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Abstract

We have searched for the regeneration of photons propagating in a transverse magnetic field. Such an effect would reveal the existence of light scalar or pseudoscalar particles such as the axion that couple to two photons. We obtain for this coupling the limit $g_{a\gamma\gamma} < (1.3 \times 10^6 \text{ GeV})^{-1}$, provided the axion mass $m_a \lesssim 10^{-3}$ eV.

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The success of the Standard Model[1] leads to the conclusion that the mass scale f_a of new interactions is much larger than the electroweak scale $G_F^{-1/2} \sim 300$ GeV. This mass scale can be probed by searching for light scalars/pseudoscalars which couple superweakly to the fermions[2]. Of such Nambu-Goldstone bosons[3], the axion[4] is the one best motivated since it emerges as a consequence of the breaking of the Peccei-Quinn symmetry[5] which provides a natural solution of the "strong CP" problem. An example of a scalar weakly coupled to two photons is the dilaton[6].

Pseudoscalars couple to two photons through the triangle anomaly (Fig. 1a), the intermediate fermions in the loop being either electrons or quarks. For the latter case we express the coupling to two photons through

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{N}{f_a} \equiv \frac{1}{M} \tag{1}$$

with N the number of flavors, $\alpha = 1/137$ the fine structure constant and f_a the symmetry breaking scale. A relation between the mass of the axion and f_a can be obtained, because it is believed that the pion is the Goldstone boson arising from the breaking of chiral symmetry. Thus[7]

$$m_a f_a = \frac{N\sqrt{z}}{1+z} m_\pi f_\pi \sim 3.6 \times 10^{-2} \quad \text{GeV}^2 \tag{2}$$

with $z = m_u/m_d \simeq 0.56$.

The best limits on the coupling $g_{a\gamma\gamma}$ of axions to two photons come from astrophysical considerations of the energy loss in stars[8] For axions that do not couple to electrons these limits are in the range $M > 10^8$ to 10^9 GeV. It is however important to carry out independent laboratory experiments on the existence of such particles. One recent experiment searched for a small optical rotation of a polarized beam of light traversing a magnetic field in vacuum[9]. Alternately it has been proposed[10] to search for what can be called "photon regeneration". In these experiments an intense laser beam travels through a region of transverse magnetic field where axions can be produced coherently in the forward direction. The laser beam is blocked but the axions continue to travel through a second identical magnet where a fraction of the axions is reconverted to photons. These regenerated photons are detected by a photomultiplier.

The term in the effective Lagrangian that couples a pseudoscalar to two photons is

$$L = \frac{1}{4} g_{a\gamma\gamma} \phi_a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} \phi_a \vec{E} \cdot \vec{B} \tag{3}$$

This implies that when a magnetic field $\vec{B}$ provides one of the two photons, the polarization of the laser beam must be parallel to the magnetic field. Conversely, for scalar particles the polarization must be perpendicular to the magnetic field. The probability for the conversion of a photon into an axion through the Primakoff effect[11] (Fig. 1b) is given by

$$P_{\gamma \to a} = \frac{1}{4} \left(\frac{B\ell}{M} \right)^2 \tag{4}$$

with B the magnetic field in eV^2 ($1T \sim 195\ eV^2$), ℓ the length of the magnetic field region in eV^{-1} ($1\ cm = 5 \times 10^4\ eV^{-1}$) and $M = 1/g_{a\gamma\gamma}$ as defined in Eq.(1). The above result is valid as long as the axion and photon fields propagate coherently in the magnetic field region. This imposes a condition on the mass of the axion detectable by this method

$$\frac{\ell m_a^2}{2\omega} < 2\pi \tag{5}$$

where ω is the photon energy. Our experiment, located at Brookhaven National Laboratory is shown in Fig. 2. We used two CBA[12] superconducting dipoles operating at $B = 3.7$ T and of length $\ell = 440$ cm each. An argon-ion laser was used and the beam was trapped in an optical cavity in the first magnet.[9] The light beam made $N_r = 200$ traversals, and the power entering the cavity was 1.5 watts combined over the two lines, $\lambda = 514.5$, and $\lambda = 488$ nm. The reflectivity of the cavity mirrors was better than 99.8% so that for this number of reflections the attentuation of the beam can be ignored. The magnet clear aperture was 3.75 inches and the cavity pattern was such that all rays when extended to the end of the second magnet remained within the aperture.

The end of the first magnet was blocked and so was the entrance to the second magnet. At the end of the second magnet, an $f = 25$ cm lens focussed any light onto the 9 mm diameter sensitive photocathode area of a 9893B/350 photomultiplier manufactured by Thorn EMI. This is a special low dark current tube which was cooled to a temperature of $-23°$ C. The 14 stage tube was operated at 2000 Volts where the charge from a single photoelectron was Q $\sim$ 20 pC. Under those conditions the dark current counting rate in the single photoelectron peak was 0.6 Hz. The quantum efficiency of the bialkali photocathode at our wavelength, is $\eta = 0.1$. The position and width of the single photoelectron peak as well as the photocathode efficiency were determined by injecting light from a light-emitting-diode located at the upstream end of the second magnet.

The PMT output was split in two parts, one half of the signal being used to provide an electronic trigger. The other half of the signal was digitized by a LeCroy 2249, CAMAC controlled, charge sensitive ADC; the sensitivity was 0.25 pC/channel and the integration gate $\Delta t = 100$ ns. The dark current (no light incident on the PMT) spectrum is shown in Fig. 3a. The large peak in the pedestal region is due to electronic noise and is clearly separated from the single photoelectron peak which is shown on an expanded scale in the inset. The fit to the data is a truncated Gaussian centered at channel 108 and with standard deviation of 34 channels; the $\chi^2/d.f = 1.27$ and the corresponding counting rate $R = 0.6$ Hz.

To avoid the effects of drifts in the dark current rate the laser light was modulated at 10 Hz using a rotary chopper whose position could be read by the data acquisition system. The data acquisition program collected an ON spectrum of events when the chopper allowed the laser beam to enter the cavity; and an OFF spectrum of events with no light in the cavity. To insure that equal time was spent in the ON and OFF states, the trigger counts in the noise region below the single photoelectron peak were monitored and compared. To simulate a signal, we allowed a small amount of light to enter directly from the first, into the second magnet. Subtracting the OFF spectrum from the ON spectrum results in the data shown in Fig. 3b. These are fitted by the same truncated Gaussian as in (a) of the figure and yield $R_{\rm ON} - R_{\rm OFF} = 2.1$ Hz and $\chi^2/d.f. = 0.89$.

In Fig. 3c we show the subtracted spectrum when the light between the two magnets is blocked. It corresponds to 220 minutes of ON data and 220 minutes of OFF data (approximately 7000 dark counts in each state). Fitting of the difference spectrum by the standard truncated Gaussian is shown in the figure and corresponds to $\chi^2/d.f. = 1.04$ and a difference counting rate

$$R_d = R_{\mathrm{ON}} - R_{\mathrm{OFF}} = -0.012 \pm 0.009\,\mathrm{Hz} \tag{6}$$

The expected counting rate for a given value of $M = 1/g_{a\gamma\gamma}$ is

$$R = \frac{1}{16}\left(\frac{B\ell}{M}\right)^4 \frac{N_r}{2}\frac{P}{\omega}\eta\eta' \tag{7}$$

where N_r is the total number of reflections in the cavity, P is the laser power, $\hbar\omega$ the photon energy; η is the quantum efficiency and $\eta' = 0.55$ is the efficiency for selecting single photoelectron events[13]. For the parameters of the experiment, as previously defined, we obtain

$$R = (0.085\,\mathrm{Hz})\left(\frac{10^6\,\mathrm{GeV}}{M}\right)^4 \tag{8}$$

From Eq.(6) we can set a 3σ limit on the observed rate, $R_{3\sigma} < 0.027\,\mathrm{Hz}$ and therefore from Eq.(8)

$$M = 1/g_{a\gamma\gamma} > 1.3 \times 10^6\,\mathrm{GeV} \tag{9}$$

Data was taken with the light polarization parallel to the magnetic field (pseudoscalars) as well as perpendicular to the field (scalars). Similar limits were obtained for both cases as given by Eq.(9). The limit on the mass of the excluded particles is obtained from Eq.(5) indicating that our result is valid for

$$m_a < 10^{-3}\,\mathrm{eV} \tag{10}$$

There exist a large number of experiments that have placed limits on possible Nambu-Goldstone bosons. (a) Accelerator experiments searching for particles with mass $m_a > 1$

MeV exploiting the decay $m_a \to e^+e^-$. These experiments are not sensitive to weak couplings[14] and typically exclude particles with couplings to fermions at the level of the weak interaction scale, $f_a \sim 300$ GeV; this would correspond to a coupling to two photons of order $g_{a\gamma\gamma} \sim (10^4 \text{ GeV})^{-1}$. (b) Strange and charmed particle decays[15] and the g-2 experiments are sensitive to massless or low mass particles, but still at a sensitivity level typical of the weak interaction scale. (c) Precision experiments at the atomic energy scale[9,16] are sensitive to massless or very l ight ($m < 10^{-3}$ eV) particles but are sensitive to couplings $g_{a\gamma\gamma} \sim (10^6 \text{ GeV})^{-1}$. (d) Astrophysical arguments[8], based on the rate of cooling of the sun, and of red giant stars, give for hadronic axions $f_a > 10^6$ GeV or $g_{a\gamma\gamma} < (10^8 \text{GeV})^{-1}$ and a pseudoscalar mass $m_a \lesssim 20$ eV. The limits from SN1987A are more stringent by three orders of magnitude.[8] (e) A laboratory search for cosmic axions which has set limits $g_{a\gamma\gamma} < (10^{12} \text{ GeV})^{-1}$ in a narrow mass range[17]. In Fig. 4 we show some of these limits as well as the prediction of Eqs. (1,2).

Our result also addresses the question of deviations from pure electrodynamics. For instance Kobzarev and Okun[18] proposed that the photon field may contain a weakly interacting component of mass m_2 and coupling e_2. Then in the geometry of our experiment, regeneration of the strongly interacting state and thus of the photon field should take place. If we follow Popov and Vasile'v[19] our results set a limit

$$m_2^4(\sin 2\theta)^2 < (10^{-6} \text{ eV})^4 \tag{11}$$

where m_2 is the mass of the weakly interacting component and $\sin\theta = e_2/e$.

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References and Notes

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Figure Captions

1. (a) The triangle anomaly that couples a pseudoscalar to two photons. (b) Primakoff effect for the creation of pseudoscalars and their reconversion into photons, in a magnetic field.
2. Schematic of the experimental apparatus showing two 4.4 m long CBA dipoles operated at a field of 3.7 T. The laser beam, of power 1.5 W, makes 200 reflections in the first dipole. A wall separates the two dipoles. In the second dipole a lens and photomultiplier are used to detect any regenerated photons.
3. Integrated charge spectrum. The pedestal is at channel 63 and the single photoelectron peak [see inset in (a)] is fitted by a truncated Gaussian centered at channel 108, with standard deviation of 34 channels. The sensitivity is 0.25 pC/channel. (a) Dark current spectrum including the electronic noise. (b) Subtracted spectrum when light is admitted from the first magnet. (c) Subtracted spectrum when the light is blocked.
4. Limits on the coupling of light scalars/pseudoscalars to two photons, vs their mass.

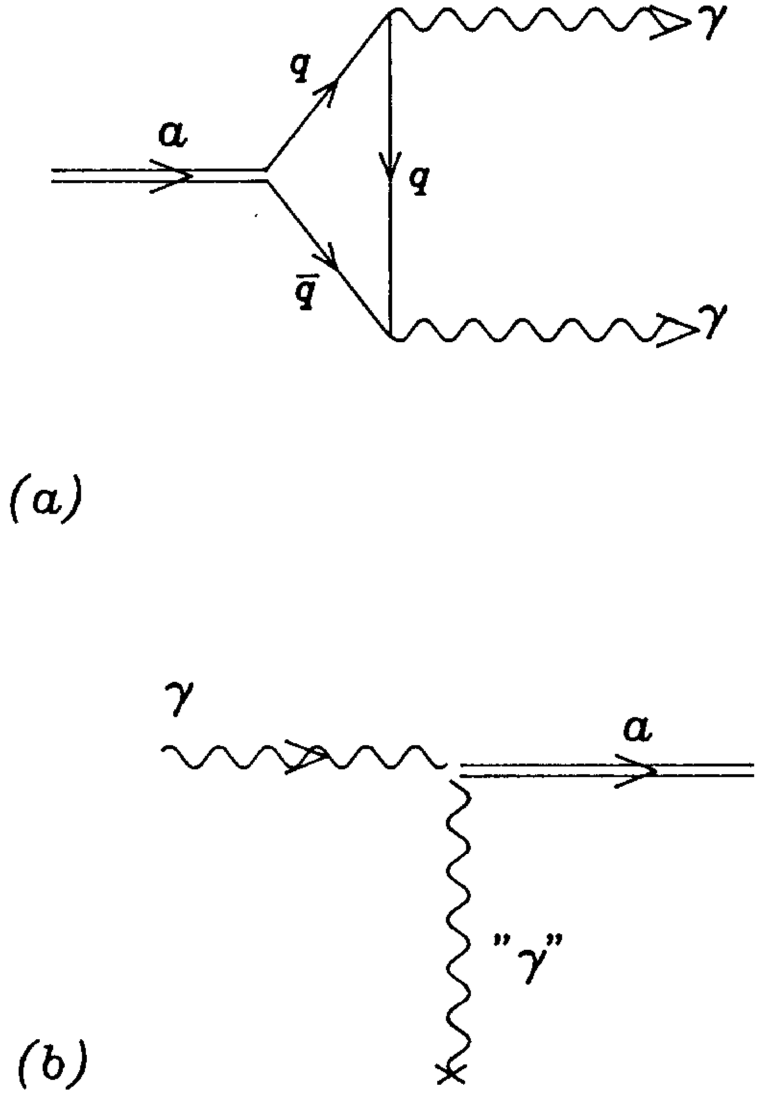


Fig. 1

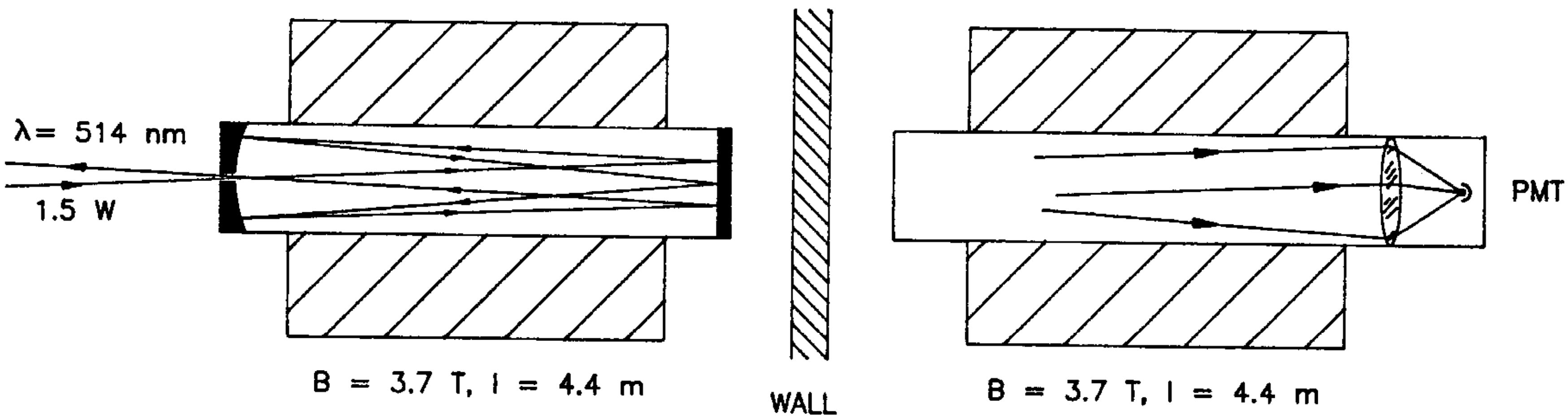
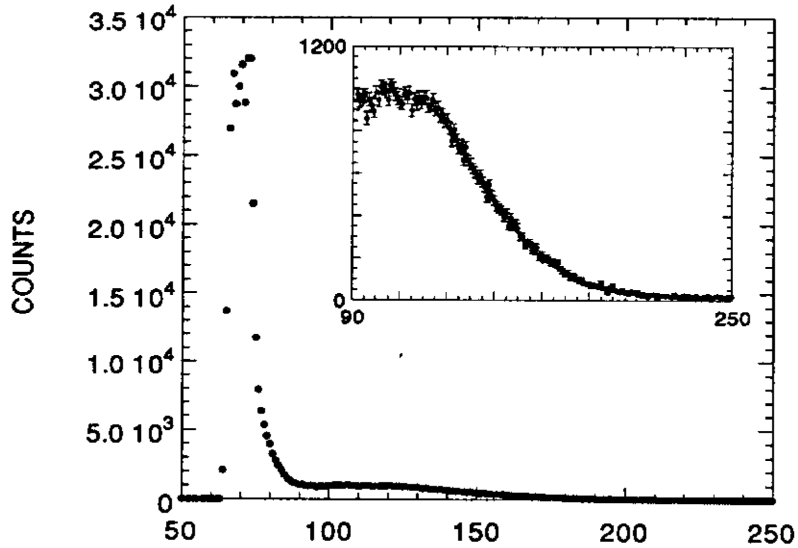


Fig. 2


COUNTS
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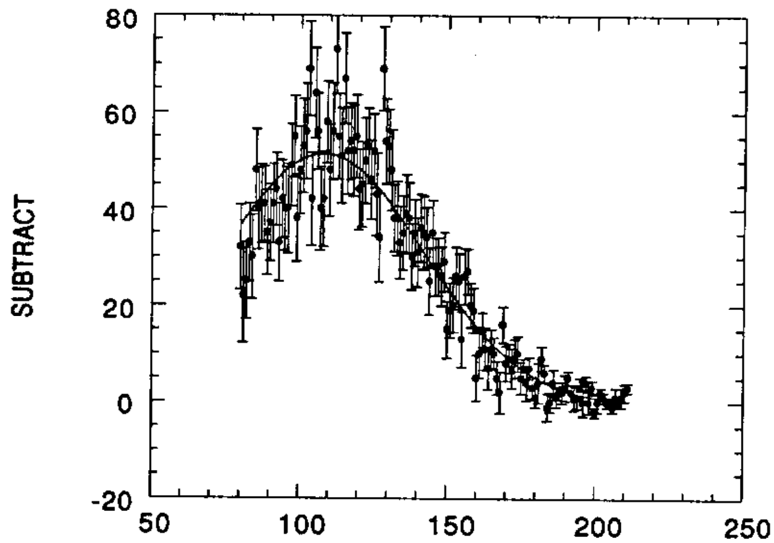
3.0 10^4
2.5 10^4
2.0 10^4
1.5 10^4
1.0 10^4
5.0 10^3
0
50
100
150
200
250
1200
0
90
250

(a)


SUBTRACT
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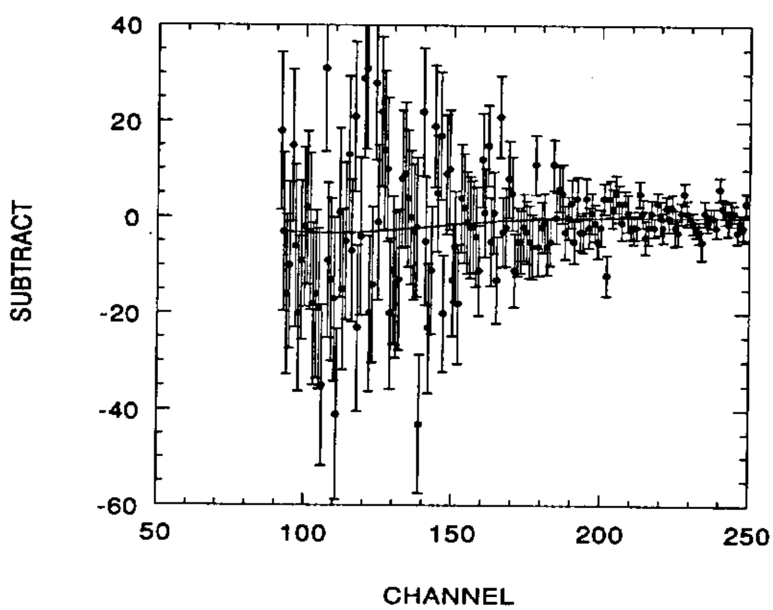
60
40
20
0
-20
50
100
150
200
250

(b)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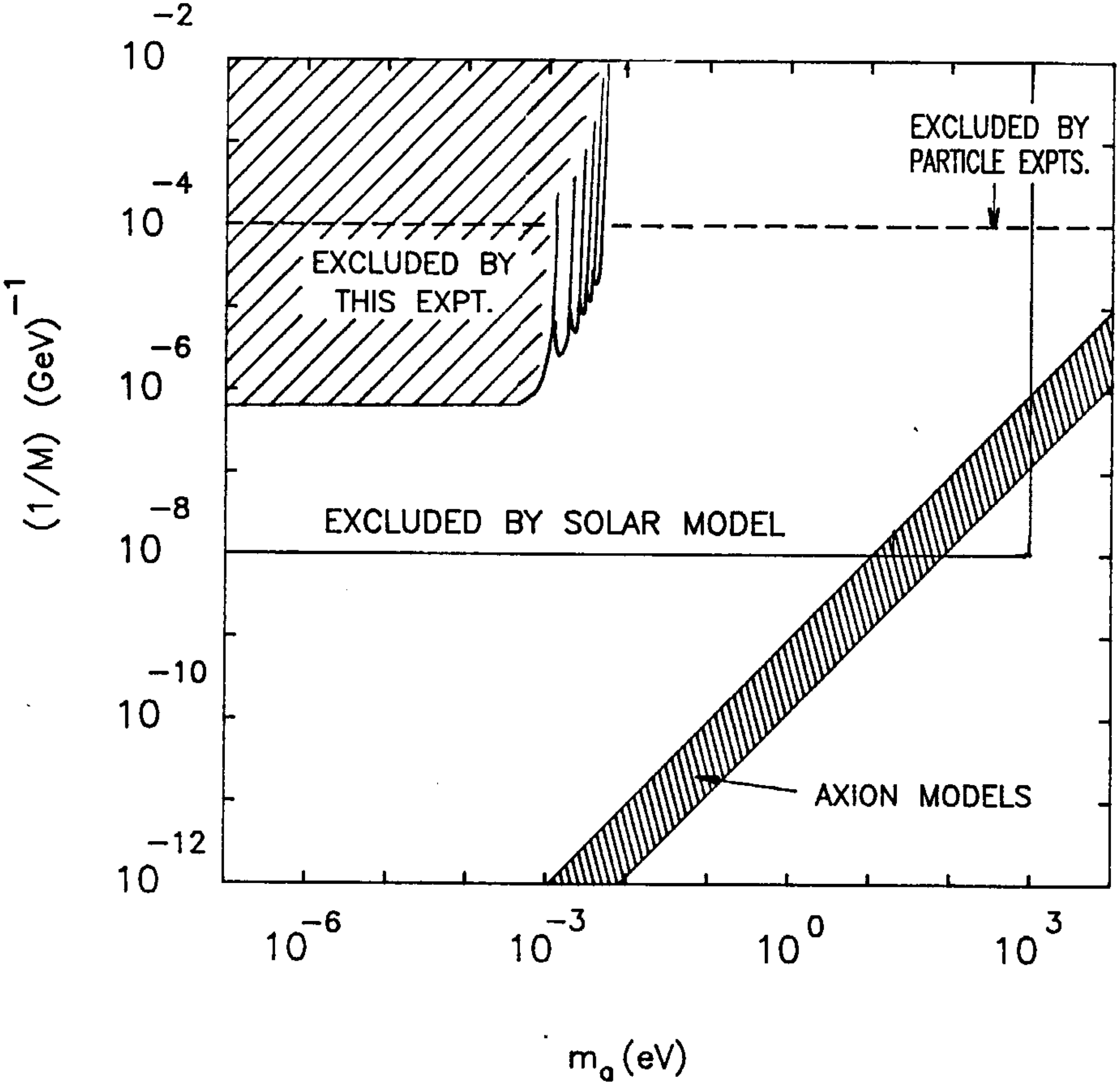
-20
-40
-60
50
100
150
200
250
CHANNEL

(c)

Fig. 3



10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
(1/M) (GeV)^-1
EXCLUDED BY THIS EXPT.
EXCLUDED BY PARTICLE EXPTS.
EXCLUDED BY SOLAR MODEL
AXION MODELS
10^-6
10^-3
10^0
10^3
m_a (eV)

Fig. 4