MINI LNS LABORATORY FOR NUCLEAR SCIENCE REVIEW

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# The Search for Dark Matter Axions

## Overview

In a classic set of observations, rotation speeds of stars in galaxies (including our own) show a universal feature: the speed is approximately constant at distances well beyond the luminous core. This implies the existence of large halos of nonluminous matter---dark matter---surrounding galaxies. Discovering what this dark matter is made of is a central challenge confronting science today.
It seems likely from the success of models of primordial nucleosynthesis in explaining the abundance of light isotopes, and of cosmological inflation in explaining the near flatness of the universe, that most dark matter is not ordinary matter---say, protons or bowling balls---but rather something new and exotic. The axion, a hypothetical elementary particle introduced to trim an annoying loose end in our understanding of Quantum Chromodynamics (QCD), is a leading candidate for dark matter.(1)

The annoying loose end in QCD is the observation that, contrary to expectations, strong interactions conserve P and CP. This problem, the "strong CP problem," is solved by the presence of the axion.(2) How this works out is not so simple to explain. Suffice to say the axion is a prediction of an elegant solution, Peccei-Quinn symmetry, to the strong CP problem of QCD. In this formalism, the axion mass is a free parameter, with plausible range from $10^{-12}$ eV to 1 MeV. However, present limits on the axion mass from astrophysical and cosmological considerations constrain the mass to the three decade window 1-1000 μeV. We are in the commissioning stage of an experiment to probe the first decade of this mass window.

## Properties of the Axion

The axion is central to solving the strong CP problem in QCD, hence one would expect that axions have direct couplings to quarks and gluons---the colored fundamental objects in particle physics. Optionally, axions could also have direct couplings to charged leptons. Through these direct couplings, axions then have effective couplings with normal matter and radiation, with coupling constants

$g_{a\gamma\gamma}$, $g_{aee}$, $g_{app}$, etc., for the axion coupling to photons, electrons and protons. If the axion is very light, its couplings are very weak and the axion is hard to detect. Such axions are called "invisible axions." Our experiment, the topic of this mini-review, explores one particular effective coupling, that of the axion with two photons.

## *Constraints on the Axion Mass*

Weinberg and Wilczek,(4) developing the symmetry ideas of Peccei and Quinn,(3) originally suggested an axion with mass near 10 keV. Such heavy axions are relatively strongly coupled and were quickly ruled out by accelerator experiments. However, at least in retrospect, there is no particularly good reason to believe the mass should be so large, and the search continues for invisible axions with masses much less than 10 keV.

In 1987, a nearby star exploded as supernova SN1987A. Much of the impulsive release of the star's gravitational binding energy eventually appeared as neutrinos. We usually think of neutrinos as interacting very weakly. However, neutrinos have a relatively short collision path length in the dense supernova core.

It takes many scatterings before a neutrino can escape, and supernova cooling is throttled by the relatively strong neutrino interactions. Two detectors, Kamiokande and IMB, recorded between them 19 neutrinos from SN1987A over about a 10 second time interval. This interval is about that expected from neutrino energy transport. An axion efficiently transports energy from the explosion, and would reduce the spread in neutrino arrival times. These data, together with an axion transport calculation(5), constrain the axion mass to below $10^{-3}$eV.

Most of the axions born in the early universe---relic axions---arose during a phase transition in the early universe. These axions form a Bose condensate with minuscule velocity dispersion. This is called "misalignment production" of axions. The present density of misalignment axions depends on the axion mass, and perhaps surprisingly, the smaller the axion mass, the greater the present day axion mass density.(6) Axions with mass somewhat less than $10^{-5}$eV would about saturate dark matter, while axions with substantially lower mass would severely overclose the universe. This misalignment axion mechanism therefore provides a lower limit near $10^{-6}$eV to the axion mass.

## *Detection of Relic Axions*

The various laboratory, astrophysical, and cosmological constraints leave an axion mass window $10^{-6}$ to $10^{-3}$eV, with $10^{-5}$eV or slightly less particularly interesting as it is here where axions would close the universe. The hypothesis that the dark matter halo of our own galaxy is made of axions can be tested by finding resonant conversion of halo axions to microwave photons in a magnetic field. Here, a tunable high Q cryogenic cavity is placed within the bore of a superconducting solenoid magnet, and the frequency

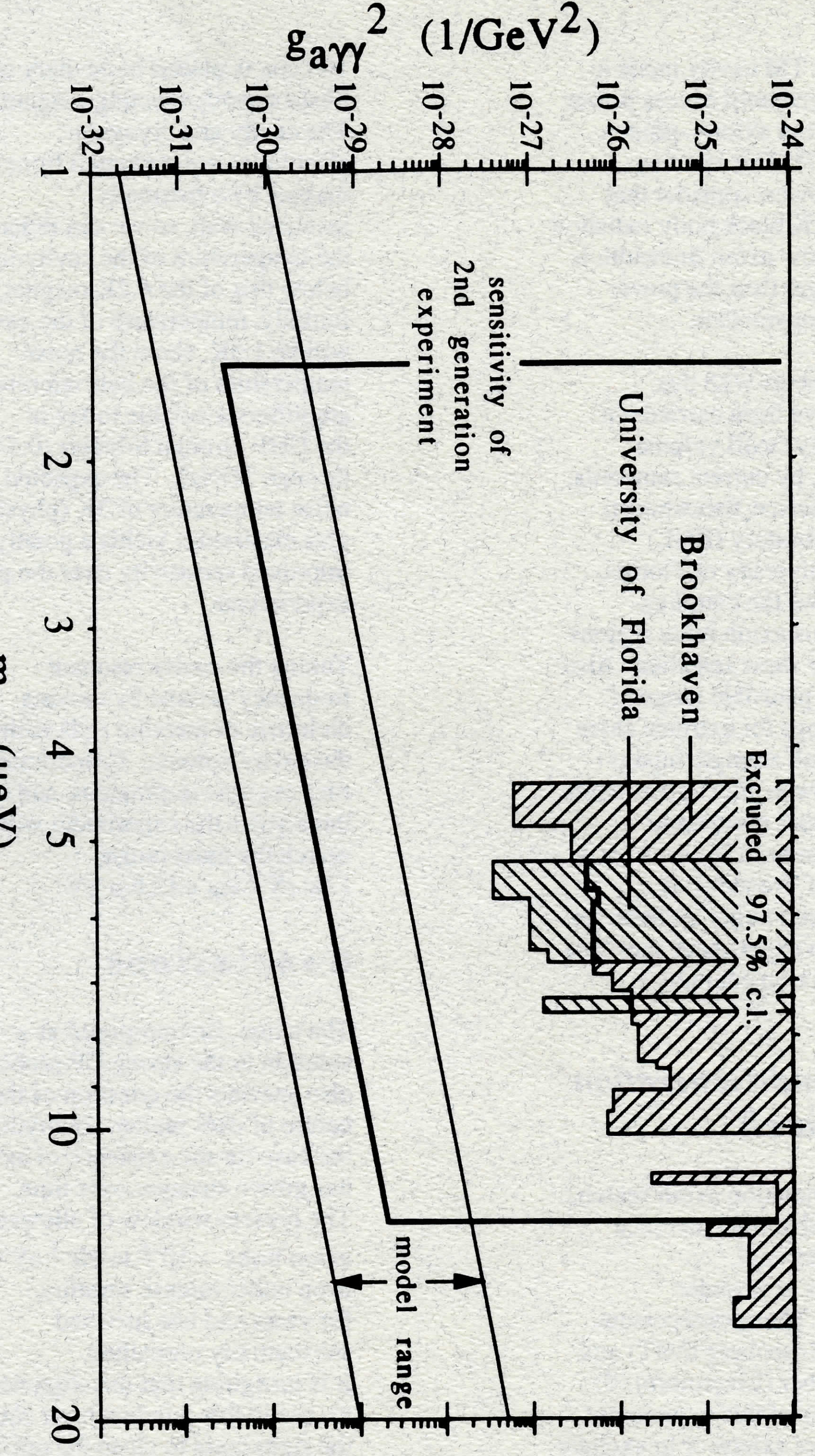


Figure 1: Exclusion regions in the axion mass versus coupling constant plane obtained by the pilot cavity experiments, and the expected sensitivity of our 2nd generation experiment. Also shown is the plausible range of coupling strengths.

of the lowest TM cavity mode is slowly changed until excess power is detected from axion---photon conversion.(7) This is a tiny amount of power; consider that the cavity's 1K black body radiation over the narrow axion linewidth is ten times larger than the power from axion conversions.

Pilot experiments with this technique have been carried out with relatively small volume magnets and, by current standards, noisy amplifiers at Brookhaven National Laboratory (BNL) and at the University of Florida. Figure 1 shows the coupling-squared versus axion mass regions eliminated by these searches. Also shown is the plausible range of axion couplings for extreme cases of zero and full strength lepton couplings. These pilot experiments have shown that reasonable sensitivity can be achieved over a wide range of frequencies. However, much larger systems are needed for an experiment sensitive to plausible axion couplings.

## *The Second-Generation Axion Search*

A second-generation axion search, to be operated at the Lawrence Livermore National Laboratory, is now under construction. The spokespersons are Leslie J Rosenberg (MIT) and Karl van Bibber (Livermore).(8) The capability of this experiment either to detect axions or to exclude them (at the 97.7% C.L.) is shown in Figure 1.

A sketch of the experiment is shown in Figure 2. The cavity, with inner diameter 50 cm and length 100 cm, is placed in the bore of a 8 Tesla superconducting magnet. The cavity and cryogenic electronics are separated from the magnet by a thermally insulated wall, so we can reduce the temperature of the cavity to below that of the 4.2K magnet. Initially, temperature of the cavity will be 1.5K, about the noise temperature of the best microwave amplifiers available today in the UHF through S-bands (0.5 through 3GHz). The expected total noise temperature of 3K (physical plus electronic) yields a greatly improved sensitivity over the pilot experiments.

Tuning the cavity resonant frequency is done by moving dielectric or metallic rods within the cavity volume. Commissioning runs are now in progress, and over three years the experiment will search the mass range $1.5\mu\,eV < m_a < 12.6\,\mu\,eV$.

## *Conclusions*

The axion, first proposed as a solution to the strong CP problem, also answers the question of the nature of dark matter. If anything, the case for the existence of axions has grown stronger over time. The present window of allowed axion mass ---$10^{-6}$ to $10^{-3}$ eV---has been under intense scrutiny for years and has survived substantially unscathed. It is intriguing that misalignment axions in this window have about the right mass to close the universe. Our RF cavity experiment is underway and will explore the first and most interesting decade of mass in the search window.

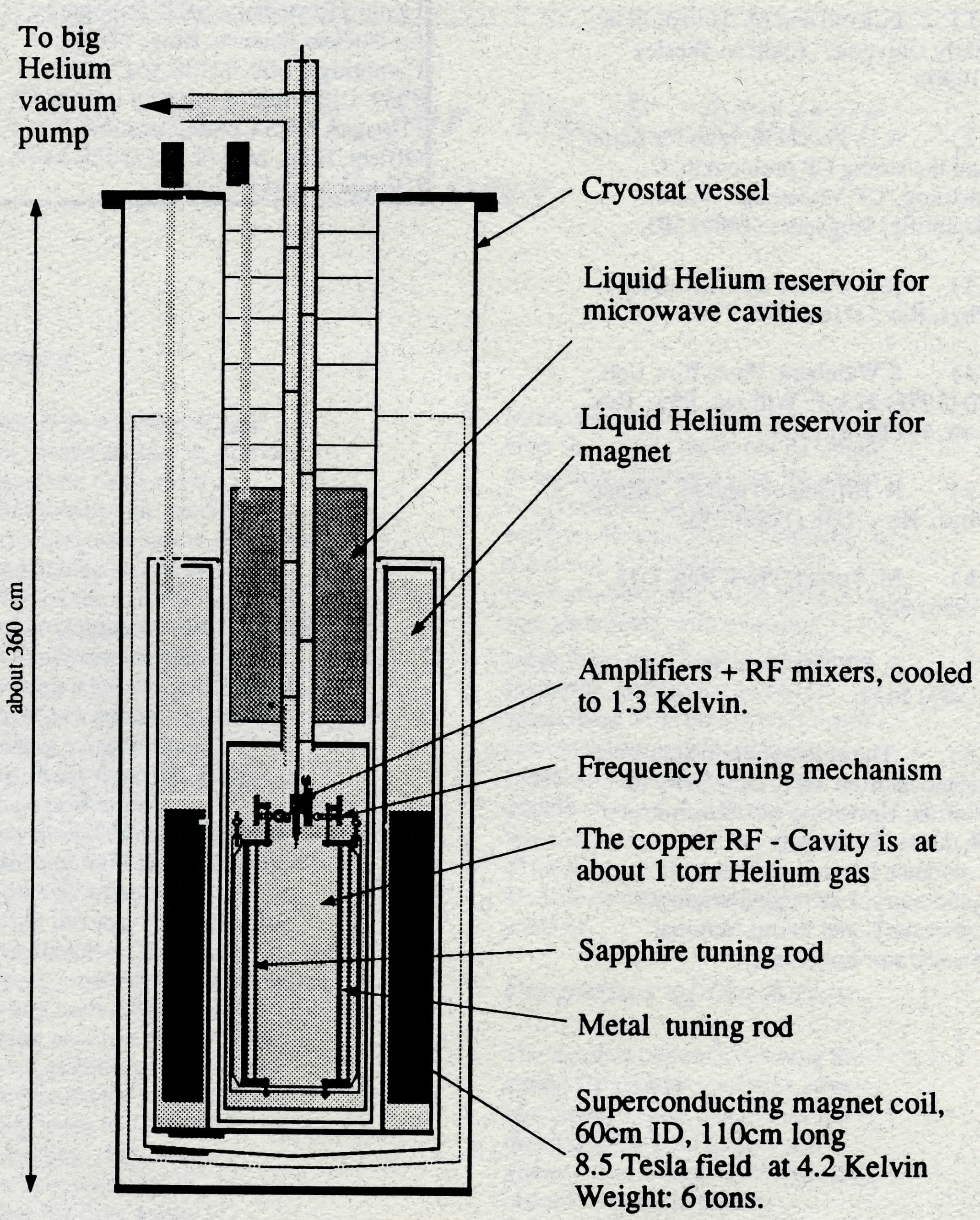


Figure 2: Sketch of the axion search experiment.

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(8) The collaboration includes scientists from MIT, University of Florida, University of California at Berkeley, University of Chicago, Lawrence Livermore National Laboratory, Lawrence Berkeley Laboratory, and Fermi National Accelerator Laboratory.

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