory.[14] The apparatus is shown schematically in Fig. 2: The cylindrical copper cavity was placed in the solenoid aperture and was operated in liquid helium. The TM_{010} mode was chosen for its high form factor and the resonant frequency was tuned by insertion of a 15-mm-diam sapphire rod along the cavity axis. The *unloaded Q* was $Q_0 = 1.9\times 10^5$ at 4 K and the cavity volume was $V = 1.1\times 10^4$ cm^3; the tuning range was 1.09–1.22 GHz. Microwave power was coupled out of the cavity by a critically coupled induction loop and fed to a GaAs field-effect-transistor amplifier also operated at helium temperature.[15] After further amplification the signal was superheterodyned and detected in a 64-channel multiplexer whose channel width was 200 Hz. The receiver electronics is shown schematically in Fig. 3.

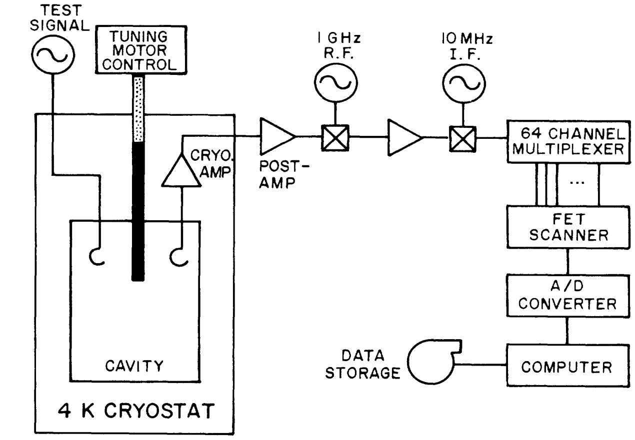

FIG. 3. Schematic diagram of the receiver electronics.

The cavity resonant frequency was continuously changed at a rate of approximately 200 Hz/sec, and the rf local oscillator tracked the cavity. Every 50 sec the cavity frequency was measured and the local oscillator was synchronized for the next sweep. A typical record containing 2000 200-Hz bins is shown in Fig. 4. The overall noise figure[16] of the system was 12.5 K at 1.09 GHz and 17.6 K at 1.22 GHz; thus the noise power was typically $P_N \approx 4\times 10^{-20}$ W per 200-Hz channel. The standard deviation of the statistical fluctuations[17] was $\sigma \approx 0.005 P_N$, so that the 5σ limit for a single bin is $P_l = 1\times 10^{-21}$ W/(200 Hz).

The frequency range from 1.09 to 1.22 GHz was swept twice. Off line the data were searched for bins that had excessive deviations from the local mean power level. For every bin the deviation from the local mean was normalized by its statistical error. The distribution of the normalized deviations for 5×10^5 bins is shown in Fig. 5; it is fitted closely by a Gaussian with unit dispersion indicating that the observed error agrees with the expected error. In the two sweeps there were ten fre-

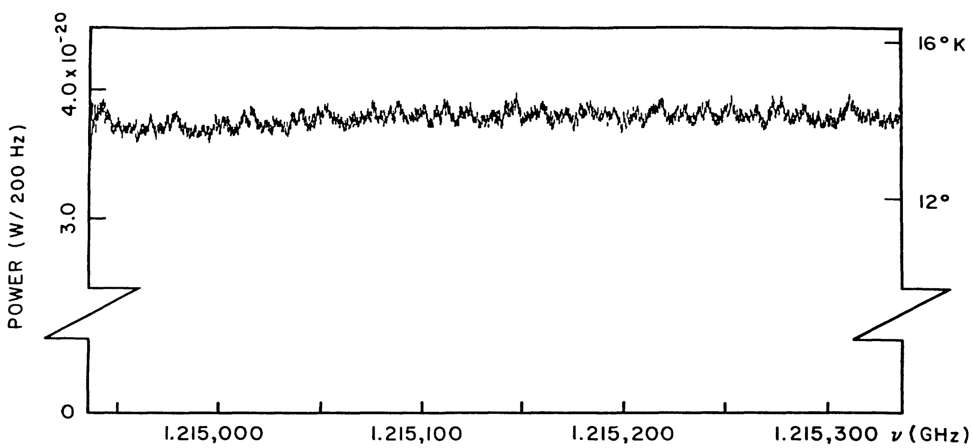

FIG. 4. Typical power spectrum covering 400 kHz with 200-Hz resolution. The statistical error is indicated for every bin.

quency bins that showed a deviation greater than 5σ. The apparatus was retuned to these frequencies and the peaks examined under higher resolution; these signals were eliminated as candidates for axion conversion because they were found to be independent of the magnetic field. We also searched for signals that occurred at the same frequency in both sweeps with a deviation greater than 3.3σ; only one such signal was found and it was independent of magnetic field.

Thus our limit on the power from a narrow axion-conversion line corresponding to 5σ may be given as

$$P_s < 1\times10^{-21}\ \text{W},\quad \Gamma_a \lesssim 200\ \text{Hz}. \tag{5}$$

Given the parameters of our detector and the local axion density from Ref. 10, the expected power from Eq. (4) is $(P_a)_{\text{theor}} = 0.3\times10^{-23}$ W. This is a factor of 300 lower than our experimental limit. Our result may alternatively be expressed as

$$(g_{a\gamma\gamma}/m_a)^2\langle\rho_a\rangle < 1.4\times10^{-41}. \tag{6}$$

The data were also examined for signals that would be several channels wide. The sensitivity for wide lines is reduced and cannot be reliably extended beyond the order of the cavity width, $\Gamma\sim10^4$ Hz. The limit can be given by the approximate expression[18]

$$P_s < 1\times10^{-21}[\Gamma_a/(200\ \text{Hz})]\ \text{W},$$
$$200 < \Gamma_a < 10^4\ \text{Hz}. \tag{7}$$

In addition to obtaining swept-frequency data, we have used the apparatus at two fixed frequencies (1.09 and 1.22 GHz) to search for conversions from particles with a continuous energy spectrum. To do so we compared the microwave power level with the magnetic field on and with the field off. The gain and reflection coefficients of the amplifier were determined under both conditions and these data were used in the fitting of the noise spectrum. From the fit we determined an effective temperature which includes the contribution of the cavity at 4 K and of the amplifier noise. We conclude that the equivalent receiver noise temperature increased by $\Delta T < 0.4$ K when the field was increased from 0 to 6 T.

From the limit on ΔT we can place a limit on axion conversions, $dP_s/df < 0.6\times10^{-23}$ W/Hz. Assuming

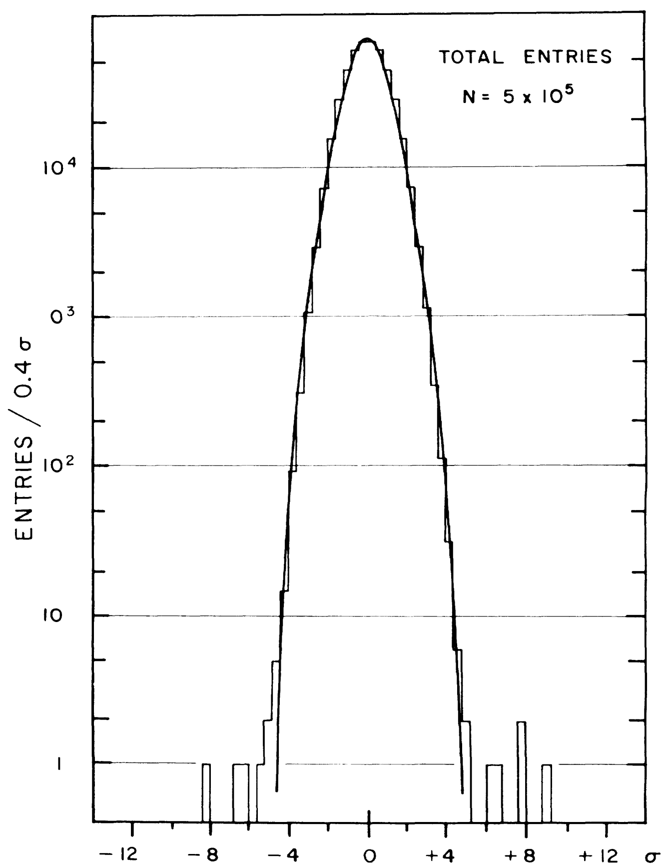

FIG. 5. Distribution of the normalized deviation from the mean for 5×10^5 bins. The fit is a Gaussian with unit dispersion.

that the spectrum is bounded between our upper and lower frequencies, $\Delta f = 130$ MHz, we find that $(g_{a\gamma\gamma}/m_a)^2 \langle \rho_a \rangle < 4 \times 10^{-35}$. Using the value of $\langle \rho_a \rangle$ from Ref. 10 gives the limit

$$g_{a\gamma\gamma} < 2 \times 10^{-30}\ \mathrm{MeV}^{1/2}\,\mathrm{cm}^{3/2}. \qquad (8)$$

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[16]This includes the contribution $T_c = 4$ K from the cavity.

[17]The output of each $\Delta f_m = 200$-Hz FWHM multiplexer channel went to a square-law diode power detector followed by an integrator whose decay time was set at $\tau = 100$ msec. The effective number of averages per decay time was $2\pi \Delta f_m \tau = 125$. By sampling the readout at 10 times/sec, we were able to achieve the equivalent of 80000 averages total for each bin as it was swept past in 64 bins; the sweep rate was typically 1 channel/sec.

[18]Equation (7) is also approximately valid for $\Gamma_a > 10^4$ Hz in which case $P_a < 10^{-20}[\Gamma/(200\ \mathrm{Hz})]$ W; this limit is also applicable to any light pseudoscalar particle; see, e.g., Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, Phys. Lett. **98B**, 265 (1981).