Early QCD theories predicted a particle with the quantum numbers of the η meson, but with a mass close to that of the pion. A term added to the QCD Lagrangian invariants in strong interactions and implied a neutron CP violation to vanish dynamically. Subsequently, Weinberg [3,4] and Wilczek [5] demonstrated that the Peccei-Quinn mechanism generated a Nambu-Goldstone boson, the axion, that couples to a charge via a virtual photon, producing an axion. Detection can occur by observing photons resulting from axions coupling to electrical charges via virtual photons.

The dense volume of photons and charges in the sun or any star produces conditions for axion production. The Ge detector then can act as the axion-photon converter and detector. When the characteristic wavelength of the axion satisfies a Bragg condition in the single crystal Ge detector, photon production would occur with an expected temporal pattern depending on the changing relative directions between the vectors from the solar core and the crystalline planes.

Extensive reviews of axion phenomenology and their effects on stellar evolution have been given by Raffelt [6,7] who gives a bound of $10^{-10}$ GeV$^{-1}$ on the coupling of axions to the two-photon vertex. The objective is to detect solar axions through their coherent Primakoff conversion into photons in the lattice of a germanium crystal when the incident angle satisfies the Bragg condition. The detection rates in various energy windows are correlated with the relative orientations of the detector and the sun [9].

This correlation results in a distinctive, unique signature of the axion. In this Letter, the results of a search using a 1 kg, ultralow background germanium detector installed in the HIPARSA iron mine in Sierra Grande, Argentina, at 41° 41' 24" S and 65° 22' W are presented. A description of the experimental setup and detector spectrum was given earlier by Di Gregorio et al. [10] and by Abriola et al. [11]. This experiment was motivated by papers by Buchmüller and Hoogeveen [12] and by Paschos and Zioutas [13]; the present technique was suggested by Zioutas and developed by Creswick et al. [9]. The original technique for searching for solar axions with magnetic helioscopes was presented by Sikivie [14].

Single Ge crystals are grown with an axis of symmetry along the (100) axis, but this detector was constructed originally for another purpose, so the (010) and (001) axes relative to the cryostat were not determined before assembly, as they should be in future experiments.

Therefore, to place a bound on the axion interaction rate, the data were analyzed for many azimuthal orientations of the crystal, and the weakest bound was selected.
The terrestrial energy spectrum and flux of axions from the sun can be approximated by the expression \[8,9\]:

\[
d\Phi = \lambda^{1/2} \Phi_0 \frac{(E/E_0)^3}{E_0(e^{E/E_0} - 1)},
\]

where \(\lambda = (g_{a\gamma} \times 10^8)^2\) and is dimensionless, \(E_0 = 1.103\) keV, and \(\Phi_0 = 5.95 \times 10^{14}\) cm\(^{-2}\)sec\(^{-1}\). The total flux for \(\lambda = 1\) integrated from 0 to 12 keV is \(3.54 \times 10^{15}\) cm\(^{-2}\)sec\(^{-1}\). The spectrum is a continuum peaking at about 4 keV decreasing to a negligible contribution above 8 keV. The differential cross section for Primakoff conversion on an atom with nuclear charge \(Z\) is \[9\]

\[
\frac{d\sigma}{d\Omega} = \frac{Z^2 \alpha \hbar^2 c^2 g_{a\gamma\gamma}^2}{16\pi} \frac{q^2(4k^2 - q^2)}{(q^2 + r_0^2)^2},
\]

where \(q\) is the momentum transfer, \(k\) is the momentum of the incoming axion, and \(r_0\) is the screening length of the atom in the lattice. For germanium, \(\sigma_0 = Z^2 \alpha \hbar^2 c^2 g_{a\gamma\gamma}^2 / 8\pi = 1.15 \times 10^{-44}\) cm\(^2\) when \(g_{a\gamma\gamma} = 10^{-8}\) GeV\(^{-1}\), or equivalently \(\lambda = 1\).

For light axions, the Primakoff process in a periodic lattice is coherent when the Bragg condition \((2d \sin \theta = n\lambda)\) is satisfied, or when \(\vec{q}\) transferred to the crystal is a reciprocal lattice vector \(\vec{G} = 2\pi(h,k,l)/a_0\). Here \(a_0\) is the size of the conventional cubic cell, and \(h, k,\) and \(l\) are integers \[15\].

It was shown that the rate of conversion of axions with energy \(E\) when the sun is in the direction \(\hat{k}\), \(\dot{N}(\hat{k}, E)\), can be written \[9\]

\[
\dot{N}(\hat{k}, E) = 2\hbar c v_c \frac{V}{\sqrt{G}} \sum_G \left| S(G) \right|^2 \frac{d\sigma}{d\Omega}(\vec{G}) \frac{1}{|G|^2} \frac{d\Phi}{dE} \delta E \delta \vec{G},
\]

where \(V\) is the volume of the crystal, \(v_c\) is the volume of a unit cell, \(S(G)\) is the structure function for germanium, and \(d\Phi/dE\) is evaluated at the axion energy of \(\hbar c |\vec{G}|^2 / 2k \cdot \vec{G}\). The structure function for germanium is

\[
S(G) = [1 + e^{i\pi(h+k+l)/2}] \times [1 + e^{i\pi(h+k)} + e^{i\pi(h+l)} + e^{i\pi(k+l)}].
\]

Note that in (3) the coherent conversion of axions occurs only for a particular axion energy given the position of the sun \(\hat{k}\) and reciprocal lattice vector \(\vec{G}\). However, the detector has a finite energy resolution; for the detector at Sierra Grande it is 1 keV FWHM at 10 keV. We take this into account by smoothing \(N(\hat{k}, E)\) with a Gaussian of the appropriate width. Finally, we take the relevant part of the energy spectrum, in this case from the threshold energy of 4 up to 8 keV (which is just below the x rays at 10 keV), and calculate the total rate of conversion in windows of width \(\Delta E\), typically 0.5 keV,

\[
R(\hat{k}, E) = 2\hbar c \frac{V}{\sqrt{G}} \sum_G \left| S(G) \right|^2 \frac{d\sigma}{d\Omega} \frac{1}{|G|^2} \frac{d\Phi}{dE} \frac{1}{2} \left[ \text{erf} \left( \frac{E - E_a(\hat{k}, \vec{G})}{\sqrt{2} \sigma} \right) - \text{erf} \left( \frac{E - E_a(\hat{k}, \vec{G}) - \Delta E}{\sqrt{2} \sigma} \right) \right],
\]

where \(E_a(h, k, l) = \hbar c |G|^2 / 2k \cdot \vec{G}\) and \(\text{erf}(x) = 2/\sqrt{\pi} \int e^{-t^2} dt\) is the error function. In Eq. (5) we have neglected the angular size of the core of the sun and the mass of the axion which is justified when \(m_a c^2\) is small compared to the core temperature of the sun \[12\], i.e., up to a few keV. In Eq. (5), \(\sigma\) is the width of the error function.

The theoretical axion detection rate for this detector, calculated with Eq. (5), is shown in Fig. 1. The position of the sun is computed at any instant in time using the U.S. Naval Observatory Subroutines (NOVAS) \[16\]. The pronounced variation in \(R(\hat{k}, E)\) as a function of time invites the data to be analyzed with the correlation function:

\[
\chi = \sum_{i=1}^{n} \left[ R(t_i, E) - \langle R(E) \rangle \right] n(t_i),
\]

where \(R(t_i, E)\) is the smooth shape of the theoretical rate at the instant of time, \(t_i, \langle R(E) \rangle\) is the average rate over a finite time interval, and \(n(t_i)\) is the number of events at \(t_i\) in a time interval \(\Delta t\), usually 0 or 1. The choice for the weighting function \(W(t, E) = R(\hat{k}(t), E) - \langle R(E) \rangle\) is motivated by the requirement that any constant background average to zero in \(\chi\), whereas a counting rate which follows \(R(\hat{k}(t), E)\) increases \(\chi\).

The number of counts at time \(t\) in the interval \(\Delta t\) is assumed to be due in part to axions and in part to background governed by a Poisson process with mean,

\[
\langle n(t) \rangle = [\lambda R(t, E) + b(E)] \Delta t,
\]

where \(b(E)\) is constant in time.

The average value of \(\chi\) is then

\[
\langle \chi \rangle = \sum_i W(t_i, E) [\lambda R(t_i, E) + b(E)] \Delta t.
\]
FIG. 1. A typical axion-photon conversion rate \( R(t, E) \) for various energy bands. The experimental energy resolution FWHM = 1.0 keV at 10 keV was used. The time scale is from 0.0 to 1.0 days for each graph. Here \( R(t, E) \) was calculated for \( g_{\alpha\gamma} = 10^{-8} \) GeV\(^{-1}\).

The expected uncertainty in \( \chi \), \( (\Delta \chi)^2 = \langle \chi^2 \rangle - \langle \chi \rangle^2 \), can be shown to be

\[
(\Delta \chi)^2 = \sum_i W^2(t_i, E) \left[ \langle n(t_i)^2 \rangle - \langle n(t_i) \rangle^2 \right],
\]

where the square bracket is \( \langle \Delta n(t_i) \rangle^2 \), which in Poisson statistics is \( \langle n(t_i) \rangle \). Accordingly,

\[
(\Delta \chi)^2 = \sum_i W^2(t_i, E) \langle n(t_i) \rangle.
\]

By (7) we have

\[
(\Delta \chi)^2 = \sum_i W^2(t_i, E) \left[ \lambda[R(t_i, E) - \langle R(E) \rangle] + \lambda\langle R(E) \rangle + b(E) \right] \Delta t,
\]

which in the limit \( \Delta t \to 0 \) becomes

\[
(\Delta \chi)^2 = \lambda \int_0^T W^3(t, E) dt + R_T(E) \int_0^T W^2(t, E) dt.
\]

The quantity \( R_T(t, E) \) is the average total counting rate, including both axion conversions and background.

The data are separately analyzed in energy bins, \( \Delta E_k \), fixed by the detector resolution (FWHM \(~\sim\) 1 keV in this case). The likelihood function is then constructed:

\[
L(\lambda) = \prod_k \exp \left[ \frac{-\left( \chi_k - \langle \chi_k \rangle \right)^2}{2(\Delta \chi_k)^2} \right].
\]

To an excellent approximation \( (\Delta \chi_k)^2 \) is dominated by the background.

As a test, typical results for the likelihood function for the cases \( \lambda = 0 \) (no axions) and \( \lambda = 0.003 \) were calculated for the DEMOS detector for one year. The correlation function analysis is sensitive to the presence

FIG. 2. Values of \( \lambda \) calculated from the 707 days of data as a function of the azimuthal angle \( \phi \). The error bars are 1\( \sigma \).
This work was supported by the U.S. National Science Foundation (INT930INT1522), the U.S. Department of Energy (DE-AC06-76RLO 1830), the Consejo Nacional de Investigaciones Científicas y Técnicas and Fundacion Antorchas de Argentina, and the Spanish Agency for Science and Technology (AEN96-1657). S. Nussinov would like to acknowledge a BSFG (Israel-U.S.A. Foundation grant). We also thank the personnel of the HIPARSA iron mine for assistance during the installation and J. A. Bangert of the U.S. Naval Observatory for supplying their vector astronomy subroutines.