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SEARCH FOR PSEUDOSCALAR COLD DARK MATTER

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Proposal (New) for Physics Exploratory Research in the Disciplines

SEARCH FOR PSEUDOSCALAR COLD DARK MATTER

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LLNL Collaborators:

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Institute for Nuclear Research of the Russian Academy of Sciences
Massachusetts Institute of Technology
University of Chicago
Fermi National Accelerator Laboratory
Lawrence Berkeley Laboratory
University of California Berkeley
Stanford Linear Accelerator Center
Wang NMR, Inc.

May 29, 1992

MASTER

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SEARCH FOR PSEUDOSCALAR COLD DARK MATTER

May 29, 1992

Abstract

All dynamical evidence points to the conclusion that the predominant form of matter in the universe is in a non-luminous form. Furthermore, large scale deviations from uniform Hubble flow, and the recent COBE reports of inhomogeneities in the cosmic microwave background strongly suggest that we live in an exactly closed universe. If this is true, then ordinary baryonic matter could only be a minority component (10% at most) of the missing mass, and that what constitutes the majority of the 'dark matter' must involve new physics, e.g. a previously undiscovered elementary particle, massive neutrinos, etc. The axion, a light pseudoscalar particle, is one of very few well-motivated candidates which may comprise the dark matter. Additionally it is a 'cold' dark-matter candidate, i.e. non-relativistic from the time of the early universe, which is preferred by the COBE data. We propose to construct and operate an experiment to search for axions which may constitute the dark matter of our own galaxy. This would be the first axion search with cosmologically significant sensitivity, and at present we have no competition in the world. As proposed by Sikivie (1983), dark-matter axions may be detected by their stimulated conversion into monochromatic microwave photons in a tunable high-Q cavity inside a strong magnetic field. Our ability to mount an experiment quickly and take data within one year is due to a confluence of three factors. The first is the availability of a compact high field superconducting magnet (the NASA SUMMA coils), and a local industrial partner, Wang NMR, who can make a very thermally efficient and economical cryostat for it. The second is an ongoing joint venture with the Institute for Nuclear Research of the Russian Academy of Sciences to do R&D on metalized precision-formed ceramic microwave cavities for the axion search, and INR has committed to providing all the microwave cavity arrays for this experiment, should this proposal be approved. The third is a commitment of very substantial startup capital monies from MIT for all of the state-of-the-art ultra-low noise microwave electronics, to one of our outstanding young collaborators who is joining their faculty. The first year's activities, for which our budget request is \$300K operating monies and \$50K capital, consists of construction and testing of all three basic components of the detector. The actual experimental search begins at the outset of the second year, with each of the five cavity arrays requiring approximately six months of operation to cover the proposed mass range.

Introduction

It is now virtually certain that at least 90% and perhaps even 99% of the mass of the universe is in a non-luminous form. The evidence for this 'dark matter' is based on very fundamental dynamical grounds, i.e. rotation curves of galaxies, virial velocities of clusters of galaxies, and large-scale peculiar motion (deviations from uniform Hubble expansion). Evidence is mounting, but is somewhat less firm, that we live in an exactly closed universe ($\Omega = \rho/\rho_{\text{crit}} = 1$). What constitutes the dark matter is one of the outstanding scientific questions of our time. Based on calculations of primordial nucleosynthesis and the present observed isotopic abundances of light species, it is now generally agreed that ordinary baryonic matter (luminous or not) could not account for more than 10% of closure density, and thus if $\Omega > 0.1$ by any appreciable amount, this would necessarily imply that a component of the dark matter involves new physics -- a previously undiscovered elementary particle, massive neutrinos, etc.

The announcement by the COBE collaboration last month of the observation of primordial fluctuations in the cosmic microwave background (and thus density fluctuations in the early universe) is of milestone significance in experimental cosmology [1-3]. The spectrum of fluctuations -- a few parts in 10^6 -- strongly support the hypothesis of an inflationary epoch during the big bang, which if true enforces $\Omega = 1$ rigorously. Furthermore, the data prefer models where most if not all of the dark matter is non-relativistic, or 'cold dark matter' (CDM), rather than 'hot dark matter' such as massive neutrinos. These weak density perturbations grew, and seeded rapid galaxy formation which we know occurred well within a billion years after the big bang. The gravitational infall also resulted in the dark matter halos we infer observationally around all galaxies, including our own. (The present value for the critical density of the universe is about $\rho_{\text{crit}} \sim 5 \text{ keV}/\text{cm}^3$, which of course represents the required density averaged over the whole universe. Our local dark-matter density, best-fit to our own galactic rotation curve, is approximately $\rho_{\text{halo}} \sim 300 \text{ MeV}/\text{cm}^3$.)

The axion, a light pseudoscalar particle, is one of the two most attractive cold dark-matter candidates (the other being weakly interacting massive particles). It is doubly compelling in that it was originally predicted to exist in the late 70's [4-6] as a consequence of the most minimal and elegant extension of the Standard Model to explain the strong-CP problem in QCD. Present laboratory, astrophysical and cosmological bounds limit the mass of the axion to be within 10^{-6} and 10^{-3} eV . The axion has two significant features relevant to experimental searches for it. The first is that its interaction with matter and radiation is proportional to its mass, and thus axions within the presently allowed window were long thought to be undetectable. The second is that the mechanism by which they would have created in the early universe (as a cold Bose-Einstein condensate) implies that the total mass of axions in the universe is *inversely* proportional to its mass, and thus axions of less than $1 \mu\text{eV}$ would have led to an overclosure problem.

In 1983 Pierre Sikivie of the University of Florida showed that contrary to current wisdom, dark-matter axions were not so 'invisible', and in fact they could be stimulated to convert into a monochromatic microwave signal, in a high- Q microwave cavity within a strong magnetic field [7]. Two small pilot experiments, one at Florida and one

at Brookhaven, were performed but only in a narrow mass range and fell far short (10-1000) in the power sensitivity expected to detect dark-matter axions [8-9].

We propose to construct and operate the first experiment that would be sensitive within the expected range of axion-photon couplings, for the most important decade in axion mass ($\sim 1\text{-}10\text{ }\mu\text{eV}$). This is a *new* proposal, which seeks to actually carry out an experimental search. A feasibility, engineering & design study was funded at a low level by a previous LDRD award. However, this previous study has significantly refocussed our thinking on how to proceed (which initially involved the massive Axicell magnets from the MFTF-B). We now have an optimized and economical design, and have brought together a very strong collaboration with commitments for contributions of major pieces of experimental hardware.

The axion experiment consists of three elements. The first is a superconducting solenoidal magnet where the figure of merit is B^2V . The second is a series of arrays of microwave cavities, of high Q -factor ($\sim 10^5$), each independently tunable. The third is state-of-the-art low noise cryogenic microwave amplifiers (GaAs FET's or HEMT's), and ancillary receiver electronics. LLNL is the principal among the four major institutions (LLNL, INR/Russian Academy of Sciences, MIT, and Florida), and will take responsibility for the magnet, and integration and operation of the whole experiment.

This will be a three-year proposal, where the Year I activity will be design and construction of the cryostat, testing of the coil modules, etc. In parallel with this will be the completion of the first microwave cavity assembly at INR, and the assembly and testing of the microwave electronics at MIT. In Year II the experiment will actually begin, and each of the five cavity arrays spanning the mass range (1.6 - 12.6 μeV) will be run in roughly 6-month cycles. Support is requested for the magnet/cryostat work, part of the p.i.s' salaries, a postdoc starting in the second year, fractions of a FTE engineer, draftsman and technician, M&S, travel, etc. The Year I request is \$300K in operating monies, and \$50K in capital equipment.

We emphasize that this experiment is a 'stand-alone' effort that will produce high-visibility physics results within the time frame of the LDRD award. It will be the first experiment with the sensitivity to possibly discover the axion. A negative result in our range of mass and coupling constant would also be scientifically important. But it would be incumbent on us to advance both in terms of power sensitivity of the experiment (i.e. push to lower values of the axion-photon coupling), as well as in mass range upward. The discipline of actual construction and operation of the experiment would establish our credibility with the DOE Office of High Energy Physics. We anticipate their support for one of a few directions that an upgrade of the experiment might take. This could be to construct a larger, higher field magnet, or to build a dilution refrigerator for the cavities (100 mK) and advance the state-of-the-art in effective noise of the microwave amplifiers for greater power sensitivity.

The Axion

This section is not meant to be a pedagogical discussion of the motivation and physics of the axion. A complete treatment would be lengthy and technical. Rather, this section

will give the minimum information necessary to appreciate how the axion comes about, why the mass range of 10^{-5-6} eV is prime territory for this search, and also the uncertainties involved. Two excellent reviews have appeared recently, which include all present constraints on the existence of the axion, accelerator-based experiments, and astrophysical and cosmological conclusions [10,11].

The axion is especially interesting because it responds to *two* fundamental problems in physics. It was predicted to exist 15 years ago as a consequence of the most simple and elegant extension to the Standard Model of particle physics to solve the "strong-CP problem". Only later was it realized that a light axion would be an excellent cold dark matter candidate.

The last remaining blemish on the theory of the strong interaction, quantum chromodynamics (QCD) is the "strong-CP problem", i.e. why the strong interaction conserves both P and CP. (P is parity, or reflection through the origin, and C is charge conjugation, or changing particles into antiparticles.) The best physical manifestation of strong-CP conservation is the absence of a neutron electric dipole moment; the present limit is $d_n < 5 \times 10^{-25}$ e·cm. But the QCD Lagrangian contains an explicitly-CP violating piece, the so-called ' θ -term'. In this term, θ is an undetermined parameter which could be any value between 0 and 2π or multiples thereof. Only for $\bar{\theta} = \theta - (\text{other unprescribed values and parameters of the theory}) = 0$ is CP-violation in the strong interaction suppressed, whereas for any arbitrary value of order $O(1)$, one would expect a non-zero neutron e.d.m. of $d_n \sim O(10^{-15})$ e·cm. The solution proposed by Peccei and Quinn involves postulating the existence of a global $U(1)$ symmetry for which $\bar{\theta}$ becomes a dynamical variable [4]. This symmetry is broken at some large energy scale f_a , but the effective potential for the axion field guarantees that $\bar{\theta}$ is set identically to zero, no matter what the values of the other unprescribed values and parameters in the theory. Weinberg and Wilczek realized that the spontaneous symmetry breaking of the $U(1)$ symmetry would generate a pseudo-Nambu-Goldstone boson, i.e. a physically manifest particle thereafter termed the axion [5,6]. As Peccei and Quinn had proposed (for no very good reason) that f_a should be the electroweak scale, ~ 250 GeV, Weinberg and Wilczek predicted that the axion should have a mass of a few hundred keV, and sufficiently strong couplings to matter and radiation to permit their detection in conventional accelerator- and reactor-based experiments, nuclear decays, etc. However, such axions were quickly ruled out, and soon it was discovered how to construct variant axion models with arbitrarily large values of f_a [12,13]. These were called "invisible" axion models because for $f_a \gg 250$ GeV, the axion is so weakly coupled that the event rates in conventional experiments are hopelessly small.

Both the mass of the axion and all its couplings to matter and radiation are inversely proportional to the symmetry-breaking scale f_a . Thus the mass m_a is given by

$$m_a = \frac{f_\pi m_\pi \sqrt{m_u m_d}}{f_a (m_u + m_d)} = 0.6 \text{ eV} \left(\frac{10^7 \text{ GeV}}{f_a} \right) \quad (1)$$

where m_π is the pion mass, $f_\pi \sim 93$ MeV is the pion decay constant, and $m_{u,d}$ are the masses of the up- and down-quarks. Likewise, the coupling of the axion to two photons which is relevant to this experiment is given by

$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{4\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B} \quad (2)$$

where α is the fine structure constant, and g_γ is a dimensionless number which depends on a parameter of the particular axion model N_e/N , which can be any rational number

$$g_\gamma = \frac{1}{2} \left(\frac{N_e}{N} - \frac{5}{3} - \frac{m_d - m_u}{m_d + m_u} \right) \quad (3)$$

(We define here $g_{a\gamma\gamma}^2 = (\alpha g_\gamma / \pi f_a)^2$. As will be seen later, this quantity subsumes all of the axion physics in the expression for the microwave signal power output in the proposed experiment.)

Light weakly coupled bosons, such as the axion, are severely constrained by stellar evolution because stars would emit such particles from their whole volume, whereas they emit photons which couple more strongly to matter only from their surface. This idea has been extensively applied to the axion using a variety of stellar objects (the sun, red giants, neutron stars, white dwarfs, and recently the supernova SN 1987a), which could have produced axions by thermal processes (Primakoff production, Compton-like scattering, axion bremsstrahlung in electron-nucleon and nucleon-nucleon scattering, etc.). Reference [11] gives an excellent discussion of this method. The supernova SN 1987a establishes the strictest bound on the axion mass, $m_a < 10^{-3}$ eV; axions between 1 meV and about 1 eV would have resulted in a dramatic foreshortening of the neutrino burst detected in both the IMB and Kamiokande large water Cerenkov detectors.

The cosmological production of axions implies a *lower* limit on the order of 10^{-6} eV. This limit follows from the requirement that the present cosmological axion density not exceed the critical density for closing the universe. When the universe cooled below a critical temperature of order f_a , the spontaneous breaking of the $U_{PQ}(1)$ symmetry would result in an initial misalignment angle of the axion field at each point in space. When the temperature further cooled below the QCD phase transition, non-perturbative QCD effects would generate an effective potential in θ endowing the axion with a mass, and the axion field will begin to oscillate about the CP-conserving direction, $\theta=0$. The energy density stored in these axion field oscillations today approximately equals

$$\rho_a^{vac}(t_0) \approx \rho_{crit}(t_0) \left(\frac{0.6 \cdot 10^{-5} \text{ eV}}{m_a} \right)^{7/6} \left(\frac{200 \text{ MeV}}{\Lambda_{QCD}} \right)^2 \left(\frac{75 \text{ km/s} \cdot \text{Mpc}}{H_0} \right)^2 \quad (4)$$

where $\rho_{crit}(t_0)$ is the present critical energy density for closure of the universe, H_0 is the present value of the Hubble constant and Λ_{QCD} is the QCD scale factor.

There are significant uncertainties in this estimate and the corresponding lower bound on the axion mass, which we will take hereafter nominally as 1 μeV to account for the uncertainties in both the Hubble constant and QCD scale factor. However, there are uncertainties beyond purely numerical ones. These involve e.g. whether inflation occurred before or after the PQ-phase transition and the details of the inflationary scenario; possible entropy release in the early universe; and possible axion radiation from cosmic axion strings. The point of view proper to experimental physics is that one

should ultimately plan for a full exploration of the three decades in mass range open to the axion. Our present point of view however is that the decade $\sim (1-10) \mu\text{eV}$ corresponding to closure density in axions under the standard vacuum realignment mechanism is the most exciting place to start, and it is precisely here which is immediately feasible experimentally.

The Cavity Microwave Detector for Galactic Halo Axions

As shown by Pierre Sikivie in 1983, axions which constitute our own galactic dark-matter halo could be detected by their stimulated conversion to microwave photons in a microwave cavity inside a strong magnetic field [7]. Such axions are non-relativistic, having only the virial velocity of the galaxy, $\beta \sim 10^{-3}$, and thus their energies have a spread only of order 10^{-6} above their rest mass. As axions couple to two photons, a Primakoff process in a static external potential (the B -field) yields one real photon of energy $mc^2(1 + O(\beta^2)) \sim mc^2(1 + O(10^{-6}))$.

The realization of this technique in an experiment consists of three major components, as shown in Figure 1. The first component is a magnet, with the largest value of B^2V achievable. Most practically this is a superconducting solenoid. The second component is one or more tunable microwave cavities with a high loaded quality factor, Q_L . (At the magnetic fields we wish to use, of order 10 Tesla, superconducting cavities are not an option, so one must use cavities made of oxygen-free high conductivity copper or possibly very pure aluminum.) The third component is state-of-the-art ultra-low noise cryogenic microwave amplifiers, and the other receiver and data acquisition electronics. The cavity or array of cavities is tuned, and the conversion probability for axions to photons goes through a sharp maximum when $h\nu = m_{ac}^2$. A frequency of 1 GHz

Figure 1. Schematic diagram of the University of Florida pilot axion experiment [14].

corresponds to an axion of mass 4.136 μeV , and thus in this experiment we are interested in the range of frequencies from below 400 MHz to above 3 GHz.

As seen in Eqn. (2), the interaction Lagrangian which couples the axion to two photons is an $\mathbf{E} \cdot \mathbf{B}$ interaction. This implies that for a right-circular cavity placed in the bore of the solenoidal magnet, only the TM_{n10} modes couple axions to photons. In fact, the only really practical mode is the TM_{010} mode, for which the 'form factor' of the mode C_{n1} (the overlap integral between the B - and E -fields) achieves a theoretical maximum of 0.69. (It is also useful to keep in mind that the frequency of the TM_{010} mode is given by $(115 \text{ MHz} / R[\text{m}])$, where $R[\text{m}]$ is the cavity radius in meters; obviously the bore of the magnet sets a lower limit to the mass of the axion that one may search for.) The power on resonance for the axion-photon conversion is given by

$$P_{nl} = \left(\frac{\alpha}{\pi} g_\gamma \frac{1}{f_a} \right)^2 V B_0^2 \rho_a C_{n1} \frac{1}{m_a} \text{Min}(Q_L, Q_a)$$

$$P_{nl} = 4 \cdot 10^{-26} \text{ Watt} \left(\frac{V}{0.22 \text{ m}^3} \right) \left(\frac{B_0}{10 \text{ Tesla}} \right)^2 C_{n1} \left(\frac{g_\gamma}{0.97} \right)^2 \cdot$$

$$\left(\frac{\rho_a}{\frac{1}{2} \cdot 10^{24} \text{ gr} / \text{cm}^3} \right) \left(\frac{m_a}{2\pi(1 \text{ GHz})} \right) \text{Min}(Q_L, Q_a)$$
(5)

where V is the volume of the cavity, B_0 the r.m.s. magnetic field strength along axis, ρ_a the density of galactic halo axions at earth, and $Q_a \sim 10^6$ is the "quality factor" of the galactic halo axions, i.e. the ratio of their mass to their energy spread.

In a real experiment, what is important is not only the conversion power, but the noise as well. The total noise is given by $T_n = T_{\text{elec}} + T_{\text{phys}}$, where the two components represent the intrinsic electronic noise temperature, and the physical bath temperature. In this proposal, the magnet cryostat is being designed for operation at a physical temperature of 1.8 K. Concerning the electronic noise, the very best low-noise microwave amplifiers in the GHz range are GaAs HEMT's (high electron mobility transistor), with an equivalent noise temperature of about 1-2 K at 1 GHz, and increasing 1 K per GHz. Below 600 MHz, GaAs FET's are the best.

The search rate of the experiment is given by

$$\frac{df}{dt} = \frac{72 \text{ GHz}}{\text{year}} \left(\frac{4}{s/n} \right)^2 \left(\frac{V}{0.22 \text{ m}^3} \right)^2 \left(\frac{B_0}{10 \text{ Tesla}} \right)^4 C^2 \left(\frac{g_\gamma}{0.97} \right)^4 \cdot$$

$$\frac{\rho_a}{\frac{1}{2} \cdot 10^{24} \text{ g} / \text{cm}^3} \left(\frac{5 \text{ K}}{T_n} \right)^2 \left(\frac{f}{1 \text{ GHz}} \right)^2 \left(\frac{Q_w}{Q_a} \right)$$
(6)

where (s/n) is the desired signal-to-noise ratio for detection of the axion (or equivalently exclusion of an axion at the 97.7% c.l.), and Q_w is the 'wall' or unloaded Q of the cavity. (The loaded Q is given by $1/Q_L = 1/Q_w + 1/Q_{out}$, where Q_{out} is the contribution due to the output coupler. The expression above assumes that the search rate is maximized by the optimization $Q_L = Q_w/3$.) With the benchmarks for the proposed experiment, we may rewrite this in a more practical form

$$\frac{1}{f} \frac{df}{dt} = \frac{6.4\%}{\text{week}} \left(\frac{4}{s/n} \right)^2 \left(\frac{B_0}{10 \text{ Tesla}} \right)^4 P^2 C^2 \left(\frac{5K}{T_n} \right)^2 \left(\frac{f}{1 \text{ GHz}} \right) \left(\frac{Q_w}{10^5} \right) \left(\frac{1}{N_{rescan}} \right) \left(\frac{\Delta f}{\delta f} \right) \quad (7)$$

where P is the packing fraction of cavities filling the magnet bore, N_{rescan} is the average number of times a given region is automatically rescanned due to showing a 2σ peak, Δf is the frequency interval between successive spectra, and $\delta f = f/Q_L$ is the cavity bandwidth. We have assumed an axion-photon coupling of one particular model, indicated later as KSFZ(a) [13], and that axions saturate the halo density of 300 MeV/cm³.

In the late 1980's, two pilot experiments were performed, one at BNL by a Rochester-Brookhaven-Fermilab collaboration [8], and one at the University of Florida [9]. We give here a brief description of the Florida experiment, which was the PhD thesis work of Chris Hagmann, presently at UC Berkeley [14]. Our proposed experiment draws more closely from the experience and design of the UF experiment, and in fact they are our collaborators on this proposal. The magnet in that experiment was 40 cm long with an inner diameter of 17 cm. The volume-averaged field over the 0.008 m³ volume was 7.5 Tesla. Some of the experimental runs were carried out at a physical temperature of 4.2 K, and others at 1.8 K. Unloaded- Q 's of 150,000 were achieved below 20 K in the two cavities that were used. As the axion signal that is being sought is narrower by around a factor of 20 from the bandwidth associated with Q_L , a power spectrum of 32 channels was measured around each central frequency of the cavity. Coarse tuning of the cavities was accomplished by radial displacement of either a dielectric or metal rod with respect to the cavity axis (allowing one to go down or up by roughly 25% in frequency with respect to an empty cavity, without undue diminution of C^2Q). Fine tuning was accomplished by longitudinal insertion of a small dielectric rod by a stepping motor and gear reduction. A detailed discussion of various conceptual designs, electromagnetic properties, required tolerances, etc. associated with high- Q cavity design and tuning for the axion experiment, along with actual cavity data is found in ref. [15].

The signal from the microwave amplifier was mixed down twice to the audio frequency range (0-32 kHz), digitized, and the power spectrum calculated real-time by a Fast Fourier Transform (FFT) board in the PC, which does both data acquisition and analysis, as well as complete automated control of the experiment. The signal was sampled at a 70 kHz rate (as required by Nyquist's theorem), and 64 successive samples measured and averaged to produce one spectrum. In a 90-second run at a given frequency, 10^5 spectra are acquired and averaged. If no peak above 2σ shows up, the PC steps the frequency of the cavity, measures the central frequency and Q of the cavity, and begins the next run. If a peak above 2σ shows up, another 10^5 spectra are taken and averaged with the first. If the peak remains statistically significant after a

Figure 2. (Top left) Typical power spectrum from the UF experiment, showing no peaks exceeding 2σ . (Top right) Spurious peak, due to a harmonic of the 16 MHz clock frequency from the PC. (Bottom) The RBF [8] and UF [9,14] exclusion regions in the mass vs. axion-photon coupling constant plane.

maximum of 5 tries, the peak is flagged for later investigation, and the experiment continues. Figure 2 top shows two spectra from the UF experiment. One is a spectrum without a candidate peak, and the other shows one of the rare candidate peaks which were detected during the entire course of the project. The beauty of the cavity microwave technique is that a real axion peak can be verified unambiguously -- when the magnetic field is turned off, the signal should go away, and the power associated with a real signal would vary as B^2 . Obviously no peak in either the UF or RBF pilot experiments satisfied that criteria. The spurious peak (Fig. 2, top right) was associated with a harmonic of the 16 MHz clock frequency of the computer. Figure 2 (bottom) shows the UF and RBF exclusion regions with respect to two axion models. The solid line labeled DFSZ [12] corresponds to a model with generic axion couplings to all fermions, but has a relatively unfavorable axion-photon coupling. The dashed line labeled KSVZ [13] corresponds to one particular choice of PQ charges within the 'hadronic' class of axions, i.e. those with no tree-level coupling to leptons or quarks, except to heavy, possibly yet-undiscovered quarks. It is provocative that for an equally plausible choice of PQ charges in a KSVZ axion (shown later), the pilot experiments would have very nearly had the power sensitivity for its detection [16]!

The Proposed Experiment

This section is a description of the experiment proposed for LDRD funding in FY 1993. A great deal of experimental detail is not warranted here as the proposed experiment, with one exception, is largely a scale-up of the UF pilot experiment which is fully described in the references below. Rather, we will emphasize the advances we have made which now make a major assault on the axion possible. We will also demonstrate that we have a critical mass of personnel, and key capital commitments for both microwave cavities and the microwave electronics.

The NASA SUMMA magnets

The easiest and most obvious way to reach into the cosmologically significant region of axion-photon coupling is a scale-up of B^2V of the magnet. For a long time we studied the feasibility of the use of the remaining pair of Axicell magnets from the decommissioned MFTF-B (3 m³, 7 T field), which would have given us an immediate factor of 300 improvement in power sensitivity over the pilot experiments. However, the sheer size of the magnets (50 tons) proved prohibitive in both initial cost to remove them and set them up in their own vessel (at least \$2.5M), and operating cost (\$250K/year for helium and power).

We have made two great discoveries in the magnet for the axion search. The first is the NASA SUMMA coils, presently at the University of Missouri, which Prof. Mark Prelas has kindly made available for us to bring here for the purposes of this experiment. There are three coils, and each 35 cm coil consists of three modules, an inner Nb₃Sn module, and middle and outer modules of NbTi. The three NASA SUMMA coils (Superconducting Magnetic Mirror Apparatus) put together make a very compact but extremely high field magnet (50 cm. clear-bore i.d., 1.1 m depth, possibly 10.5 Tesla at

Figure 3. Design of a thermally efficient cryostat, and 1.8 K refrigerator for the NASA SUMMA coils.

1.8 K), weighing only 4.5 tons. Along with the magnet comes all the power supplies, control hardware, and high quality spare superconducting wire.

The NASA SUMMA magnet gives us an immediate factor of 50 over the UF pilot experiment, before counting any incremental improvements in HEMT amplifiers, etc..

The second breakthrough has been the involvement of an industrial partner, Wang NMR of Livermore. Sou-Tien (Bert) Wang is one of the premier superconducting magnet builders in the world, having built more than 70 in his career at Argonne and at LLNL. (He was a key person in the design and construction of the MFTF-B.) Now principally in the medical NMR business, he performed a study for us resulting in a very economical and thermally efficient cryostat and 1.8 K refrigerator design. Operating the coils in persistent mode with removable leads, and bringing to bear medical NMR cryostat technology to our experiment, it is estimated that the helium consumption would be no more than about 3.5 liters/hour even if all the mechanical motion was transmitted to the tuning mechanism of the cavity arrays with s.s. tubing; if G-10 is used, the helium consumption might only be 350 ml/hour. Figure 3 shows the design of the cryostat, magnet and 1.8 K refrigerator.

The timeline for delivering a complete system is one year, and will cost \$400K. This includes all transportation of the magnet components from Columbia, Missouri, fabrication of the cryostat, persistent switch, etc., testing of the coils, and refurbishing of the power supplies and control system.

Bert is also a high energy physicist, and will be a collaborator on the experiment. He has offered to us his new plant in which to actually run the experiment, should it be convenient to do so. Wang NMR is located on North Canyons Parkway, just across I-580 from the Livermore airport, about 10 minutes drive away. We are considering this seriously, as we have Russian collaborators for whom it might be much easier to have work there than within the Lab, where they need to be escorted continuously.

The INR Microwave Cavities

As one searches for axions higher in mass, the radius of the microwave cavities goes down as the inverse of the axion mass. Therefore to take maximum advantage of the B^2V of the magnet it is essential to use arrays of cavities, each cavity being independently tunable, and whose outputs are power-combined. (This is distinct from *coupling* cavities, however.) Neither of the pilot experiments ever ran with more than one cavity. As a final chapter to his thesis, however, Chris Hagmann successfully demonstrated the principle of combining the output from two cavities in a test at 300 K. The magnitude and shape of the Q -curve of the combined cavities was in exact agreement with theory. Nevertheless, the fabrication and efficient operation of arrays of many combined cavities was perceived to be the major obstacle to mounting a full-scale experiment.

A year ago, a strong group from the Institute for Nuclear Research of the Russian Academy of Sciences headed by Dr. Nikolai A. Golubev joined our collaboration, proposing that they take complete responsibility for providing all the microwave

AXION 4-CAVITY TEST

Sht. 2 OF 2

Figure 4. Conceptual design of the INR 4-cavity array. Total diameter 460 mm; length 900 mm.

cavities for the experiment. Furthermore, they suggested a novel technology for fabricating the cavities, namely metalized precision-formed ceramic. Ceramic cavities are light, strong and require a minimum of machining after being fired to hold mechanical tolerances. INR has long experience in metalized ceramics, principally for beam pipe in rapid-cycling synchrotrons.

During a visit to the INR laboratories in Troitsk, in October, 1991, a Memorandum-of-Understanding was written between INR, LLNL and the University of Florida for R&D on metalized ceramic cavities. Basically, INR agreed to provide both full-size single cavities (to test different coatings, e.g. Al, Cu, and metalization techniques) and a 4-cavity array (to test the automated tuning of multiple cavities). Figure 4 shows an approximate engineering drawing of the 4-cavity prototype array. The ceramic components are being made at the Lutch aircraft company in Kharkov, and the magnetron sputtering is done by the Zinit optical company in Zilinograd. The results at 300 K are encouraging. The measured Q in the TM_{010} mode for one of their large cavity is 39,000 compared to a theoretical maximum of 43,600. However, only by testing the cavities at LHe temperature can one confirm the quality of the coating.

Three INR physicists and engineers will visit LLNL for the month of September, where the 4-cavity array will be tested at 4.2 K in a 50 cm i.d. LHe dewar in the MFE cryogenics test lab. This array is already of the full size that would be used in our actual experiment in the NASA SUMMA magnet. They will spend October at the University of Florida, testing magnetoresistive effects at 4.2 K with single cavities in the magnet and dewar used in the UF pilot experiment.

The experiment will require five arrays to cover the mass range proposed. The first is a single large cylindrical cavity. The second is large cylinder partitioned into two cavities of semicircular cross section. The third is the 4-cavity array presently under construction. The fourth and fifth are 8- and 16-fold close-packed arrays. Details on the design of an experiment with a large number of cavities may be found in ref. [17].

The Vice-Director of INR, Dr. Valery Rubakov has sent a letter to Bruce Tarter confirming our understanding that they would provide all the cavities required, tuning mechanisms, etc. should this experiment be approved and funded.

The microwave electronics

The extreme weakness of the signal being looked for puts a premium on state-of-the-art ultra-low noise microwave amplifier technology. The collaboration is strong in this area, both in manpower and in capital commitments.

A key collaborator in this experiment will be Prof. Leslie Rosenberg, who joined the effort only a few months ago. He is one of the best young high energy physicists in the country, and most recently was responsible for most of the design and construction of the electronics and data acquisition system for the CASA experiment (Chicago Air Shower Array) in Dugway, Utah. He has recently accepted an offer to join the faculty at MIT, with the expressed intention of working solely on the axion search for his first term there. Effectively he is staking his promotion to tenure on this experiment. The Department, Dean and Provost have been extremely supportive of his intentions. MIT

is giving him approximately \$300K in capital equipment money to build up the entire microwave electronics for the experiment, and about \$60K in operating money. This is of course contingent on the experiment being approved and funded this year by LLNL.

Frank Nezrick of FNAL, one of the two principal senior people in the Rochester-BNL-FNAL pilot cavity microwave experiment has also recently joined us. He brings long experience in microwave techniques, as well as microwave electronics (synthesizer, local oscillator, network analyzer, etc.) used in the RBF experiment.

Walter Ferguson of MFE is our own local expert in microwave electronics, and has begun characterizations of a copper-plated s.s. 3-GHz prototype cavity that was fabricated by our UCB/LBL collaborators a year ago. Francesco Villa of SLAC is also a great resource.

Other resources and personnel

Chris Hagmann at Berkeley, and Dave Tanner and Neil Sullivan at Florida have overall experience in the cavity axion experiment. We will make use of the free machine shop time at Florida to do most of our shop work. For example, each cavity array will require a custom-made flange for the top of the cryostat from which it will be suspended, and through which all mechanical and electrical penetrations are made. It is possible that we will be able to make use of both FNAL, and LBL through our collaborator Dennis Moltz, for limited technical support as well.

Discussion

Scientific deliverable

Figure 5 shows the region in axion mass and axion-photon coupling where galactic halo axions would either be discovered ($s/n > 4$), or excluded (97.7% c.l.) by our experiment. The actual limit will probably be somewhat better due to improvements in GaAs HEMT amplifiers even in the past two years. The nominal axion mass for closure of the universe is $6 \mu\text{eV}$, assuming that the standard vacuum realignment mechanism dictates the axion contribution, but as previously mentioned there are large uncertainties here. The three model lines (DFSZ, and two choices of parameters for KSVZ axions) give a fair representation of our uncertainty in how strongly the axion couples to photons.

Strategy

This experiment will make a factor of 100 improvement in power sensitivity over the pilot experiment, and cover a much broader mass range. It would be the first experiment with cosmologically significant sensitivity, although it is clear that at present we could not exclude a DFSZ axion. Nevertheless, theory should never be taken too seriously. Whenever one can make even an order-of-magnitude improvement in an experiment, or reach into the physical region of interest for the first time, it is imperative to do so as soon as possible.

Figure 5. Region of mass and axion-photon coupling that the proposed experiment will be sensitive to.

Our strategy of an experiment with a compact high field magnet, and emphasis on as low a total noise as possible is driven by three motives. (i) The first and most important is the reason of timeliness as mentioned above. Our experiment is small enough (physically and budgetarily) that we will be taking data one year after starting. There has been a great awakening of interest in the dark-matter problem within the past year, even within the past months. While we have no competition at present, it is unlikely that situation will pertain forever. A third pilot effort existed at KEK in Japan, but was discouraged from proceeding to a large-scale experiment at that time due to budgetary pressures resulting from the Japanese B-Factor project. A Kyoto-Osaka group was engaged in advanced receiver technology for the axion search. (ii) The second reason is that we envision the way to push this experiment in the future is by advancing on the front of low total noise (the quantum limit at 1 GHz is 50 mK). We have depth in this area and are anxious to begin R&D on customized HEMT's, possibly maser amplifiers, etc.. But this requires lowering the physical temperature (i.e. by a dilution refrigerator) in parallel with reduction in electronic noise, and that is easier for a smaller rather than a larger detector. (iii) The third is that we will also want to continue upward in mass, which will involve progressively smaller cavity structures. Trading off high field vs. volume (and one can make an insert booster coil to raise the field higher still) minimizes the number of cavities one needs to deal with.

Future funding

Should the axion not be found in this experiment, we will want to advance both in power sensitivity (and thus downward in $g_{a\gamma\gamma}^2$), and upwards in mass. Both will depend on insights as we go along. From several conversations with the DOE Office of High Energy Physics over the past two years, we know they are very interested in a coherent effort towards finding or excluding the axion. We believe DOE would be receptive to a proposal for an upgrade, particularly one that emphasized advances in ultra-low noise microwave electronics. P.K. Williams of DOE has already indicated to Les Rosenberg that he would encourage submission of an R&D proposal immediately. Also, once the experimental 'platform' is established, future running of the experiment should be very economical, and this we could seek from DOE as well.

It is reasonable to ask why DOE/HEP would not fund the full construction of the experiment here from the outset. Beyond the usual sensitivities concerning ER putting money into a DP lab in competition with support of university groups, there is a more pressing issue. The DOE Office of High Energy Physics requested guidance from the High Energy Physics Advisory Panel (HEPAP) on how to manage the 'base program' over the coming decade in the face of enormous fiscal pressures due to the SSC. HEPAP in turn charged a subpanel headed by Prof. Michael Witherell of UCSB to carry out this study. Their report, submitted this April, was not encouraging with respect to growth in the area of non-accelerator particle physics, or anything else for that matter. In fact, the projections for FY93 indicate a 20% decrease from FY92 in non-accelerator physics from what was only a \$15M/year portfolio.

Important Remark

We believe that we have an optimized concept for the axion experiment, and that the time has never been more ripe to launch the effort. The project has the great benefit of very substantial commitments of manpower and capital resources, particularly the offer by the Institute of Nuclear Research of the Russian Academy to provide all of the microwave cavities, and the offer by Prof. Rosenberg of MIT of \$300K in microwave electronics. However, it is equally clear that if this LDRD proposal is not approved this year, both these commitments will evaporate, and the opportunity for LLNL to play a leadership role in the search for the axion will be permanently lost.

Budget and Timeline

FY93 Budget

The budget request for FY93 is \$302K in operating money, and \$50K in capital equipment, as detailed below (in \$K).

Operating:

Manpower Total	82.2	0.25 KVB, 0.25 (M.E. + Des.)
Procurements	205.0	Principally Wang NMR
Travel (Foreign)	3.0	Support of INR visitor, 1 mo.
Travel (Domestic)	1.0	
Stores	1.0	
TID	1.0	
Lab. Gen'l. Exp.	8.8	
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PROJ. OP. TOTAL	302.0	

Capital:

Fluke Local Oscillator (100 MHz-2 GHz)	13.0
Fluke Local Oscillator (10 MHz)	14.0
H-P Power Meter	8.0
H-P RF Switch	7.0
Berkshire Cryogenic Amplifier	8.0
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PROJ. CAP. TOTAL	50.0

Timeline

The major milestones for the cryostat work by Wang NMR are shown in Figure 6.

The major milestones for the cavity work by INR are:

- (1) Completion/reporting prototype tests at LLNL, UF 9-10/1992
- (2) Fabrication of first array (460 MHz central freq., single cavity)
- (3) Transport to LLNL

The major milestones for the microwave electronics work at MIT are:

- (1) Establishment of lab space
- (2) Procurement of all receiver components
- (3) Assembly and testing with 3 GHz prototype cavity
- (4) Writing data acquisition and analysis software
- (5) Transport to LLNL

The major milestones for integration and project oversight at LLNL are:

- (1) Engineering and design of the flange for the first cavity array
- (2) Machining of the flange at UF or FNAL
- (3) Writing experiment control software
- (4) Integration of cavity/tuner & cryogenic amp on flange

The longer term timeline is shown in Figure 7, indicating six-month run periods with one cavity array in parallel with the preparation of the next array.

Figure 6. Timeline for the magnet and cryostat work in FY93.

Figure 7. Timeline for construction and operation of the axion search experiment.

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Service

1992-pres. Member, Physics Department LDRD Committee
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1986-1989 LLNL Lab-Wide Institutional and Research Committee, Vice-Chairman, FY89, Chairman, FY90
1983-1985 Chairman, Exec. Comm., LBL 88" Cyclotron Users Group
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Research Interests

High energy electron scattering from nucleons and nuclei.

Experimental possibilities for detection of axions or other light bosons.

Inelastic electron, hadron scattering to giant resonances and their decay.

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STANDARDIZED IR&D CURRICULUM VITAE FY-93

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Search for Lepton Flavour Violation in Z^0 decays.

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(1990) Lawrence Berkeley Lab (Berkeley)

(1991) Massachusetts Institute of Technology (Cambridge)

(1992) Princeton University (Princeton)

(1992) Notre Dame University (South Bend)

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Entered 05/29/1992

Modified 05/31/1992

Block 1 - General Information

Proposal Title

Search for Pseudoscalar Cold Dark Matter

Proposal Type DE

Technical Area

Particle and Nuclear Physics

☐ Proposal continued from FY92

Proposal tracking N°

Block 2 - Principal Investigator

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Block 3 - Responsible AD

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Block 4 - Responsible Resource Mgr

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Block 5 - Co-Investigators

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First/Last Name

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Directorate

First/Last Name

Phone

L-Code

Directorate

First/Last Name

Phone

L-Code

Directorate

Block 6a - Project Description

Project Abstract

It is virtually certain that at least 90% of the mass of the universe is in a non-luminous form. Both dynamical evidence, and observation of primordial fluctuations in the cosmic microwave background support the hypothesis of an exactly closed universe, predominantly composed of 'cold dark matter'. One of the most attractive cold dark matter candidates is a previously undiscovered elementary particle called the axion. Dark-matter axions may be detected by their stimulated conversion to microwave photons in a tunable high-Q cavity in a strong magnetic field. We propose to perform the first axion search that could possibly detect axions comprising our own galactic halo. This proposal capitalizes on the availability of a compact high field superconducting magnet, a commitment from the INR/Russian Academy of Sciences for all the microwave cavities required for the experiment, and substantial university capital monies for the microwave electronics. The experiment would take data within one year, and run for two years thereafter.

Block 6b - Project Description

Major Accomplishments and Results - FY 1992

A large, empty rectangular box with a solid black border, occupying the majority of the page below the header. It is intended for the user to provide a detailed project description and list major accomplishments and results for FY 1992.

Block 6c - Project Description

Proposed Work and Anticipated/Desired Results - FY 1993

The first year will consist entirely of the construction and integration of the cavity microwave axion experiment. Early in the first year, we will let the contract for the construction of the cryostat, the mounting and testing of the NASA SUMMA magnets within it, and the refurbishing of the power supplies, control system and quench protection circuit. This work will be substantially complete by the end of FY 1993. We will design and fabricate the top flange for the cryostat from which the first cavity array will be suspended in the magnet. This will be complete in time for the delivery of the first cavity array by our INR collaborators. The microwave electronics will be procured, assembled and tested at MIT, and shipped to the laboratory. We will also conduct the search and appoint a postdoctoral researcher at LLNL in support of the project for the following two years. The experimental run with the first cavity array will begin early in the second year.

Get information for Blocks 7 - 13 from your resource manager.

Items with a bold outline will be automatically calculated by the system.

Block 7 - Manpower Expenses

	FY1993	FY1994	FY1995
A. FTE..... (for estimate, use FTE=1800 manhour)	0.50	1.25	1.50
B. Wage Expense..... (FTE x Ave Annual Salary x 1.210)	\$44,772	\$119,481	\$155,571
C. Support Department Burden..... (Burden Rate x Wage Expense)	\$3,855	\$7,890	\$8,276
D. Overhead..... (75% x Wage Expense)	\$33,579	\$89,611	\$116,678
Manpower Total	\$82,206	\$216,982	\$280,525
E. Labor - Consultants.....			
F. Labor - LBL.....			
G. Labor - Post Doctorates.....		\$70,000	\$73,430
H. Labor - Summer Hires.....			
I. Labor - Supplemental.....			
J. Labor - Supplemental + 60.0% Overhead.....			
Other Labor Total		\$70,000	\$73,430

Block 8 - Capital Equipment Summary Requests Over \$5000 (FY1993-FY1995)

FY1993	Priority	Item	Cost
1		Fluke L.O. 0.1-2 GHz	\$13,000
1		Fluke L.O. 10 MHz	\$14,000
1		H-P Power Meter	\$8,000
1		HP RF Switch	\$7,000
1		Cryogenic Amplifier	\$8,000

\$50,000

FY1994	Priority	Item	Cost

FY1995	Priority	Item	Cost

Block 9 - Procurements

	FY1993	FY1994	FY1995
A. Procurements.....	\$205,000	\$210,000	\$10,000

Block 10 - Expenses

	FY1993	FY1994	FY1995
A. Foreign Travel.....	\$3,000	\$12,600	\$19,800
B. Domestic Travel.....	\$1,000	\$2,000	\$2,000
C. Stores.....	\$1,000	\$5,000	\$3,000
D. Other		\$50,000	\$55,000
Total Expenses.....	\$5,000	\$69,600	\$79,800

Block 11 - Services Facilities

	FY1993	FY1994	FY1995
A. Materials Fabrication Division (MFD).....	\$0	\$0	\$0
B. Technical Information Department (TID).....	\$1,000	\$1,000	\$2,000
C. Plutonium Facility.....	\$0	\$0	\$0
D. Other.....	\$0	\$0	\$0
Total Services/Facility.....	\$1,000	\$1,000	\$2,000

Block 12 - Computers

	FY1993	FY1994	FY1995
LCC:			
NERSC:			
Other:			
Total Computers			

Block 13 - Totals

	FY1993	FY1994	FY1995
A. Project Operational (Blocks 7, 9, 10, 11, and 12).....	\$293,206	\$567,582	\$445,755
B. Laboratory General Expense (3% of the values in A. for 3 years).....	\$8,796	\$17,027	\$13,373
C. Project Operational Cost Total (Sum of A. and B.).....	\$302,002	\$584,609	\$459,128
D. Project Capital Equipment (Block 8).....	\$50,000		
Project Grand Total (C+D)	\$352,002	\$584,609	\$459,128

**DATE
FILMED**

11 / 26 / 93

END