SLAC–PUB–3872
January 1986
(T/E/AS/I)

LABORATORY LIMITS ON SOLAR AXIONS FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

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Submitted to *Physical Review D*

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⋆ Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.

ABSTRACT

Laboratory bounds on the couplings to electrons of light pseudoscalars such as axions, familons, majorons, etc. are set with an ultralow background germanium spectrometer using a realistic model for the sun. In particular Dine-Fischler-Srednicki axion models with $F/2x_e' \lesssim 0.5 \times 10^7\ GeV$ are excluded. It should be emphasized that this is a laboratory bound. It does not rely on a detailed understanding of the dynamics and evolution of red giants, white dwarfs or other stars as do the more speculative astrophysical bounds which are competitive with our laboratory bound. The lower limit should be improved to $F/2x_e' > 1.8 \times 10^7\ GeV$ in the near future. It is shown that semiconducting Ge detectors for axions could eventually set limits $F/2x_e' > 10^8\ GeV$. If discovered, axions or other light weakly interacting bosons would not only allow us to study physics at energies beyond the reach of accelerators but would also provide a new laboratory tool to study the deep interior of stars.

1. Introduction

There are arguments in both theoretical elementary particle physics and astrophysics for the proliferation of neutral weakly interacting particles. On the theoretical side, gauge theories suggest the existence of many new particles: neutrinos, axions,[1] familons,[2] majorons,[3,4] etc. On the experimental side, observations of the galactic rotation curves suggest that most of the matter in the universe is non-luminous,[5] and a variety of arguments suggest that this matter may be non-baryonic,[6] e.g. might be made of neutral weakly interacting particles. Because these new particles interact so weakly, some enhancement mechanisms must be relied on to detect them. For example, one suggested enhancement mechanism for detecting neutrinos,[7] which works well for neutrino energies of a few MeV, relies on their coherent nuclear scattering.[8] Until now, detectors for weakly interacting particles,[5] such as axions, have been limited by either high minimum energy deposition thresholds or the level of background. However, recent progress in experimental techniques[9] has made feasible the measurement of energy depositions as small as atomic energies using detectors with very low background. In a previous paper,[10] it has been shown that, at these energies, atomic bound state effects lead to great enhancements ($10^5 - 10^6$) in the detection rates of axions.

Atomic enhancements are quite familiar. A well known example is the photoelectric effect. The photoelectric cross section per unit mass of germanium, for example, is $\sim$ 3000 times larger than that of hydrogen around 1.5 keV total photon energy. This is because Ge has electrons with binding energies of 1 keV and H does not. Similar enhancements occur in any atom with keV electron binding energies.

Enhancements similar to those in the photoelectric effect should also occur for the ionization of atoms by absorption of axions or other bosons coupled to electrons. This process for axions, depicted in Fig. 1, is called the axioelectric effect or axionization. Such effects are expected to be large for solar axions since their energy should be comparable to atomic energies because the average solar temperature is near 1 keV. The effect is directly analogous to the photoelectric effect; a boson is absorbed by a bound electron which is then ejected from the atom. In the dipole approximation, and considering axion energies $\omega \ll m_e$ in natural units ($\hbar = c = 1$), we have

$$\sigma_{\text{axioelectric}} = \frac{\alpha_{axion}}{\alpha_{em}} \left(\frac{\omega}{2m_e}\right)^2 \sigma_{photoelectric} \tag{1}$$

and

$$\alpha_{axion} = (2x_e' m_e/F)^2 \frac{1}{4\pi} \tag{2}$$

where $\alpha_{em} \simeq (137)^{-1}$ and x_e' is a constant of order unity,[11] which Srednicki argues is greater than one in the DFS model. F is defined by the axion-electron interaction Lagrangian

$$\mathcal{L} = 2x_e' \frac{m_e}{F} \, a \, \bar{e} \, i\gamma_5 e \ . \tag{3}$$

Here a is the axion field. Note that Eq. (1) includes all Coulomb effects for the nonrelativistic electron. The axion mass can be related to F by[11]

$$m_{\text{axion}} \simeq 7.2 \ eV \left[\frac{10^7 GeV}{F}\right] \ . \tag{4}$$

The most reliable theoretical lower bound may be placed on F by requiring that the solar bremsstrahlung axion luminosity not exceed the photon luminosity and therefore that the sun not burn too quickly and thus be older than $\sim 4.5 \times 10^9$ years, the age of the oldest known meteorites.[12–14 ♯1] This gives

$$\frac{F}{2x'_e} \gtrsim 1.08 \times 10^7 \ GeV \ . \tag{5}$$

Motivated by this bound, the axionization cross sections per kg for C, Si, Ge and Pb (from Eq. (1)) for $F/2x'_e = 10^7 \ GeV$ are plotted in Fig. 2. It is clear that the detector should have the lowest background possible, and Fig. 2 shows that it should have energy resolutions of 1 keV or better; this is the case of semiconducting detectors, as well as of superconducting colloid and other low temperature detectors. Because of their low threshold energy, such detectors can make use of the huge enhancement in the axioelectric cross section. It has been shown[10] that the axioelectric event rate for solar DFS axions could exceed by 4 to 5 orders of magnitude the published design capabilities of planned bolometric detectors.[7,19]

Since DFS axions couple directly to electrons, it is not necessary to rely on coherent nuclear scattering, as was the case of other weakly interacting particles. *Thus in the case of DFS axions there is no advantage in using low temperature, superconducting detectors.* The semiconducting detectors would work as well as a superconducting colloid and would provide the same energy sensitivity and radioactive background.

♯1 Speculative astrophysical arguments have been made which place more severe lower bounds on F: $F > 4 \times 10^7 \ GeV$ (red giant cooling)[12], $F > 4 \times 10^9 \ GeV$ (He ignition in red giants),[15] $F > 6 \times 10^8 - 3 \times 10^9 \ GeV$ (x-ray pulsar cooling)[16], and $F > 10^9 \ GeV$ (white dwarf cooling.[17] All of the above arguments rely on the details of models of stars which are very different than the sun; the strongest bounds rely on a proper understanding of stellar evolution. Cosmological arguments suggest an upper bound on F of $10^{12} \ GeV$.[18]

This letter discusses the use of an ultralow background semiconducting germanium spectrometer as a detector of solar axions. Because of its low band gap (0.69 eV at 77° K) and high efficiency for converting electronic energy loss to electron-hole (e-h) pairs (2.96 eV per electron-hole at 77° K), germanium detectors are probably the best suited of all existing particle detectors for the detection of DFS axions. In addition their low level radioactive background makes them ideal for the search for this rare phenomenon in as well as other exotica such as neutrinoless double beta decay.

In the following, a solar model[12,13,14] is used wherein the solar axion flux is calculated with solar temperature $T = 1$ keV. The expected solar axion flux is shown in Fig. 3. Only the bremsstrahlung emission process is used as a source of axions.[14] For $F/2x_e' = 10^7\ GeV$, the axionization event rates in Ge can be obtained by multiplying $\sigma_{\text{axioelectric}}$ (see Fig. 2) with the solar axion flux. In Fig. 4 the number of events per kg per day for germanium are plotted against the incoming axion energy for $F/2x_e' = 0.5 \times 10^7\ GeV$ (solid line) and $F/2x_e' = 10^7\ GeV$ (dashed line). The major contribution to the event rate comes from a narrow band between 1 keV and 10 keV. This is because both the solar axion flux and the axioelectric cross section peak in this region. In the following the expected rates are compared with the count-rates observed in an ultralow germanium spectrometer.

The PNL/USC group has developed a 135 cm^3 intrinsic Ge detector[20,21] having a radioactive background lower than conventional low background gamma-ray spectrometers. The detector was placed in the Homestake gold mine at a depth equivalent to 4000 meters of water in order to eliminate the cosmic ray induced background. The detector was also surrounded by super-pure copper and 11 tons of pure lead to eliminate the radioactive background from the rock.

Recently, the energy threshold of the detector was reduced to 4 keV. Six weeks of low energy data are shown in Fig. 5. These data represent a superbly low radioactive background, and have already been used to obtain limits on cold dark matter candidates.[22]

The radioactive shield was upgraded by the use of 448 year old lead, from a sunken Spanish galleon, in place of the super-pure copper which has some cosmogenic radioactive contamination. The modest background reduction achieved with this change confirms the supposition that the majority of background in the low energy portion of the spectrum is coming from the ^{210}Pb in the solder connection and an indium contact ring, both of which are scheduled for removal.

The detector background has a smooth contribution from the Compton scattering of high energy photons from γ emitters (e.g. ^{40}K) as well as narrow line components. The low energy peaks are primarily due to the presence of ^{210}Pb in a solder connection used to make electrical contact with the diode and in direct line of sight to the surface of the detector. The energy threshold was set at 4 keV because of microphonic noise (from blasting in the mine) at lower energies. Three months of data were accumulated, of which six weeks were free of microphonic noise. This six week subset of data is quoted in the following as Data Set I.

Also plotted in Fig. 4 are some of the experimental points (crosses) for $\omega \geq$ 4 keV. The statistical error on these data is estimated at $\pm$ 25%. From this the experimental bound

$$\frac{F}{2x'_e} \gtrsim 0.5 \times 10^7 \; GeV \tag{6}$$

is deduced.

For $2x'_e = 1$ the laboratory bound on the DFS axion mass is

$$m_a \lesssim 14.4 \; eV \; . \tag{7}$$

If $2x'_e > 1$ as argued by Srednicki[11] stronger laboratory bounds on the axion mass result.

The coupling of axions to photons is irrelevant for the above considerations; only the coupling of axions to electrons[11] matters. Therefore bounds similar to (6) are obtained for any light pseudoscalars (or light scalars as we will see later) that couple to electrons. Familons[2] and singlet-Majorons[3] (associated with right-handed neutrinos) have couplings similar to (3) where $(2x'_e)$ is replaced by a model dependent coupling constant and F is the large global horizontal symmetry breaking scale. Triplet-Majorons[4] (associated with left-handed neutrinos), appear if lepton number is a global symmetry spontaneously broken (up to this point the same applies to single-Majorons) at a scale v_T, the vacuum expectation value of a triplet Higgs field, small with respect to the electro-weak scale. From the coupling[4] of Majorons, M, to a pseudoscalar electron current the Lagrangian,

$$\mathcal{L} = 2\sqrt{2} \; G_F v_T m_e M \bar{e} i \gamma_5 e \; , \tag{8}$$

is obtained. By comparison with (3) the bound analogous to (6) becomes

$$v_T \lesssim 6.9 \; MeV \; . \tag{9}$$

For the interaction of a light scalar ϕ ($m_\phi \ll 1$ keV) with a scalar electron current,

$$\mathcal{L} = \lambda \bar{e} e \phi \ , \tag{10}$$

the cross section for ionization via a process analogous to Fig. 1 is

$$\sigma_{scalarelectric} \simeq \frac{\lambda^2}{4\pi\alpha}\, \sigma_{photoelectric} \tag{11}$$

including all Coulomb effects for nonrelativistic electrons. This does not suffer the suppression factor $(\omega/2m_e)^2$ so that bounds on

$$\alpha_{scalar} = \lambda^2/4\pi \tag{12}$$

from the scalarelectric effect could be $\sim 10^6$ times stronger than those on α_{axion} in Eq. (2) from the axioelectric effect for energy depositions of 1 keV. This of course also applies for theoretical astrophysical bounds on α_{scalar} analogous to those in Refs. 12-17 from the theoretical limits on light scalar emission from stars and overclosure of the universe.[18] It is obvious that similar bounds can be given for light bosons ($m \ll 1$ keV) of any spin (new vector particles, gravitons) whose energy is ~ 1 keV.

There is a problem of conceptual self-consistency which must now be faced. We have given a laboratory bound for axions $\frac{F}{2x_e^\prime} \gtrsim 0.5 \times 10^7\ GeV$. Imagine that $\frac{F}{2x_e^\prime}$ were indeed $0.5 \times 10^7\ GeV$. Then according to (5), the solar axion luminosity $\mathcal{L}_a$ would be approximately four times the solar photon luminosity $\mathcal{L}_\gamma$. But in order to calculate the axion flux in Fig. 3 in the first place, a model of the sun was used in which the dynamics were dominated by QED, weak and nuclear processes;

axion physics was supposed unimportant for solar dynamics. This might not be the case if $\mathcal{L}_a \simeq 4\,\mathcal{L}_\gamma$ and so the laboratory bound might be conceptually self-inconsistent. Note, however, that a laboratory bound stronger by a factor 2 to 3 *would* be conceptually self-consistent. Thus, future improvements in our laboratory bounds are crucial and will now be discussed.

The shapes of the low energy x-ray lines suggest that the PNL/USC Ge spectrometer has an energy resolution of ΔE(FWHM) $\approx$ 500 eV in this region. The strong increase of noise below $E_{\text{threshold}} = 4$ keV is believed to be largely due to microphonics engendered by mining operations. Hardware and software are being developed to reduce this noise and permit lowering of the energy threshold to 1 keV. Furthermore, the solder and indium are in the process of being removed in a second prototype and the background is projected to be reduced by another factor of 10 or more. Note in Fig. 4 that the axioelectric absorption peak in germanium occurs at lower incoming axion momentum. For example the axionization rate for $\omega = 1.4$ keV is ~ 16 times that for $\omega = 4.7$ keV. Thus an improvement in the limit may come from examination of the Ge data for ω near the peak.

In the Appendix, future improvements of the Ge spectrometer and their influence on axion bounds are discussed. The following improvements are planned for the immediate future:

- background improvement due to removal of the solder point and thus of ^{210}Pb radioactivity and also the indium contact ring.
- improvement of the detector energy threshold by the use of microphonic rejection techniques.

These two improvements should permit us to reach a bound of $F/2x_e' > 1.8 \times 10^7 GeV$. For $F/2x_e' = 1.8 \times 10^7 GeV$, 23 counts/(kg - month) are expected with energy deposition greater than 1 keV. Thus the problem would still be background suppression and not the detector mass and axion statistics.

Further improvements are possible in the second generation of ultralow background Ge detectors (1987-88) with a multidetector structure and considerably higher mass. Furthermore, Monte Carlo simulation of the detector/shield system and multiple coincidence/anticoincidence counting should permit rejection of the background due to Compton scattering, especially for energies close to the Ge absorption edges. Then, experimental limits of $F/2x_e' > 10^8\ GeV$ ($v_T \lesssim 0.3$ MeV) may become possible. However, for $F/2x_e' = 10^8\ GeV$, 0.28 counts/(kg - year) with energy greater than 1 keV are expected and both much better background suppression and better statistics are needed. Fortunately, the PNL/USC and UCSB/LBL[23] groups are both planning to operate Ge-detectors with a mass of about 10 kg.

In conclusion, our DFS bound $F/2x_e' \gtrsim 0.5 \times 10^7\ GeV$ is a laboratory bound relying on a realistic model of the sun, the closest and best understood star. We have also displayed limits for Majorons ($v_T \lesssim 6.9$ MeV for triplet Majorans) and for most familons which couple directly to electrons. (One can think of models in which familons couple mainly to quarks for which our bound does not apply.) Our laboratory bound does not rely on a detailed understanding of the dynamics and evolution of red giants, white dwarfs, neutron stars or other stars as do the more sophisticated theoretical bounds which are competitive with our laboratory bound. Using the axioelectric effect, semiconducting Ge detectors could eventually set limits $F/2x_e' > 10^8\ GeV$ ($v_T < 0.3$ MeV) or, more exciting, see solar axions or other light bosons. The discovery of these particles would not only allow us to study physics at energies beyond the reach of accelerators but would also provide a new laboratory tool to study the interior of stars.

ACKNOWLEDGEMENTS

The authors would like to thank ITP, Santa Barbara for their hospitality at the ITP Workshop on Cryogenic Methods of Detection of Neutrino and Dark Matter Candidates. SD is supported by NSF grant PHY83-10654 and is an A. P. Sloan Foundation Fellow, BWL is supported by DOE contract DE-AC03-76SF00515, GDS is an NSERC (Canada) Postgraduate Scholar, DNS is supported by NSF grant PHY-83-06693 and GG by NSF grant PHY-82-1524.[9] RLB is supported under DOE Contract DE-AC06-76RL0 1830, and FTA is supported by NSF Grant PHY-8405654.

APPENDIX

In this Appendix a very preliminary analysis is given of possible improvements on the axion bounds presented in this paper from ultralow background germanium detectors. First the question of axion statistics is discussed. In Table 1, the expected axion count rates for various values of $F/2x_e^{\prime}$ with energy deposition greater than 1 keV are presented. Remember that the PNL/USC detector is 0.710 kg of germanium. It is clear that axion statistics do not present a problem up to $F/2x_e^{\prime} = 5 \times 10^7\ GeV$. In order to reach $F/2x_e^{\prime} \gtrsim 10^8\ GeV$ detectors of mass $\sim$ 10 kg should be used. Fortunately the PNL/USC and UCSB/LBL collaborations will both deploy in the next years germanium detectors of this size in the near future.

The sources of background reduction will now be discussed. In Table II possible improvements in the reduction of background are listed. The first two are instrumental in nature and are discussed in the text.

After removing the solder and indium from the proximity of the detector, the very low energy background ($E \leq 10$ keV) will come from outside of the crystal, mostly as Compton scattered high energy photons, e.g. emitted by ^{40}K or ^{60}Co. A Monte Carlo simulation of the interaction of these photons with the Ge will be performed. The complexity of this task is mitigated and the precision improved by the fact that there are only a few high-energy lines remaining in our detector. This Monte Carlo simulation should have an uncertainty of 10%. Further improvement via the Monte Carlo can be achieved by comparison of the count rate just below and above the Ge axioelectric (and photoelectric) edge. This is because the number of counts due to axions should change by a factor of 6 at the absorption edge whereas the energy distribution of Compton scattered events should be smooth. Thus the uncertainty of Monte Carlo simulation, close to the absorption edge, will eventually be $\sim 5\%$.

Further improvements will be possible with the second generation multi-crystal gamma ray spectrometers. The PNL/USC design surrounds one ultra-pure Ge detector by other Ge detectors which act as an active shield. In such a very massive detector configuration the probability of a single Compton scattering leaving only a few keV is very small; most events will have a signature of a few Compton scatterings in the different detectors and thus can be rejected by anti-coincidence. The PNL/USC Group plans to build a Ge spectrometer using 14 detectors each of 0.7 kg. Two of the detectors are largely shielded by the others by at least 5 absorption lengths for ~ 1.4 keV photons which minimizes the probability of the inner detector receiving a photon near the Ge absorption edge from the shield, and thus the Monte Carlo simulation near the Ge axioelectric absorption edge would be even more accurate. In the last 3-4 years the PNL/USC group achieved about 3 orders of magnitude suppression of both low and high energy background, and the above additional improvements seem feasible.

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Table 1

Axioelectric Event Rate

$F/2x_e'$ GeV	$counts/(kg.yr)$
0.5×10^7	4.5×10^4
10^7	2.8×10^3
2×10^7	1.7×10^2
5×10^7	4.5
10^8	2.8×10^{-1}

Table II

Improvements in Background Suppression

Task	Improvement factor Signal/Background	$\frac{F}{2x_e'} \gtrsim (GeV)$	Projected Date
1) Remove radioactive solder point	10	0.9×10^7	1986
2) Energy sensitivity up to $\sim$ 1 keV†	16	1.8×10^7	1986
3) Monte-Carlo modeling of low energy background especially near germanium photoabsorption edge	20	3.8×10^7	1986?
4) 10 kg mass multi-detector	50	10^8	1988/9

† In the USC/PNL detector elimination of microphonic background through installation of anti-coincidence seismograph/microphone/strain gauge systems.

FIGURE CAPTIONS

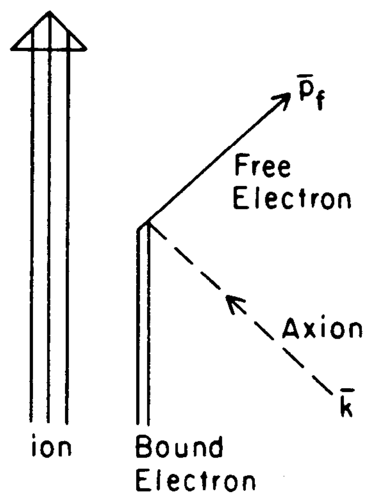
1. The axioelectric effect.

2. Axionization cross section per kg for C (dots), Si (dot-dash), Ge (dash) and Pb (solid). Note again that for axion energies of 1 keV there is an enhancement of about 10^3 for Si relative to hydrogen, and that the cross section at low energies is enhanced relative to the cross section at high energies by $\approx 10^4$.

3. The flux of solar axions on earth for solar temperature $T = 1$ keV from bremsstrahlung production for $F/2x_e' = 10^7\ GeV$.

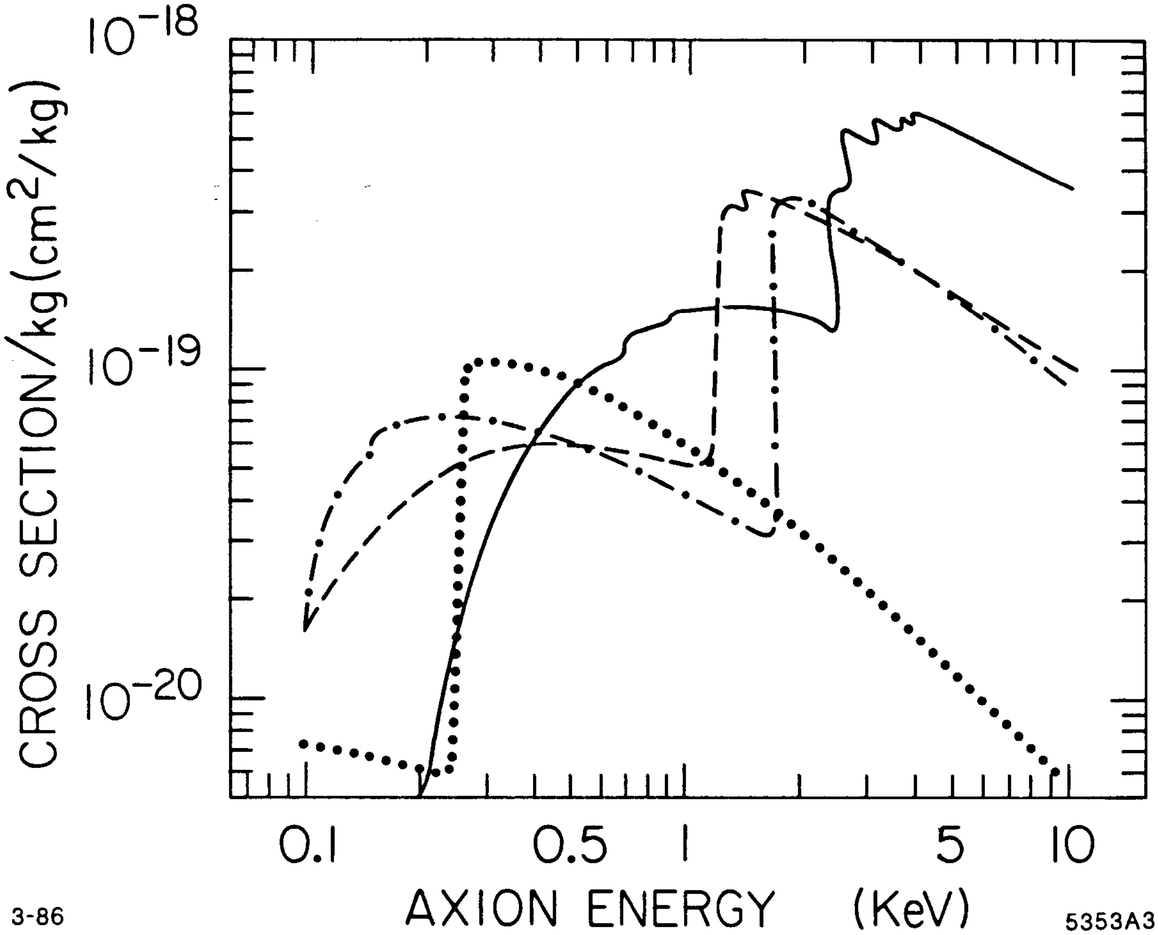
4. Solar axion events per kg per day for Germanium for $F/2x_e' = 0.5 \times 10^7\ GeV$ (solid) and $F/2x_e' = 10^7\ GeV$ (dashes). The crosses are from PNL/USC Data Set 1. Note that the axioelectric absorption peak at $\omega \sim 1.4$ keV gives an event rate ~ 16 times that at $\omega \sim 4.7$ keV, our lowest energy data point.

5. PNL/USC Data Set 1 (1000 hours).



$\bar{p}_f$
Free
Electron
Axion
$\bar{k}$
ion
Bound
Electron
3-86
5353A2

Fig. 1



10^{-18}
10^{-19}
10^{-20}
CROSS SECTION/kg(cm²/kg)
0.1
0.5
1
5
10
AXION ENERGY (KeV)
3-86
5353A3

Fig. 2

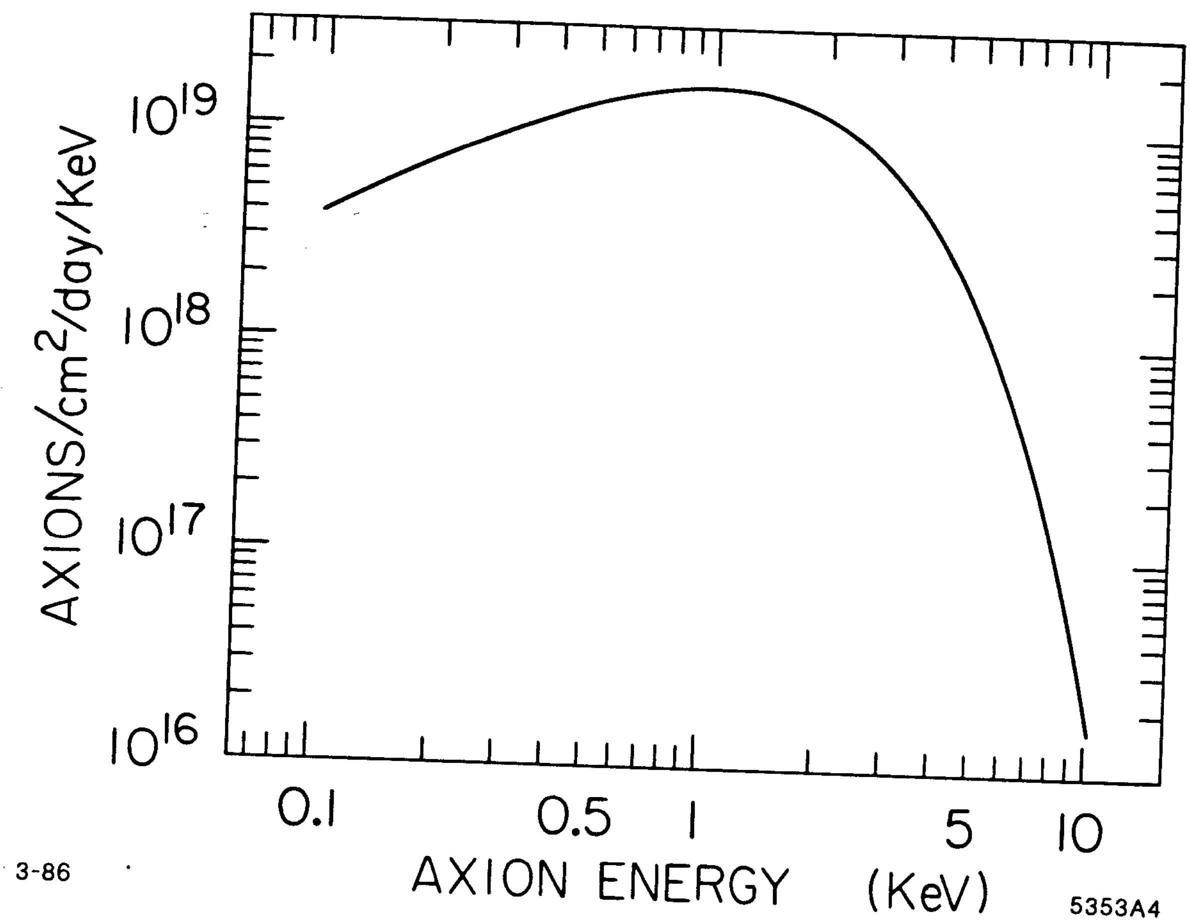
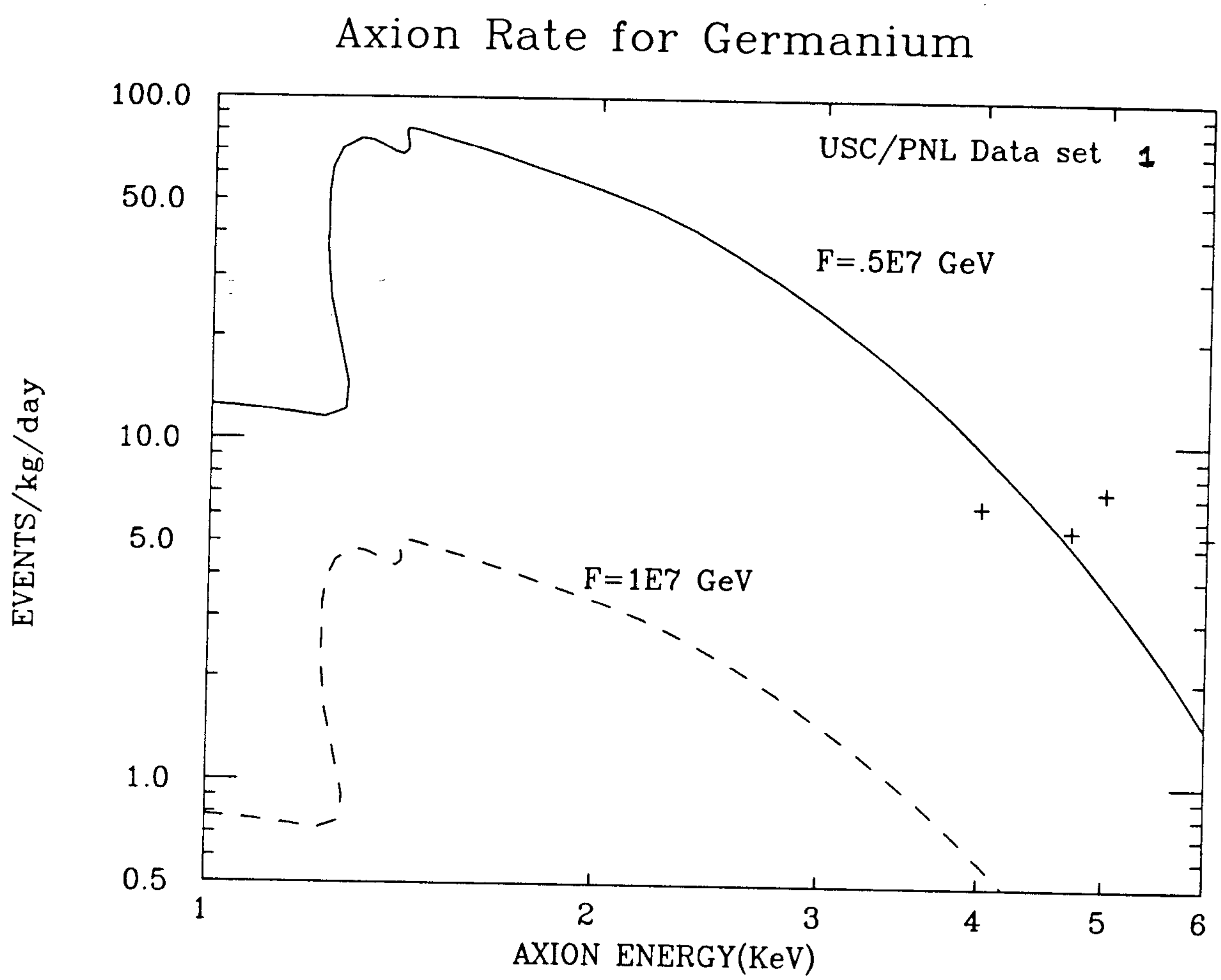
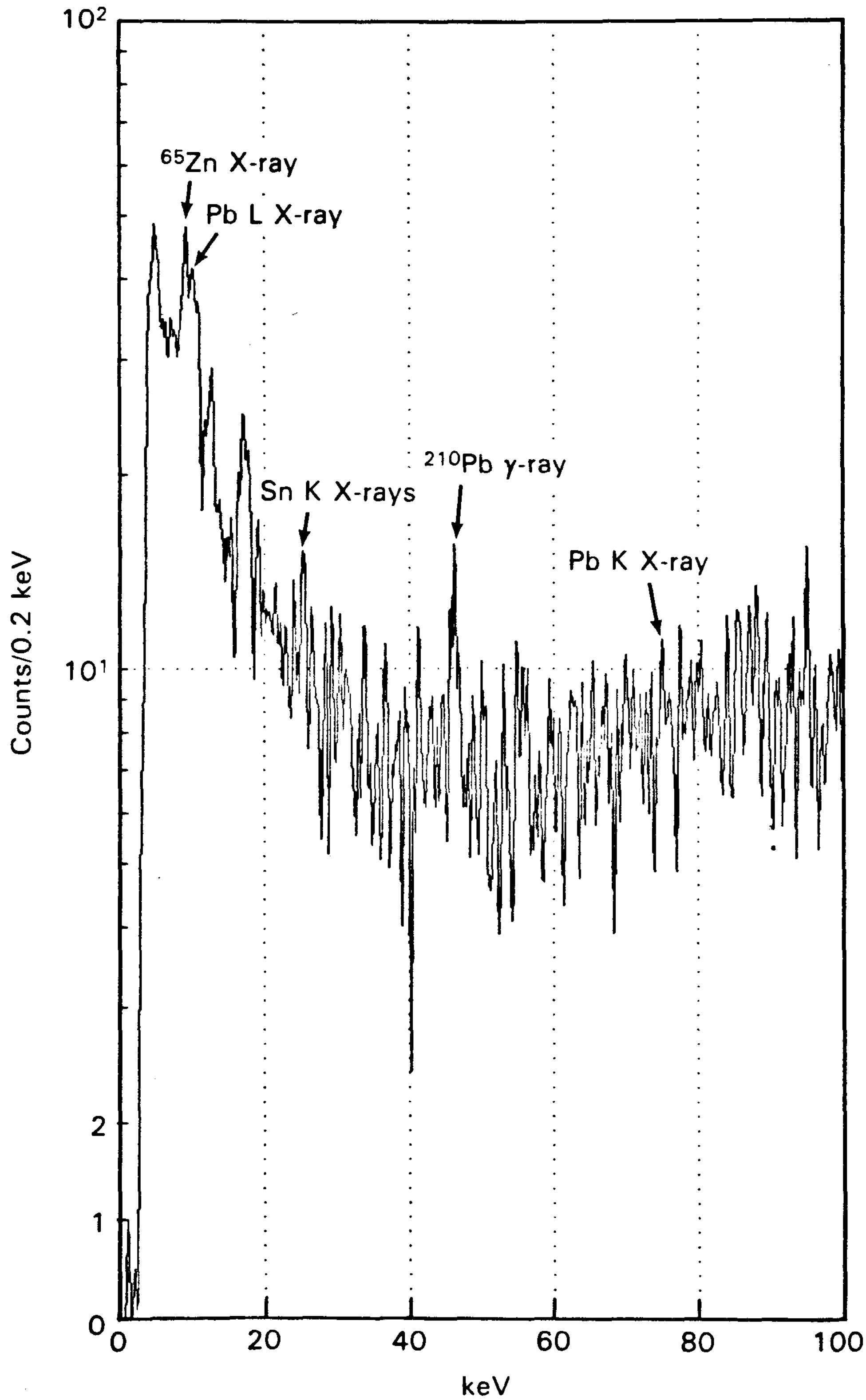

AXIONS/cm²/day/KeV
10^19
10^18
10^17
10^16
0.1
0.5
1
5
10
AXION ENERGY (KeV)
3-86
5353A4

Fig. 3



Axion Rate for Germanium
USC/PNL Data set 1
F=.5E7 GeV
F=1E7 GeV
EVENTS/kg/day
100.0
50.0
10.0
5.0
1.0
0.5
1
2
3
4
5
6
AXION ENERGY(KeV)

Fig. 4



^{65}Zn X-ray
Pb L X-ray
Sn K X-rays
^{210}Pb γ-ray
Pb K X-ray
Counts/0.2 keV
keV
10^2
10^1
2
1
0
0
20
40
60
80
100

Fig. 5