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ABSTRACT

We report preliminary results from a search for galactic axions in the mass range $4.5 < m_a < 5.0$ μeV. For an axion line width $\Gamma_a \leq 8\times10^{-13}$ eV, 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 the local galactic axion density $\rho_a = 300$ MeV/cm^3. We have also searched for the presence of a continuous spectrum of light pseudoscalar particles; assuming that the local galactic axion density is composed of axions with masses uniformly distributed between 4.5 and 5.0 μeV, we find that $g_{a\gamma\gamma} < 2\times10^{-30}$ MeV$^{1/2}$ cm$^{3/2}$ $\simeq 10^{11}$ GeV^{-1}. Limits have also been set on the production of light pseudoscalar x particles; we find $g_{x\gamma\gamma} < 10^{-24}$ MeV$^{1/2}$ cm$^{3/2}$ $\simeq 10^{-5}$ GeV^{-1} for $0 < m_x \leq 4\mu$eV.

INTRODUCTION

Based on surveys of luminous objects in the universe, theoretical prejudice for a critically closed universe, and on rotation curves of galaxies and galactic clusters,[1] it is generally accepted that the total mass in the universe, and in our galaxy, greatly exceeds the observable luminous matter.[2] Primordial nucleosynthesis arguments[3] constrain baryonic matter to less than 20% of the critical density needed for an Ω=1 universe. Dark matter, therefore, composes a large fraction of the mass of the universe and most likely is dominated by non-baryonic particles. Many dark matter candidates have been proposed, most are exotic.[4] At times features of the large scale structure of the universe appeared to rule out an interesting candidate, the neutrino; it may now be reappearing. Overall, little is known about the constituent nature of the dark matter. A leading candidate is a very light pseudoscalar particles, the so-called "invisible axion."[5]

Who ordered the axion? In 1977 Peccei and Quinn[6] introduced a new global symmetry which is spontaneously broken in such a way as

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to cancel the CP violating terms that are present in the QCD Lagrangian but not observed (e.g. the electric dipole moment of the neutron). Wilczek and Weinberg[7] pointed out that the breaking of the P-Q symmetry must give rise to a pseudoscalar Goldstone boson named the axion.

Experimental searches[8] at accelerators and reactors have failed to detect axions with $m_a \gtrsim 150$ keV. Models with very light, weakly interacting axions were then proposed.[5] In this class of models, the axion is very stable and the mass of the axion and its coupling to fermions are inversely proportional to the temperature or the vacuum expectation energy, f_a, at which the P-Q symmetry was broken;

$$m_a = m_\pi \left(\frac{f_\pi}{f_a}\right) N \frac{\sqrt{z}}{1+z} \qquad (1)$$

and

$$\tau(a\to\gamma\gamma) = \tau(\pi^\circ\to\gamma\gamma) \left(\frac{m_\pi}{m_a}\right)^5 N^4 \frac{z^3}{(1+z)^4} \qquad (2)$$

where $f_\pi = 93$ MeV, $z = m_u/m_d \simeq 0.5$, and N is the number of quark doublets giving for N = 3,

$$m_a \simeq 2\times10^{-5} \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right) \mathrm{eV} \qquad (3)$$

$$\tau(a\to\gamma\gamma) \simeq 10^{53} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^5 \mathrm{sec}\ . \qquad (4)$$

What is the allowed range of the axion vacuum expectation value? Theory places no constraint on f_a. Accelerator experiments[8] constrain $f_a > 300$ GeV. Observations of the cooling rate limits of red giant stars and the sun[9] constrain $f_a > 10^{10}$ GeV. To not overclose the universe ($\Omega \lesssim 2$) constrains $f_a \lesssim 5\times10^{12}$ GeV. Therefore, the region allowed by these cosmological considerations is $10^{10} < f_a \lesssim 5\times10^{12}$ GeV.

What is the expected value of f_a if the universe is just closed, i.e. $\Omega=1$? This closure condition gives[10]

$$f_a \lesssim 4\times10^{12}\ \mathrm{GeV} \left(\frac{H}{100}\right)^2 \left(\frac{\lambda_{QCD}}{200}\right)^{3/4} \Delta \qquad (5)$$

where there is uncertainty in H, the Hubble constant ($50 < H < 100$ km/sec-MPC), λ_{QCD}, the quark-hadron transition energy ($50 < \lambda_{QCD} <$

300 MeV), and Δ which characterizes the dynamics of the phase transition ($1/4 < \Delta < 1$). The closure condition yields the range $0.9\times10^{11} < f_a \sim 6\times10^{12}$ GeV or $1.2\times10^{-6} < m_a < 3\times10^{-4}$ eV, with a best guess of $m_a = 10^{-5}$ eV, $f_a = 3.5\times10^{12}$ GeV. More recent estimates[11] based on special care with the uncertainties in the calculation and with the propagation of errors yield, for an axion dominated universe, an upper limit to the axion mass $m_a \lesssim 2.5\times10^{-4}$ eV. Using these estimates as a guide and giving consideration to available technology, we decided to concentrate our axion search to the region $4.5 < m_a < 25$ μeV, $9\times10^{12} > f_a > 1.5\times10^{12}$ GeV.

Axions should have been produced when the universe cooled below a temperature of order f_a and the vacuum underwent a phase transition from its symmetric to its present broken P-Q state.[10] As the universe continued to expand, axions condensed into galaxies with their present velocity being equal to the virial galactic velocity $\beta = 10^{-3}$, Turner has calculated the expected axion density near the earth on the assumption that galactic halo is due primarily to the presence of axions.[11] He finds

$$\langle\rho_a\rangle = 5\times10^{-25} \text{ g/cm}^3 \approx 300 \text{ MeV/cm}^3. \qquad (6)$$

AXION DETECTION SCHEME

The axion couples to quarks and fermions and via a triangle graph to two photons. As seen from Eq. (4), the free decay of the axion into any decay mode is rare. Sikivie proposed[12] that using the two photon decay, axions may be detected via the Prinakoff effect[13] by supplying a virtual photon from a strong externally applied electromagnetic field and detecting the decay of the axion into the second photon. The energy of the detected photon is equal to the energy of the axion. Since the axions in our galaxy move with the non-relativistic virial velocity $\beta \sim 10^{-3}$, the axion decay photon will have an energy $E_\gamma = m_a\ (1+\beta^2/2)$. A more detailed calculation[14] predicts a full-width for the converted photon line of $\Gamma_a \approx 10^{-7}\ m_a$. It is the narrowness of this line that makes the detection of galactic axions possible. Note that the converted photon of an axion of mass ~5 μeV lies in the microwave domain with a frequency of ~1.2 GHz.

The interaction Lagrangian of the axion in Gaussian units is given by

$$L_{int} = -(g_{a\gamma\gamma}/4\pi)\vec{E} \cdot \vec{B}\ \phi_a \qquad (7)$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields respectively, ϕ_a is the axion field, and coupling constant $g_{a\gamma\gamma}$ is given by

$$g_{a\gamma\gamma} = m_a \left[\frac{e^2}{\bar{h}c}\right] \frac{(\bar{h}c)^{3/2}}{f_\pi m_\pi} (\sqrt{2}\pi)^{-1}$$

$$= (1.1\times10^{-34} \text{ MeV}^{1/2} \text{ cm}^{3/2}) \left[\frac{m_a}{10^{-5} \text{ eV}}\right] \qquad (8)$$

As proposed by Sikivie[12], the axion conversion process can be enhanced by detecting the conversions in a resonant electromagnetic cavity placed in a magnetic field with cavity mode and geometry chosen to maximize $\vec{E}\cdot\vec{B}$. If the cavity has a quality factor Q, then the axion conversion rate to a single photon is

$$R_{a\to\gamma} = \frac{\epsilon_o c^2}{\hbar^2} \quad g^2_{a\gamma\gamma} \quad \frac{1}{\omega} QB_o^2 \; G_j^2 \tag{9}$$

where B_o is the externally applied magnetic field, ω is the frequency of the converted photon, and G_j^2 is a geometric form factor measuring $\int\vec{E}\cdot\vec{B}_o d^3x$ for the cavity mode j: the mode is chosen so as to keep G_j^2 of order unity. For our experimental parameters $R_{a\to\gamma} = 1\times10^{-17}$ sec^{-1}.

For a given axion density $\langle\rho_a\rangle$, and cavity volume V, the power detected by a critically-coupled receiver is

$$P_a = \frac{1}{2} \left(\frac{g_{a\gamma\gamma}}{m_a}\right)^2 \langle\rho_a\rangle \; \omega Q[\epsilon_o(cB_o)^2]VG_j^2 \tag{10}$$

where we have introduced the combination

$$\left(\frac{g_{a\gamma\gamma}}{m_a}\right)^2 = 1.3\times10^{-46} \quad \frac{cm^3}{MeV} \tag{11}$$

because it is an exact prediction of theory for N=3 (see Eq. (1)). This detection scheme has been theoretically studied [12,14] for rectangular electromagnetic cavities. Since the resonant frequency of the cavity must equal the axion mass, an axion search over a large mass range requires a cavity which can be tuned over a large range while preserving a high quality factor, Q. The breakthrough occurred with our development of a right-circular cylinder cavity operated in the TM_{010} and TM_{020} modes, which can be tuned over a 15% range by inserting a single-crystal sapphire rod along the symmetry axis.

EXPERIMENTAL SETUP

We have initiated an experimental program to search for galactic axions in the mass range $4.5 < m_a < 25$ μeV, which corresponds to the resonant frequency of the detection cavities being varied over a frequency range $1 < f_\gamma < 6$ GHz. Preliminary results are reported here for the mass range $4.5 < m_a < 5.0$ μeV. The experiment was developed around an eight-inch cold bore 6.6T Nb-Ti superconducting solenoid[15] located at Brookhaven National Laboratory. The detector is shown schematically in Fig. 1. The OFHC cylindrical copper cavity, 18 cm in diameter and 40 cm in length, was placed in the solenoid aperture and was operated in the liquid helium. The TM_{010}

mode was chosen for the first scan because of its high form factor ($G_1^2 \simeq 0.67$) and dearth of resonance crossings with changing frequency. The resonant frequency was tuned by inserting or retracting a 0.6-inch diameter single-crystal sapphire rod along the cavity axis using a motor drive under computer control. The tuning range was ~12%; 1.22 GHz with the rod removed and 1.09 GHz with the rod fully inserted. The unloaded cavity Q for the data presented below was 190,000 at 4°K. The best Q we had achieved at this frequency has been 360,000.

How do we look for the axion signal? Recall that the axion converts in the cavity producing a photon of energy equal to the axion total energy. The cavity is tuned to be resonant at the searched axion mass or photon frequency. The problem then is to see at the converted photon frequency power deposited in the cavity in excess of the averaged cavity noise power at that frequency. At 1.2 GHz the cavity with a loaded $Q = 9\times10^4$ has a frequency bandwidth of 13,000 Hz. The effective Q of the axion, the ratio of its total energy to its kinetic energy, is $\sim9\times10^6$, giving a width of the axion of ~130 Hz at a central frequency of 1.2 GHz. To search for the axion signal we measure in frequency space the power distribution across the cavity resonant bandwidth, 13,000 Hz, looking for a narrow ~130 Hz power peak. For optimal signal-to-noise the receiver should have a bandwidth comparable to the axion bandwidth. For optimal realtime utilization the receiver should be sensitive to the entire cavity bandwidth simultaneously. This was achieved by using in the final receiver stage a multiplexer of 64 amplifier channels of 200 Hz bandwidth, operating in parallel to cover the cavity bandwidth. Two-stage superheterodyning was used to keep the multiplexer operating in a fixed frequency range.

A schematic flow diagram of the electronics is shown in Fig. 2. Microwave power was coupled out of the cavity by a critically-coupled induction loop and fed to a GaAsFET amplifier; these operated at helium temperature.[18] After further amplification the signal was superheterodyned using dual balanced mixers in two stages and detected in the 64-channel multiplexer whose individual channel width was 200 Hz. To average out the variation in cavity response over its bandwidth, the resonant frequency of the cavity was swept at 200 Hz/sec by driving the sapphire crystal in synchronization with the rf local oscillator (LO). With the on-line computer, the appropriate multiplexer channels were co-added to produce summed power in fixed frequency bins. Every 50 seconds the cavity resonant frequency was automatically measured using a scalar network analyzer and the LO was synchronized for the next sweep. These operations were performed under control of a Hewlett-Packard model 310 computer. The multiplexer data were read out every 100 msec and averaged on-line before being transferred to a VAX 11/780 for further processing and storage. A typical record containing two-thousand 200 Hz bins is shown in Fig. 3. The overall noise figure of the system, including the 4°K physical temperature of the cavity, was 12.5°K at 1.09 GHz and 17.6°K at 1.22 GHz; thus, the noise power was typically $P_N \approx 4\times10^{-20}$ watts per 200 Hz channel.

The output of each 200 Hz FWHM multiplexer channel went to a square-law diode power detector followed by an integrator whose decay time was set at 100 msec. This gave 168 effective averages per decay time. By sampling the readout at 10 times/sec, we were able to achieve the equivalent of 80,000 averages total for each bin. The standard deviation of the statistical fluctuations was therefore $\sigma \approx 0.5\% \; P_N$, so that the 5σ limit for a single bin is $P_s < 1\times10^{-21}$ watts.

RESULTS

Search for Narrow Width (200 Hz) Axions.

The frequency range from 1.09 to 1.22 GHz ($4.5 < m_a < 5.0\ \mu$eV) was swept twice. Off-line the data were searched using two algorithms for bins that had power levels with 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. 4; it is fitted closely by a Gaussian with unit dispersion indicating that the observed error agrees with the expected error. In the two sweeps, ten frequency bins were found which showed a deviation greater than 5σ; these are listed in Table I. The apparatus was retuned to these frequencies and the peaks examined under higher resolution. Figure 5 shows one of the peaks as observed on a spectrum analyzer at 50 Hz bandwidth resolution. All signals were eliminated as candidates for axion conversion because they were found to be independent of the magnetic field.

Thus, our limit on the power from a narrow axion conversion line corresponding to 5σ is

$$P_s < 1\times10^{-21} \text{ watts}, \; \Gamma_a \lesssim 200 \text{ Hz} . \tag{12}$$

Given the parameters of our detector and the local axion density of Eq. (6), the expected power from Eq. (10) is

$$(P_a)_{\text{theoretical}} = 0.3\times10^{-23} \text{ watts} \tag{13}$$

Our limit is, therefore, a factor of 300 above that expected from an axion dominated universe. Our results may alternatively be expressed as

$$\left(\frac{g_{a\gamma\gamma}}{m_a}\right)^2 \langle\rho_a\rangle < 1.4\times10^{-41} \tag{14}$$

Search for Wider Width (200-10^4 Hz) Axions.

The data were also examined for signals that would be several 200 Hz channels wide. The sensitivity for wide lines of power is reduced and cannot be reliably extended beyond the cavity width of $\sim 10^4$ Hz. The limit can be given by the approximate expression[17]

$$P_s < 1\times10^{-21}\ (\Gamma_a/200\ \mathrm{Hz})\ \mathrm{watts},\ 100 < \Gamma_a < 10^4\ \mathrm{Hz}\ . \quad (15)$$

Search for Axions with a Continuous Energy Spectrum.

In addition to the swept frequency data discussed above, we have used the apparatus at two fixed-frequencies (1.09 and 1.22 GHz) to search for conversions from pseudoscalar particles with a continuous energy spectrum. We compared the microwave power level in the cavity 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 fitting the noise spectrum. Such a spectrum is shown in Fig. 6 together with the calculated fit.[18] 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 received noise temperature at the first amplifier changed by less than $\Delta T = \pm 0.4$°K when the field was increased from 0 to 6.6 Tesla.

From the upper limit on ΔT we can place a limit on axion conversions $dP_s/df < 0.6\times10^{-23}$ W/Hz. Assuming that the spectrum is bounded between 1.09 and 1.22 GHz, $\Delta f = 130$ MHz, we find that

$$\left(\frac{g_{a\gamma\gamma}}{m_a}\right)^2 \langle\rho_a\rangle < 4\times10^{-35} \quad (16)$$

Using Eq. (6) for $\langle\rho_a\rangle$ gives the limit

$$g_{a\gamma\gamma} < 2\times10^{-30}\ \mathrm{MeV}^{1/2}\ \mathrm{cm}^{3/2}\ . \quad (17)$$

Search for the Production of Light Pseudoscalar Particles.

Let us further pursue the above conclusion that the equivalent received noise temperature at the first amplifier changed by less than $\Delta T = \pm 0.4$°K when the magnetic field was increased from 0 to 6.6 Tesla. We can interpret the decrease in received noise temperature to place a limit on the production of any light pseudoscalar x, by the electromagnetic field in the cavity due to its finite temperature. For a single-cavity mode, the total number of photons is $n_\gamma = k_B T_c/\hbar\omega$ and the pseudoscalar production rate is bounded by

$$P_x < 2k_B \Delta T \Gamma_c = 1\times10^{-19}\ \mathrm{W} \quad (18)$$

where Γ_c is the cavity width which is of order 10^4 Hz. Therefore the conversion rate is limited by

$$R_{\gamma\to x} < \frac{n_{x/sec}}{n_\gamma} = \frac{P_x}{k_B T_c} = \frac{2\Delta T}{T_c}\,\Gamma_c = 2\times10^3\ \mathrm{sec}^{-1} \qquad (19)$$

Since $R_{\gamma\to x} = R_{x\to\gamma}$, Eq. (9) with the parameters for our apparatus and the limit of Eq (19) imply that

$$g_{x\gamma\gamma} < 10^{-24}\ \mathrm{MeV}^{1/2}\ \mathrm{cm}^{3/2} \simeq 10^{-5}\ \mathrm{GeV}^{-1} \qquad (20)$$

The limit of Eq. (20) is predicated only on $0 < M_x < 1$ GHz ($0 < M_x <$ 4 μeV), and does not assume the presence of galactic dark matter in the detector.[19]

FUTURE PLANS

Our present program is to search for galactic axions in the mass range $4.5 < m_a < 25$ μeV, using the basic detection scheme described in this paper. The corresponding frequency range for the search is $1.0 < f_\gamma < 6.0$ GHz, which can be covered using six different diameter electromagnetic cavities, each operated in the TM_{010} and TM_{020} resonant mode. Tuning these cavities will require sapphire rods of different diameters chosen in a balance between a large tuning range and minimizing mode crossings while still preserving a high Q.

The present results are from a double sweep of the first cavity operated in the TM_{010} mode, 1.09 to 1.22 GHz. The second cavity is presently being scanned at 200 Hz/sec in the TM_{010} mode, 1.22 to 1.42 GHz. Within the next few months the first cavity will be scanned using a 0.4-inch diameter sapphire tuning rod in the TM_{020} mode, 2.43 to 2.80 GHz. Whenever the physical cavity or resonant mode is changed, the matching rf cryogenic amplifier must also be changed. We hope to cover the range 1.0 to 6.0 GHz in about two years.

From Eqs. (12) and (13), we observe our present limit on narrow axions is a factor of 300 above that expected from an axion dominated universe. What are our plans to improve the sensitivity of the experiment? Can the factor of 300 be achieved? We are already developing a high field insert to boost the solenoid field to 12-15T; giving an improvement x5. The cavity length can be increased by 40%; improvement x1.4. Understand and maintain a high cavity Q; improvement x2.2. Developing better rf cryogenic amplifiers using a state-of-the-art GaAs FET's or HEMT's; improvement x2. Improve the overall system noise temperature by operating the cavity and rf amplifier at sub-liquid helium temperatures; improvement x2-5 (??). Improve receiver design; improvement (?). It appears that one may come within a factor of two of the axion dominated universe predictions if all of these improvements work as projected above.

For the more distant future, we have submitted a letter of intent to Brookhaven National Laboratory for an experiment to search for the direct production of "invisible axions." The experiment follows the ideas of Zavattini;[20] and utilizes the upcoming life test of the SSC prototype dipole magnets. The experiment consists of passing a polarized laser beam through the magnetic field. Because of the $\vec{E}\cdot\vec{B}$ coupling, Eq. (7), for axion production, the magnet acts as a birefringent medium and a 45° polarization will be rotated. This experiment, while not as sensitive as the present narrow axion search, has the advantage of covering a large mass range and being sensitive to any Goldstone boson with a mass less than ~1 eV.

A comparison can be made of the sensitivities of different experiments by showing the excluded regions on a coupling constant vs axion mass plot. In Fig. 7 is shown the region excluded by the present results, by the expected future results from the present experiment without major upgrade, and by the new proposed laser experiment. Also shown is the cosmological limit determined from the sun and the theoretical correlation between coupling constant and axion mass, Eq. (8).

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17. Eq. (15) is also approximately valid for $\Gamma_a > 10^4$ in which case $P_a < 10^{-20} \times (\Gamma/200)$ watts; 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).
18. The observed structure is due to reflection from the amplifier input and from the cavity port. For details of the fit see B. Moskowitz and J. Rogers, "A Signal and Noise Analysis of the Microwave Galactic Axion Detectors", in preparation (1987).
19. A light particle with coupling of such strength would give rise to an observable macroscopic force with a range of a few centimeters. See J. E. Moody and F. Wilczek, Phys. Rev. D30, 130 (1984).
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Table I Frequency bins with deviation from the mean in excess of 5σ

Date	Frequency (H_z)	Deviation in σ's	
October 86	1.148, 974, 600	9.6	
	1.166, 926, 312	10.4	
November 86	1.091, 535, 213	5.3	
	1.104, 027, 737	8.7	coincident
	1.128, 536, 193	5.2	
December 86	1.104, 027, 076	6.5	coincident
	1.140, 000, 290	6.3	
	1.145, 351, 433	5.2	
	1.165, 267, 988	7.7	
	1.170, 000, 952	8.8	

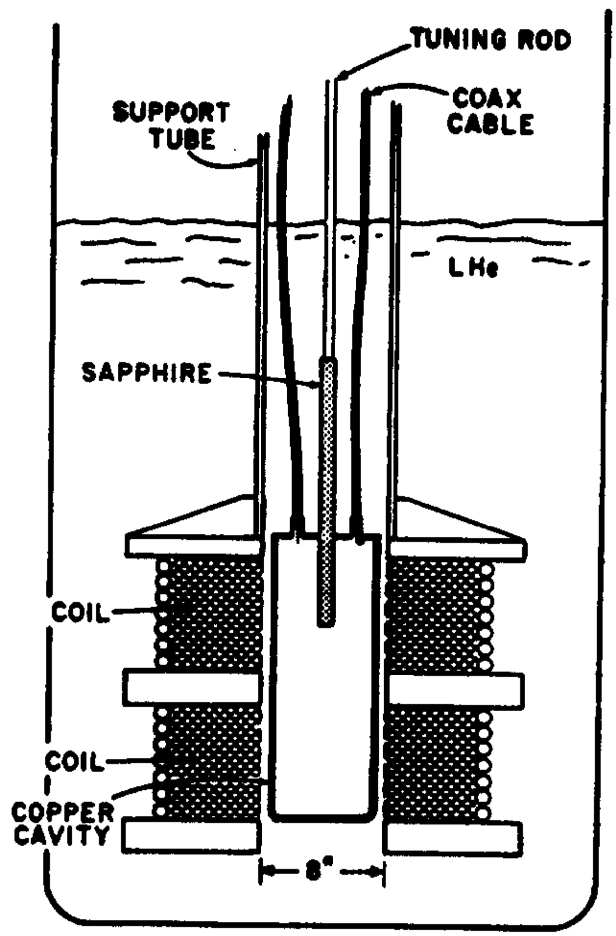

Fig. 1. Schematic diagram of the axion detector. A copper rf cavity is located in a 6.6T superconducting solenoid. The sapphire tuning rod is axially located. Detector system is within a liquid helium filled cryostat.

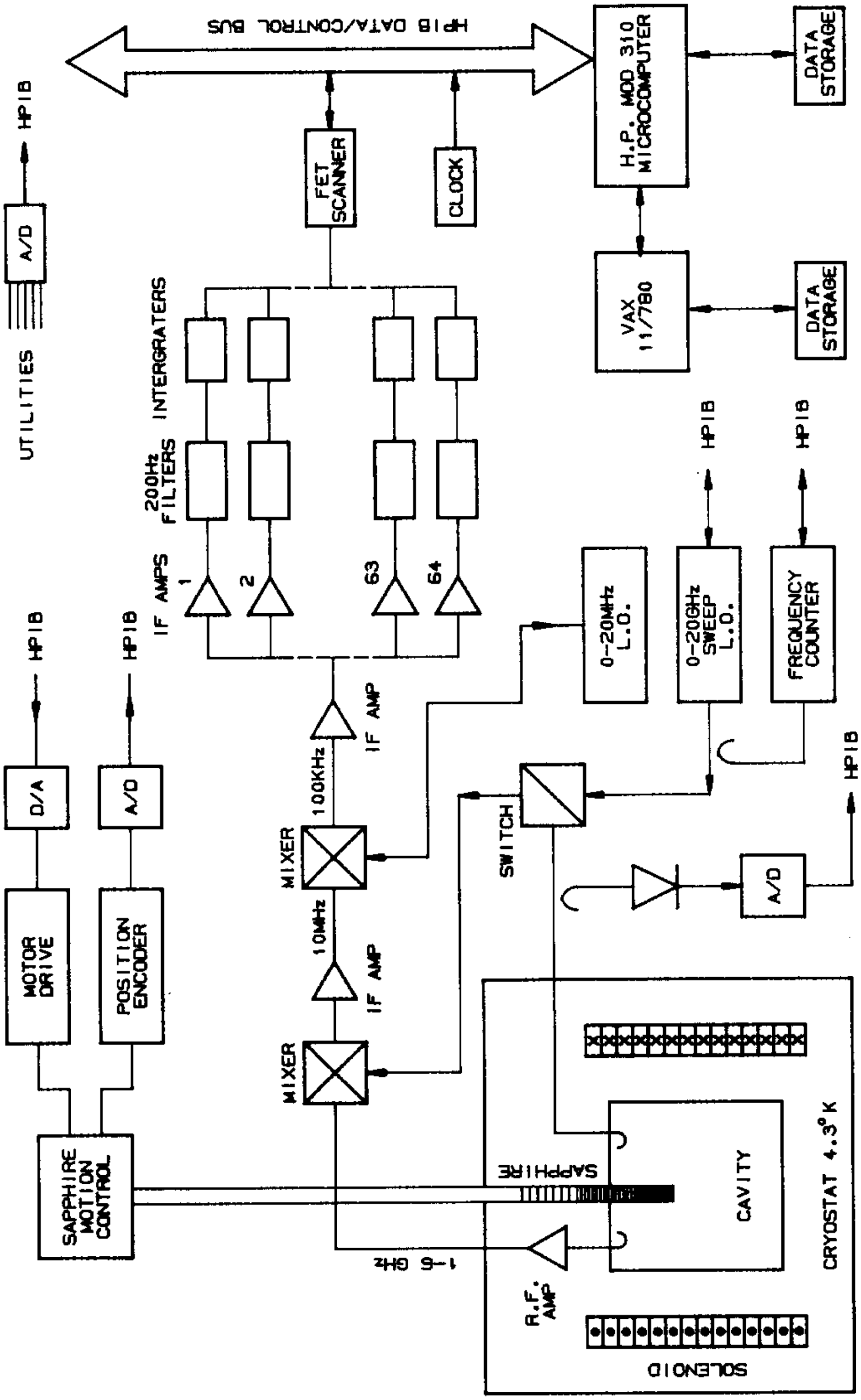

FIGURE 2
AXION DETECTOR -ELECTRONIC SCHEMATIC

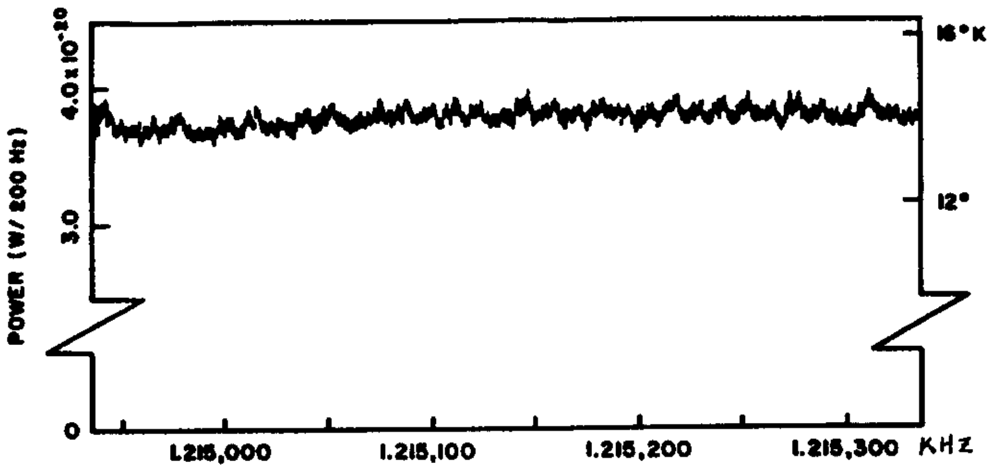

Fig. 3. A typical power spectrum covering 400 kHz with 200 Hz resolution. The statistical error is indicated for every bin.

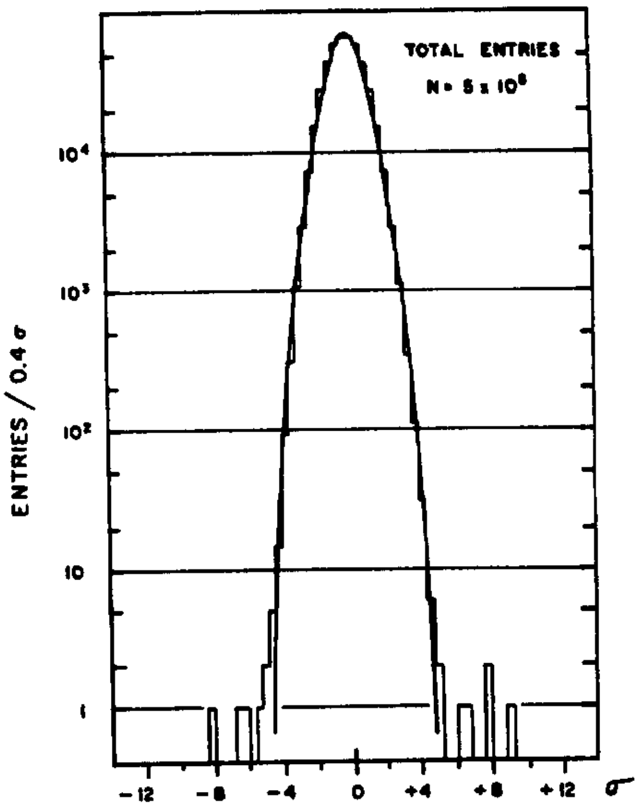

Fig. 4. Distribution of the normalized deviation from the mean for $5{\times}10^5$ bins. The fit is a Gaussian with unit dispersion.

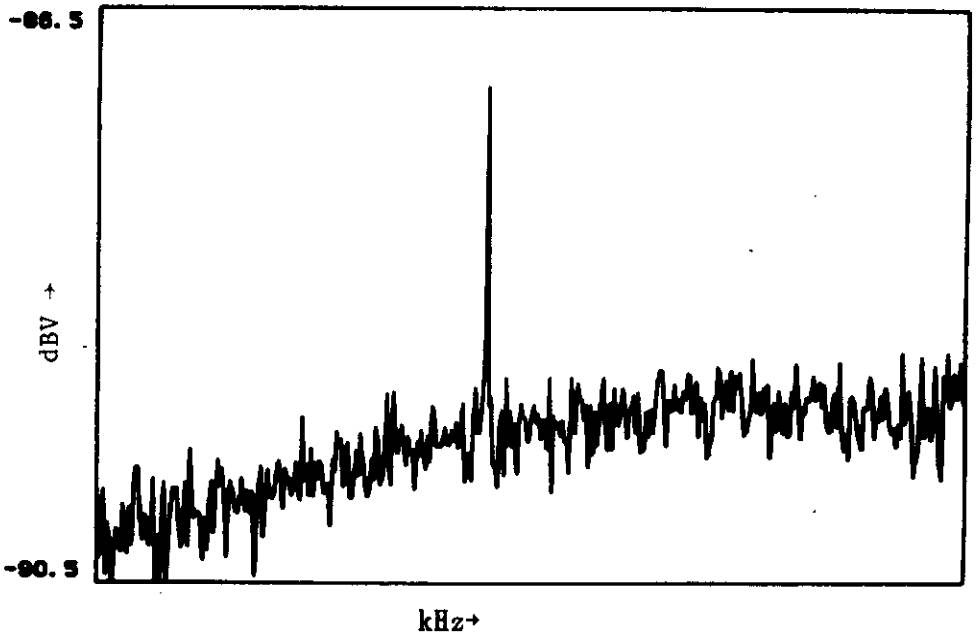

Fig. 5. One of the spurious peaks that appears at 1.165 GHz displayed with 50 Hz resolution.

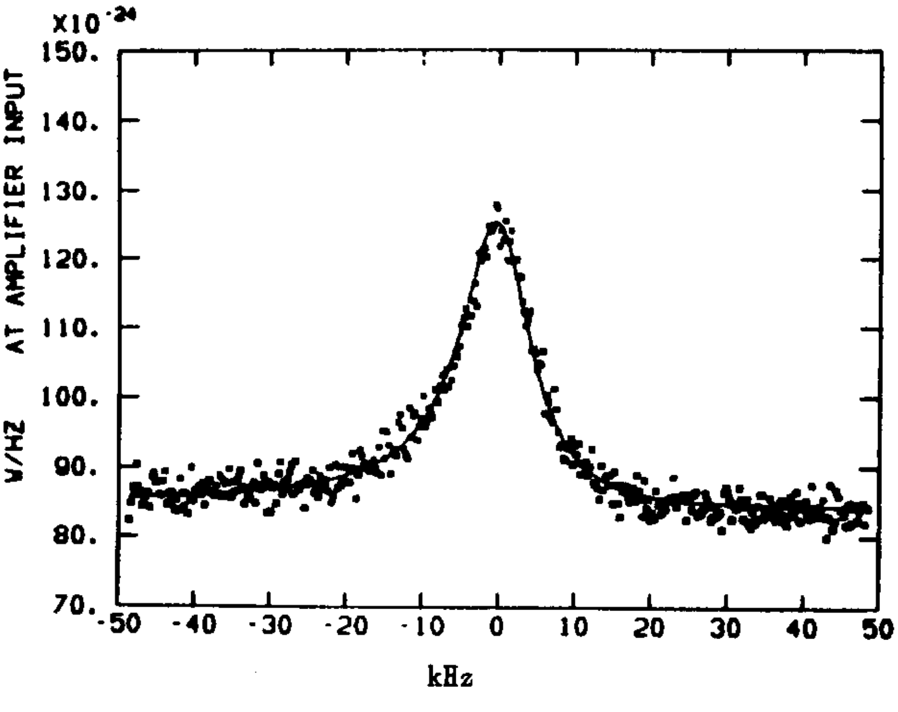

Fig. 6. The noise power spectrum at fixed frequency 1.09 GHz. The solid line is a fit of the data to a model discussed in Ref. 18.

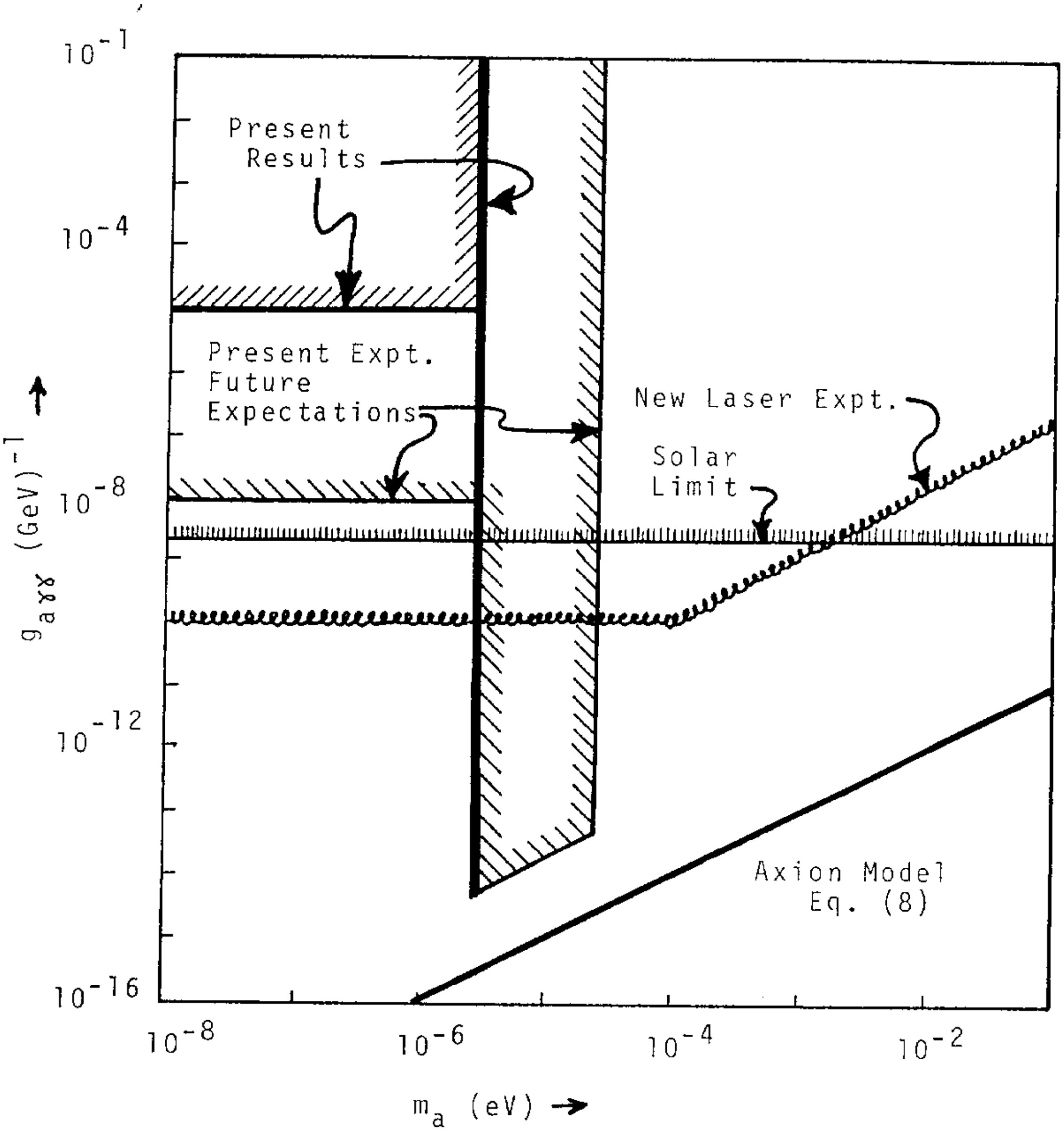

Fig. 7. Limits on the coupling constant for axion decay into two photons as a function of axion mass for present and future experiments. The axion model, Eq. (8), is also shown.