EXPERIMENTAL CONSTRAINTS ON THE AXION DARK MATTER HALO DENSITY

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ABSTRACT

Most of the mass of the Milky Way is contributed by its halo, presumably in the form of noninteracting cold dark matter. The axion is a compelling cold dark matter candidate. We report results from a search that probes the local Galactic halo axion density using the Sikivie radio frequency cavity technique. Candidates over the frequency range 550 MHz $\leq f \leq$ 810 MHz (2.3 μeV $\leq m_a \leq$ 3.4 μeV) were investigated. The absence of a signal suggests that the axions of Kim and Shifman, Vainshtein, & Zakharov contribute no more than 0.45 GeV cm^{-3} of mass density to the local dark matter halo over this mass range.

Subject headings: dark matter — Galaxy: halo — instrumentation: detectors

1. INTRODUCTION

Measurements such as the BOOMERANG and MAXIMA cosmic microwave background radiation power spectra (de Bernardis et al. 2000; Hanany et al. 2000) and Type Ia supernovae data (Perlmutter et al. 1999; Reiss et al. 1998) suggest that dark matter makes up the bulk of the matter content in the universe. The agreement between expectations from big bang nucleosynthesis (Burles et al. 1999) and the primordial abundance of the lightest elements (Olive, Steigman, & Walker 2000) strongly constrains the total baryonic content to be a small value, implying that the majority of the dark matter must be nonbaryonic. The results of other diverse astrophysical measurements based on the Sunyaev-Zel'dovich effect (Grego et al. 2001), strong gravitational lensing (Cheng & Krauss 2000), and galactic flows (Zehavi & Dekel 1999) lend powerful support to this picture.

Although the nature of dark matter remains unknown, its gravitational effect is pronounced: much of the dynamics of spiral galaxies cannot be understood without there being a massive dark matter halo (Sofue & Rubin 2000). Two categories of particle cold dark matter (CDM) candidates have survived experimental and theoretical scrutiny over time: the lightest supersymmetric particle (Goldberg 1983; Ellis et al. 1984) and the axion (Weinberg 1978; Wilczek 1978). Neutrinos and other forms of hot dark matter are thought to contribute insignificantly to closure density and, in any case, cannot explain structure formation. Galaxy formation requires CDM, i.e., dark matter that is already nonrelativistic at the time of decoupling. Recently, experiments have begun with the sensitivity to either detect or exclude possible CDM halo candidates. In this Letter we present upper limits on the local axion halo density derived from a search for CDM axions.

2. AXION PHYSICS

The axion is the pseudo–Nambu-Goldstone boson (Weinberg 1978; Wilczek 1978) associated with a new spontaneously broken global $U_{\mathrm{PQ}}(1)$ symmetry invented to suppress strong charge-parity (CP) violation (Peccei & Quinn 1977). There is some model dependence in assigning $U_{\mathrm{PQ}}(1)$ charges to particles: in the Kim (1979) and Shifman, Vainshtein, & Zakharov (1980; hereafter KSVZ) scheme, the axion only couples to quarks at tree level, while in the grand unified theory–inspired Dine, Fischler, & Srednicki (1981) and Zhitnitsky (1980a, 1980b; hereafter DFSZ) model, it couples to both quarks and leptons. The axion acquires a mass that scales inversely with the (unknown) energy scale f_a at which the $U_{\mathrm{PQ}}(1)$ symmetry breaking occurs. Initially, f_a was presumed to be the electroweak energy scale, but such massive axions were quickly ruled out in, e.g., beam-dump experiments (Asano et al. 1981). Subsequently, it was proposed that axions possess such small couplings to matter and radiation that for all practical purposes they would remain forever "invisible." Shortly thereafter, an experiment was proposed that could make even very light axions detectable (Sikivie 1983, 1985). The US Axion Search experiment is predicated on this approach whereby the axion converts into a single photon via the inverse-Primakoff effect. We use a resonant cavity permeated by a strong static magnetic field, where the large number density of virtual photons from the field enhances axion decay.

The allowed axion mass is constrained to between 10^{-2} and 10^{-6} eV. Axions with a mass greater than 10^{-2} but less than a few electron volts would have cooled the core of supernova 1987a to such an extent that the distribution of neutrino arrival times would be inconsistent with observation (Turner 1988). Even heavier axions have been ruled out by a variety of astrophysical and terrestrial searches (Turner 1990; Raffelt 1990; Ressell 1991; Gnedin 1999). Conversely, if the axion mass is less than some value, they would have been overproduced in

the early universe. This lower mass limit has been calculated for various axion production mechanisms under different early-universe scenarios, e.g., "vacuum realignment" (Preskill, Wise, & Wilczek 1983; Abbott & Sikivie 1983; Dine & Fischler 1983), "string decay" (Battye & Shellard 1994; Yamaguchi, Kawasaki, & Yokoyama 1999; Hagmann, Chang, & Sikivie 2001), and "wall decay" (Chang, Hagmann, & Sikivie 1999). The vacuum misalignment mechanism provides a lower mass limit of $\sim 10^{-6}$ eV, which we adopt for our search strategy; the other mechanisms produce a value that is in fairly close agreement. Common to all of these mechanisms is the misalignment of the axion field with respect to the CP-conserving (minimum energy) direction when the axion mass turns on during the QCD phase transition. Axions produced in this way are very cold. Their typical momentum was on the order of the inverse of the horizon scale at the QCD phase transition ($p_a \sim 10^{-8}$ eV) when the temperature was on the order of 1 GeV. The cosmological energy density in these cold axions is on the order of (Kolb & Turner 1990)

$$\Omega_a \sim 0.5 \left(\frac{\mu\text{eV}}{m_a}\right)^{7/6}. \qquad (1)$$

Hence, if m_a is on the order of a few MeV, the mass range in which we search, axions contribute significantly to the energy density of the universe. Studies of large-scale structure formation support the view that the dominant fraction of matter is in the form of CDM. Since CDM necessarily contributes to galactic halos by falling into the gravitational wells of galaxies (halo axions in our Galaxy possess a virial velocity of $\sim 10^{-3}c$), there is excellent motivation to search for axions as constituents of our Galactic halo (Hagmann et al. 1998).

There is a substantial body of evidence that our own Galaxy is surrounded by a massive dark halo, although its exact properties are not well constrained (Zaritsky 1998; Alcock 2000). Of particular interest to this Letter is the local dark matter halo density, whose value depends on the degree of halo flattening as well as the core radii of the various dark matter components. To derive a reliable mass density, one can turn to parameterizations of the density distribution, rejecting distributions that fail to match observational constraints, such as reproducing the local rotation speed of 200–240 km s^{-1} (Gates, Gyuk, & Turner 1995). A key element of this approach is the use of microlensing data to estimate the fraction of local dark matter that is in the form of compact objects. Employing this methodology, one arrives at a halo density of $9.2^{+3.8}_{-3.1} \times 10^{-25}$ g cm^{-3}. If massive compact halo objects (MACHOs) comprise a negligible fraction of the local halo density, then the above number is likely an underestimate. The local halo density may also be enhanced because of our proximity to a possible dark matter caustic (Sikivie 1998). Our experimental analysis directly constrains the local density of the axionic component of the halo and as such is independent of astronomical observations and assumptions.

3. EXPERIMENTAL TECHNIQUE

The interaction between axions and photons can be written as

$$L = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}, \qquad (2)$$

where $g_{a\gamma\gamma}$ is the relevant coupling, a the axion field, and $\boldsymbol{E}$ and $\boldsymbol{B}$ the electric and magnetic fields, respectively. Since $g_{a\gamma\gamma}$ is very

small in the mass range of interest, the spontaneous decay lifetime of an axion to two real photons is vastly greater than the age of the universe. In our experiment, located at the Lawrence Livermore National Laboratory, a high-Q resonant cavity and superconducting magnet stimulate axion conversion into a single real photon. Resonant conversion occurs when the cavity resonant frequency equals the axion rest mass. Because this mass is a priori unknown, resonant frequencies are changed by moving either ceramic or metallic tuning rods from the wall to the center of the cavity. For a resonant cavity with a loaded quality factor Q_L, the axion-to-photon conversion power is

$$P = 4 \times 10^{-26} \text{ W } \frac{V}{0.22 \text{ m}^3} \left(\frac{B_0}{8.5T}\right)^2 C_{\text{nl}} \left(\frac{g_\gamma}{0.97}\right)^2 \frac{\rho_a}{0.5}$$

$$\times 10^{-24} \text{ g cm}^{-3} \frac{m_a}{2\pi(\text{GHz})} \min(Q_L, Q_a), \qquad (3)$$

where V is the cavity volume, B_0 the magnetic field strength, C_{nl} the mode-dependent cavity form factor, g_γ the reduced coupling constant (equal to $g_{a\gamma\gamma}\pi f_a/\alpha$), ρ_a the axion halo density, and $\min(Q_L, Q_a)$ the smaller of either the cavity or axion quality factors. Typical values for the first four parameters are 0.2 m^3, 7.5 T, 0.6, and 0.97, respectively. The copper cavity has a loaded (critically coupled) $Q_L \sim 10^5$, whereas Q_a, the ratio of the energy to the energy dispersion of the axion, is a factor of 10 or so larger over the present frequency range. The total power that results from equation (3) is on the order of $\sim 10^{-22}$ W; our cavity and amplifiers are cooled to a few degrees kelvin to minimize thermal noise. Figure 1 is a schematic of the axion receiver chain. A microwave signal centered at the cavity resonant frequency and approximately 30 kHz wide is coupled out of the cavity by an electric field probe and subsequently mixed down (in two stages) to near audio frequencies. At any given frequency, 10^4 spectra are averaged by fast Fourier transform (FFT) hardware, with each spectrum sampled for 8 ms. The corresponding Nyquist resolution of 125 Hz is well matched to the width (~ 750 Hz) of axions thermalized by interactions with the galactic gravitational potential.

The Dicke radiometer equation (Dicke et al. 1946) dictates the integration time necessary to achieve a specified signal-to-noise ratio

$$\text{S/N} = \frac{P}{T_n} \sqrt{\frac{t}{B}}, \qquad (4)$$

where P is the axion power from equation (3) (times a factor that accounts for the external coupling), T_n is the noise temperature, t is the integration time, and B is the axion bandwidth (defined as f/Q_a). Since the desired S/N is not attained in a single pass over a given frequency interval, data in a single-frequency bin are the result of combined data from numerous overlapping spectra. The S/N for this multiple-pass data in the interval 550 MHz $\leq f \leq$ 810 MHz is shown in Figure 2. A second data set was formed by co-adding six neighboring bins into single 750 Hz bins suitable for the virialized axion signal. To determine the number of candidate peaks that must be rescanned to obtain an overall confidence limit of $\geq 90\%$, artificial peaks are injected into the data via software. As the cut threshold is lowered, the number of candidate peaks increases rapidly. A typical cut threshold of 2.3 σ (six bin) applied to our data yields numerous candidates that are rescanned to an S/N commensurate with the original data. These data are subsequently
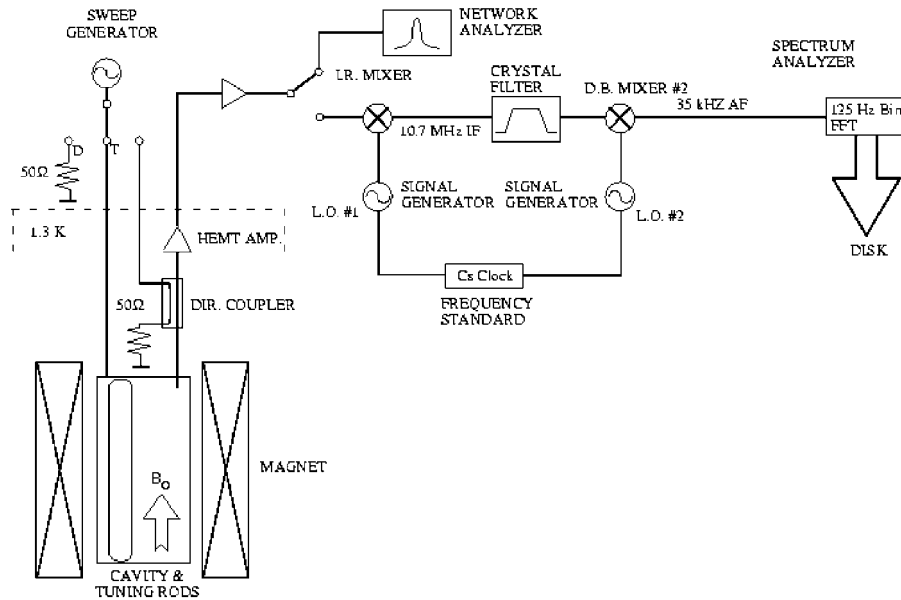
Fig. 1.—Axion receiver chain

added to the original data, and from these combined data sets a reduced set of candidates is generated and scanned at the corresponding frequencies. A final round of data combining produces a persistent candidate list. Candidates above a threshold of 3.5 σ in these data are manually inspected. A detailed description of the experiment and analyses may be found in Peng et al. (2000) and Asztalos et al. (2001).

4. RESULTS

We have examined these data for candidates in each of 2.08×10^6 125 and 750 Hz bins in the region 550 MHz $\leq$ $f \leq$ 810 MHz. A total of 13,712, 1369, and 34 candidates survived each stage of six-bin data cuts, respectively. All 34 persistent candidates have been identified with strong external radio peaks. To derive an upper limit on the axion contribution to the local halo density, we fix the axion-to-photon coupling $g_{a\gamma\gamma}$ at the KSVZ level and invert equation (3) to calculate ρ_a as a function power deposited in the cavity and axion mass. The

absence of a persistent signal in these data over this range permits us to impose the limits shown in Figure 3, where we plot the excluded axion dark matter halo densities for both KSVZ (*lower histogram*) and DFSZ (*upper histogram*) axions as a function of axion mass and frequency over the interval 550 MHz $\leq f \leq$ 810 MHz. The small variations in these density limits represent effective integration times somewhat longer or shorter than that prescribed by equation (4). The nominal excluded mass density lies near 0.45 GeV cm^{-3} for KSVZ axions and 3.0 GeV cm^{-3} for DFSZ axions. The former is comparable to the best estimate of the local dark matter halo density.

5. CONCLUSIONS

There is abundant evidence that our own Galaxy, like other spiral galaxies, contains a vast dark matter halo. Observation
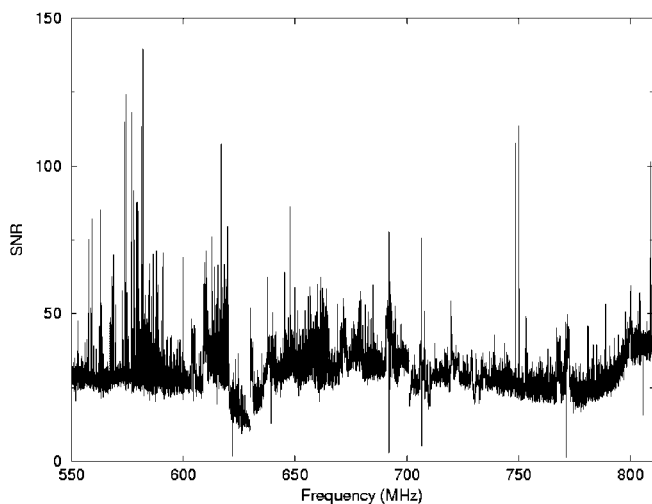

Fig. 2.—S/N for the complete six-bin combined data set. The minimum target S/N ratio for these data is 10.
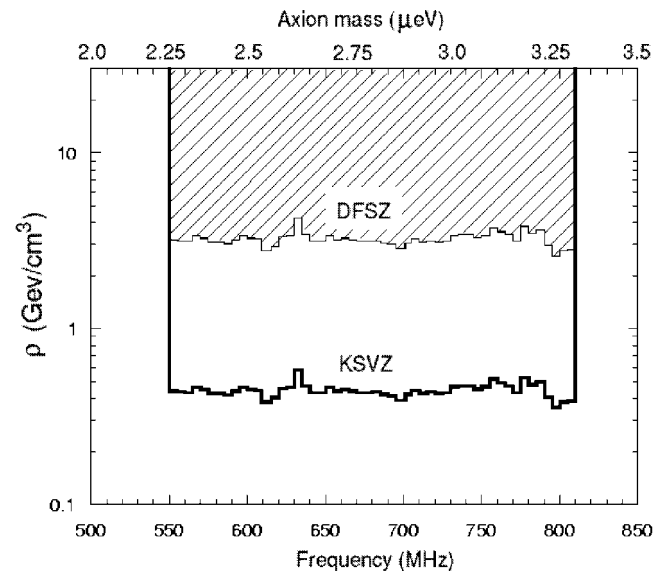

Fig. 3.—Excluded axion dark matter halo densities as a function of mass and frequency for both KSVZ (*lower histogram*) and DFSZ (*upper histogram*) axions.

can neither differentiate the various candidates, nor well constrain other parameters that describe the halo, e.g., the local dark matter density. Since 1995 we have been using a single resonant cavity to search for axions that may constitute the local dark matter halo over the frequency interval 550 MHz $\leq f \leq$ 810 MHz. The lack of a persistent signal allows us to exclude the axion from contributing more than 0.45 GeV cm^{-3} to the halo dark matter mass density over the mass range of 2.3×10 eV$^{-6} \leq m_a \leq 3.4 \times 10^{-6}$ eV, should axions couple only to hadrons according to the KSVZ prescription, with 90% confidence. This restriction is relaxed to around 3.0 GeV cm^{-3} in the DFSZ model, also with 90% confidence. It should be noted that other KSVZ- and DFSZ-like implementations exist. Some of these models (including some DFSZ-like models) give rise to coupling constants that are larger than the benchmark KSVZ $g_{a\gamma\gamma}$ used in this Letter (Kim 1998). These, too, are ruled out by our results over the mass range quoted above.

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