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Abstract

A proposed experiment is described to search for dark-matter axions in the mass range 0.6-16 μeV. The method is based on the Primakoff conversion of axions into monochromatic microwave photons inside a tunable microwave cavity in a large volume high field magnet. This proposal capitalized on the availability of two Axicell magnets from the MFTF-B fusion machine at LLNL. Assuming a local dark-matter density in axions of $\rho_a = 0.3$ GeV/cm^3, the axion would be found or ruled out at the 97% c.l. in the above mass range in 48 months.

I. INTRODUCTION

The axion[1,2] was first postulated as an elegant solution to the strong CP problem. The strong CP problem can be stated as the paradox which arises between the apparent lack of P and CP violation in the strong interaction in QCD (experimentally manifested as an immeasurably small neutron electric dipole moment) and P and CP violation in the weak interaction in QCD (in particular, $K_L \rightarrow 2\pi$). The mass of this axion and all its couplings to matter and radiation are proportional to f_a^{-1} (f_a is the Peccei-Quinn symmetry breaking scale). Many experiments[2] were originally performed based upon predictions that f_a was ~250 GeV. However, these experiments and arguments based on stellar evolution constrain the mass of the axion to be less than 10^{-3} eV. It has long been thought that axions in this mass range could be the dark matter which was produced in the early universe. However, it was assumed that their extraordinarily weak couplings would render them nearly invisible until Sikivie[3] proposed that axions may be converted to microwave photons in a high-Q tunable microwave cavity in a sufficiently strong magnetic field. (Although we will give a brief description of this technique here, more details may be found elsewhere.[4]) It is generally argued that ~90% of the matter in the universe is non-luminous and that if this dark matter is in the form of relic axions, then the closure density would confine m_a >10 μeV (within an order of magnitude). Two reviews of the status of the axion have recently appeared[5,6] which give much greater detail.

In this paper we describe a proposal to search for axions as suggested by Sikivie.[3] Essentially we intend to build a large scale-up of two pilot experiments (Rochester/BNL/FNAL[7] and the University of Florida[8]). In this method, the condition for axion-photon conversion is $h\nu = m_a c^2$ (ν = 115 MHz/r (m) for the TM_{010} mode optimal for the experiment), and the power on resonance is

$$P = \left(\frac{\alpha}{\pi} g_\gamma \frac{1}{f_A}\right)^2 V B_z^2 \rho_a C \frac{1}{m_a} \mathrm{Min}(Q_L, Q_a). \qquad (1)$$

Here f_A is the PQ-symmetry breaking scale, g_γ the axion-photon coupling, V the active volume of the experiment, B_z the magnetic field parallel to the cavity axis, C the form-factor of the mode (0.69 for TM_{010}), and m_a the axion mass. The Q_L is the loaded quality factor of the cavity (of order 10^5) and $Q_a \sim 10^6$ the ratio of the mass to energy spread of the galactic axions.

II. DESCRIPTION OF THE DETECTOR

As previously mentioned, the proposed experiment is a fairly straightforward scale-up of two pilot efforts (Rochester/BNL/FNAL,[7] and the University of Florida (UF)[8,9]), the discussion of which does not need to be reproduced here. It is clear that the power sensitivity of the pilot experiments, in the mass range which has been measured, falls short of the expected signal by approximately 10^3. The Florida experiment for example had a sensitive volume of 0.008 m^3 and an average field of 7.5 T, and thus $B^2V = 0.45\ T^2m^3$. The principal advantage of the proposed experiment will be a very much larger magnetic volume. This larger magnetic volume has become possible because of the availability of two Axicell magnets from the decommissioned MFTF-B at Livermore placed flush against one another.

The Axicell magnets consist of Nb-Ti conductor, layer wound on an iron spool-piece, of almost 2000 turns each. The design operating current is 4238 A, or 8.37×10^6 Amp-turns per magnet. Each Axicell magnet has a clear-bore diameter of 1.34 m and is 1.14 m in depth. The total inductance of the pair is 15 Henries, and the total stored energy is 160 MJ at operating current.

The magnets will be mounted in a tank (also surplus from the MFTF-B program, a neutral beam injector vessel) with a re-entrant well separating the vacua for the magnets and the copper cavities (Figure 1). This will allow entry and work of short duration on the cavities without breaking vacuum or thermally cycling the magnets. Between the inner radius of the magnet and the cavity packages is a thin annular 1.7K refrigerator and shield (Figure 2). The coil leads will be modified to work in persistent mode with the switch in the lead stack (Figure 3). The cooling will be performed by a helium refrigerator next to the experiment, utilizing a nearby facility to purify, compress and return the boil-off He. The available volume for the microwave cavities is 2.7 m^3, and the r.m.s. value for B_z is 7 T. The major improvement in this experiment over previous experiments is the increase of $B_z{}^2V$ by approximately 300.

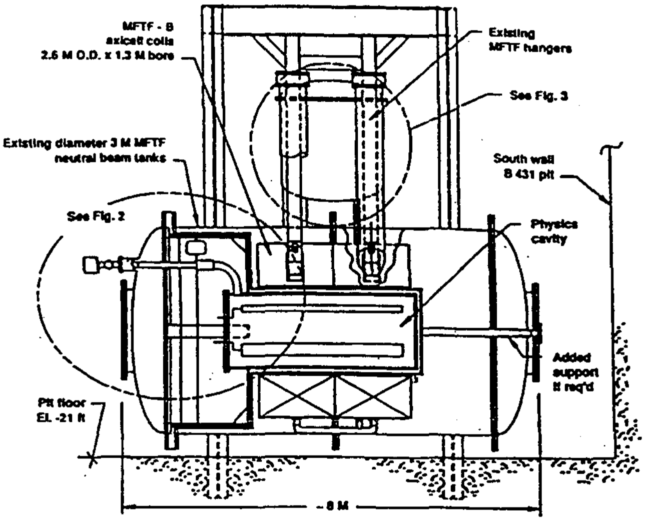

Fig. 1. Conceptual design of the axion experiment vessel, showing the magnets, current leads, re-entrant well, microwave cavity, and couplings between the outside world and the cavity. Note the vacuum partition between the magnet and the cavity environments.

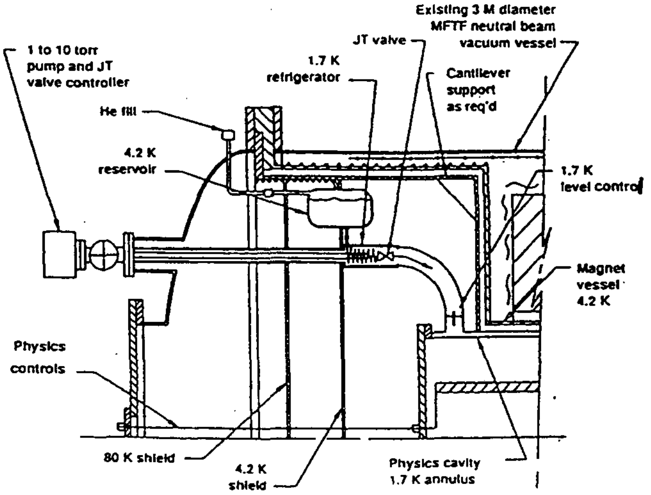

Fig. 2. Detail of the refrigerator used for cooling the cavity and cryogenic amplifier.

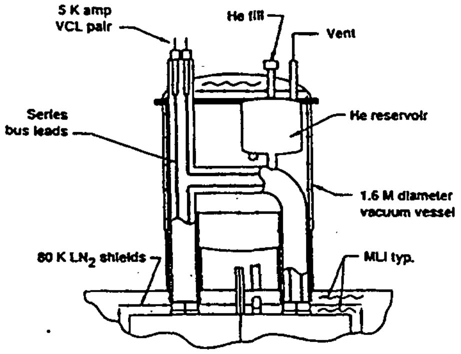

Fig. 3. Detail of the current leads and He reservoir tank located above the main tank.

It must be remembered that the diameter of the magnetic volume limits the maximum diameter of a single cavity that may be placed inside and thus the lowest end of the frequency range that may be searched. As $h\nu = mc^2$, the mass range that can be covered is limited by the geometry of the cavities that can be fabricated and inserted into the magnet. (A frequency of 1 GHz corresponds to 4.126 μeV, etc.) Cavities may be tuned downward 20% or upward 30% or so by radial displacement of a dielectric rod or metal post, respectively, without too great a loss in C^2Q.[9] As in the RBF and UF experiments, the cavities must be made of OFHC copper for optimum Q. Furthermore adequate care must be taken in the uniformity of their cross-section to avoid mode localization.[9] The cavities could, of course, be manufactured from solid copper. However, the necessarily thick tubes required to minimize the gravitational sag also would make the cavity system extremely heavy. We are thus investigating the possibility of copper coating both stainless steel and ceramics. The former cavity concept has recently been checked (manufactured at LBL, tested at UF). The measured Q at 4.2 K is much lower than that of the theoretical value if one assumes that we are in the anomalous skin thickness regime. The ceramic option is a solution being tested by the INR, Moscow. They also intend to construct the final cavity sets.

In order to cover a continuous range in masses from 0.6–16 μeV (148–3900 MHz), nine arrays of cavities are planned. All but the first involve multiple cavities whose outputs are combined through standard power splitter/dividers into a single output. Power splitters/combiners combine the outputs of the cavities without introducing cross-coupling between them. (The nature of the power splitter/dividers available requires that the number of cavities be 2^n.) The first three use essentially the entire available magnetic volume, and are built on a right circular cylinder: (1) undivided; (2) divided into 2 cells of semicircular cross-section; and (3) divided into 4 cells of quarter-circular cross-section. The frequencies of the TM_{010} modes for a semicircular cross-sectional cell, and a quarter-circular cross-sectional cell are $f' = 1.56f$, and $f'' = 2.1f$ respectively, where f is that for the cylinder without partition (see Figure 4). The fourth set is built upon 8 cylinders—7 cylinders surrounding 1 in the center, each of radius $r = 0.30R$, where R is the full radius of the available magnetic volume. We subsequently will subdivide these eight cavities as in the case of the single large cavity but here, however, it becomes necessary to longitudinally segment the cells to minimize problems associated with unfavorable aspect ratios (length/radius).[9]

These six cavity arrays will constitute the Phase I part of this experiment. As can be seen in Table I, this will yield a tuning range of 148–1350 MHz or an axion mass range of 0.6–5.6 μeV.

The axion mass range from 5.6–16 μeV will be searched for in Phase II of this experiment. The exact design of the cavities will not be determined until we begin to assimilate

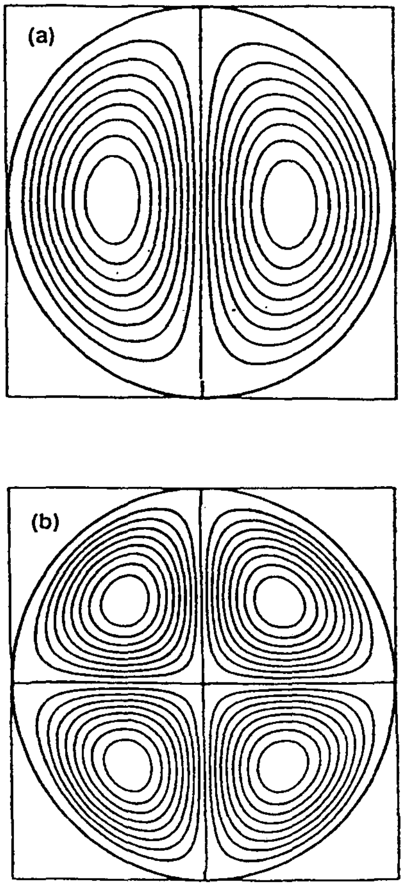

Fig. 4. Contours of the TM_{010} mode electric field strength for the cases of (a) semicircular cross-section cavities, and (b) quarter-circular cross-section cavities, made by longitudinal partitioning of a right circular cylindrical cavity.

Table I. Parameters of the nine cavity arrays proposed.

Number of cavities	Arrangement	*r*/*R*	Packing fraction	Frequency MHz	Tuning Range MHz
1	O	1	1	180	148-233
2	⊖	1	1	281	233-325
4	⊕	1	1	378	325-488
8	O × 8 × 2	0.30	0.73	595	488-770
16	⊖ × 8 × 2	0.30	0.73	928	770-1070
32	⊕ × 8 × 2	0.30	0.73	1250	1070-1350

experience from Phase I. However, it is clear that all higher numbers of cavities will require some form of longitudinal segmentation. In addition to making the translational symmetry requirement easier to fulfill (to avoid mode localization), longitudinal segmentation relieves the problem of mode-crowding. It is desirable to minimize the number of crossings of intruder TE modes through the TM_{010} mode. Whenever this happens, mode-mixing occurs and a notch in the tuning range is lost. In order to keep the total lost tuning range to <1%, we choose two-fold segmentation for arrays (4), (5) and (6). With these arrays, and use of dielectric and metal tuning rods, it is possible to cover the proposed mass range continuously (Table I).

Power combining of multiple cells involves some care. Prior to each data collection run, one cell (the master) must first be stepped in frequency, and the others (slaves) must be tuned in turn to the frequency of the first. Also it is important that the signal cables of all the cells to the power combiner be of the same length, and the coupling Q_h and the central frequencies of all the cells be nearly the same, in order to avoid power reflection at the combiner. Combining of two cells at 300K has been demonstrated by Hagmann.[10] We will learn how to handle the practical problems that may arise as one starts from low-order arrays to progressively higher order (and presumably more challenging) arrays, as we proceed.

III. SEARCH RATE

The power on resonance from the conversion of axions to photons in the TM_{n10} mode is given in equation (1) which can be rewritten conveniently in terms of benchmark values for all parameters as follows

$$P_{nl} = 3\times10^{-26}\ \text{Watt}\left(\frac{V}{3\ \text{m}^3}\right)\left(\frac{B_z}{7\ \text{Tesla}}\right)^2 C_{nl}\left(\frac{g_\gamma}{0.36}\right)^2 \cdot$$

$$\cdot\left(\frac{\rho_a}{5\times10^{-25}\ \text{g/cm}^3}\right)\left(\frac{m_a}{2\pi(1\text{GHz})}\right)\text{Min}(Q_L,Q_a)\,. \qquad (2)$$

The benchmark value for the axion-photon coupling, $g_\gamma = 0.36$ applies to the simplest axion models, for example that of Dine, Fischler, Srednicki and Zhitnitskii (DFSZ).[11] In other models, g_γ can be larger or even smaller.

The search rate (df/dt) involves not only the expected conversion power, but also on the total noise (the sum of the physical temperature of the cavity and the noise temperature of the microwave receiver), the desired signal-to-noise ratio, s/n, and the cavity Q. The search rate is given by

$$\frac{df}{dt} = \frac{55\ \text{GHz}}{\text{year}}\left(\frac{4}{s/n}\right)^2\left(\frac{V}{3\ \text{m}^3}\right)^2\left(\frac{B_z}{7\ \text{Tesla}}\right)^4\left(\frac{g_\gamma}{0.36}\right)^4 \cdot$$

$$\cdot\, C^2\left(\frac{\rho_a}{5\times10^{-25}\ \text{g/cm}^3}\right)\left(\frac{5K}{T_n}\right)^2\left(\frac{f}{1\ \text{GHz}}\right)^2\left(\frac{Q_w}{Q_a}\right). \qquad (3)$$

The dependence on Q_w is particular to the case of $Q_w < 3Q_a$, which will always pertain in the present experiment. Here Q_w (w = "wall") is the quality factor that would be achieved if absorption in the walls were the only mechanism for removing energy from the cavity. The other contribution is due to the output coupler, Q_h (h = "hole"), and the loaded Q of the cavity, Q_L is given by $Q_L^{-1} = Q_w^{-1} + Q_h^{-1}$. In the limit where $Q_w < 3Q_a$, the search rate is maximized by the choice of $Q_h = Q_w/2$. The intrinsic cavity quality factors have been calculated for oxygen-free high conductivity copper in the anomalous skin-depth limit.

The cavity bandwidth exceeds the anticipated width of the axion spectrum ($\sim v^2/c^2$) mc^2 throughout the search range by characteristically an order of magnitude or more. Thus at each central frequency, the power spectrum emitted by the cavity will be measured (using fast Fourier transform techniques). This power spectrum will be collected in bins of width approximating the expected width of the axion line. Each spectrum will be searched for 2σ peaks in single bins and combinations of neighboring bins. If a 2σ peak is found, another set of spectra will be taken and averaged with the first. If the peak remains statistically significant this process will be repeated up to a maximum of 5 times, after which the peak will be flagged for later investigation. The total search rate therefore must take into account the rescan frequency (80% of the spectra are expected to have positive peaks exceeding 2σ and will be repeated at least once), and further the degree to which adjacent spectra are overlapped. A more explicit rendering of eqn. (3) is given below, assuming the DFSZ value of g_γ, a local halo density of 5×10^{-25} g/cm^3 (assumed to be entirely axionic), $Q_a = 10^6$, and a volume of 2.8 m^3 available for the cavities

$$\frac{1}{f}\frac{df}{dt} = \frac{4.9\%}{\text{week}}\left(\frac{4}{s/n}\right)^2\left(\frac{B_z}{7\ \text{Tesla}}\right)^4 P^2C^2\left(\frac{5\ K}{T_n}\right)^2$$

$$\left(\frac{f}{1\ \text{GHz}}\right)\left(\frac{Q_w}{10^5}\right)\left(\frac{1}{N_{rescan}}\right)\left(\frac{\Delta f}{\delta f}\right). \qquad (4)$$

In eqn. (4), P is the packing fraction of cavities in the volume, N_{rescan} is the average number of times a given region is rescanned on account of persistent 2σ peaks, Δf is the frequency interval between successive spectra, and $\delta f = f/Q_L$ is the cavity bandwidth. The overlapping of adjacent spectra will be approximately 20%. Table II presents the tuning ranges, expected total noise temperature, quality factors, fractional search rate and total run time for each cavity array. The total time for the experimental program will also include some down time, both for changing of cavity arrays, and also for the tuning of multicavity arrays prior to each run. The scan rate is between 1.3 and 2.1% per week. To achieve a signal-to-noise ratio of 4 for DFSZ axion in Phase I, the total run time would be under 3 years. If (s/n) were to be raised to 5, the time would be 4.5 years; if reduced to 3, it would be 1.5 years.

Table II. Search rate of the proposed experiment. Rate and time estimates were made under the condition that a DFSZ axion would be seen with (s/n) = 4, and presumes the intrinsic cavity quality factors and effective total noise temperatures as shown.

Number of cavities	Arrangement	Tuning Range MHz	T_n K	Q_W	$\frac{1}{f}\frac{df}{dt}$ %/wk	Time weeks
1	O	148-233	6	530000	1.3	36
2	⊖	233-325	6	370000	1.4	23
4	⊕	325-488	6	300000	1.9	24
8	O × 8 × 2	488-770	5	280000	1.8	27
16	⊖ × 8 × 2	770-1070	5	190000	1.9	17
32	⊕ × 8 × 2	1070-1350	5	160000	2.1	11

IV. SUMMARY OF THE PROPOSED EXPERIMENT

The scope of the proposed experimental search is shown in Figure 5. The ordinate is in $g_{a\gamma\gamma}^2$, where

$$g_{a\gamma\gamma} = \left(\frac{\alpha}{4\pi} g_\gamma \frac{1}{f_A}\right).$$

Shown also are results from the Rochester-Brookhaven-Fermilab, and University of Florida pilot experiments, as well as the DFSZ and KSVZ[12] model predictions between the mass coupling. We propose to cover the region between 0.6 and 16 μeV, with a s/n = 4 in two phases.

One of the fundamental decisions for Phase II and possibly even an extension to higher frequencies (and thus larger masses) which must be made is whether to use a stronger magnetic field (lower volume) or to use even more cavities. As this implies cavities of yet smaller radii, it may be unwieldy to couple this large number in the same volume. At this point we must consider the use of Axicell insert coils to boost the field to a value of about 100 cm. The overall loss in B^2V of about a factor of 8 would be compensated for in the simplicity of dealing with many fewer cavities.

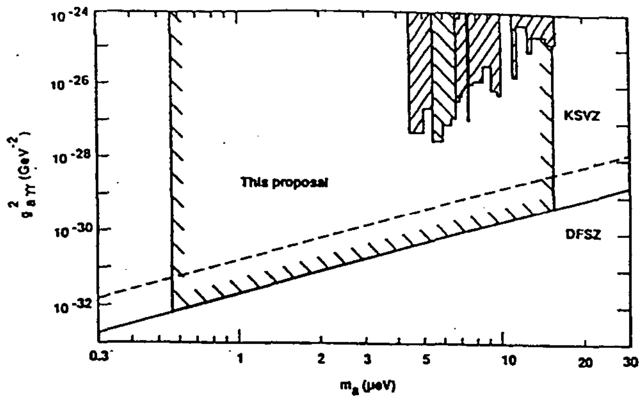

Fig. 5. Experimental limits on the electromagnetic coupling $g_{a\gamma\gamma}$ of the axion. Values in the shaded areas at upper right have been excluded by the RBF and UF searches. Values equal to or greater than the DFSZ limit for an axion mass between 0.6 and 16 μeV would be ruled out by this experiment.

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