Molecular Axion DArk Matter Experiment (MADAME)

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1 Goal of experiment

This experiment aims to search for axion dark matter with large axion decay constant, f_a, from the Planck scale down to the scale of grand unification (GUT scale $\sim 10^{16}$ GeV) or possibly even as low as $\sim 10^{15}$ GeV. This part of parameter space is theoretically well motivated since the physics responsible for the generation of axion-like particles naturally occurs at these scales. Further, an axion in this region of parameter space can also easily contribute to a significant component of the dark matter. Current axion detection techniques cannot search for axions whose decay constants are above $\sim 10^{12}$ GeV, far below fundamental scales. There is thus great scientific interest in developing techniques that can search for the axion if it lies in this region of parameter space.

2 Experimental setup

The axion can act as dark matter because its cosmological evolution results in the axion field oscillating about its minimum with a frequency equal to its mass. The amplitude of this oscillation contributes to the local dark matter density and is limited by it. This experiment aims to exploit these oscillations to detect the axion. These oscillations give rise to time varying CP odd nuclear moments, such as electric dipole and Schiff moments, that are directed along the nuclear spin. In an electrically polarized molecule, where the molecular axis has a well defined direction, if the nuclear spins are also suitably polarized, the large internal electric fields of the molecule will couple to the CP odd nuclear moments (such as the electric dipole and Schiff moments) giving rise to time varying shifts to molecular energy levels. These effects can be enhanced by using elements with large Schiff moments such as the light Actinides. The energy level shift in such a molecule can be $\sim 10^{-24}$ eV or larger. While challenging, this energy shift may be observable in a molecular clock configuration with technology presently under development. The detectability of this energy shift is enhanced by the fact that it is a time varying shift whose oscillation frequency ($\sim$ kHz - MHz) is set by fundamental physics and is therefore independent of the details of the experiment.

A molecular clock configuration that can detect this effect is described in figure 1. Begin with an ensemble of cold (milli-kelvin) polar molecules of some actinide element. Through the application of suitable magnetic and electric fields, the molecules are polarized with their nuclear spin placed perpendicular to the molecular axis. In the setup described in figure 1, this is achieved through the application of a magnetic field in the vertical direction and an electric field along the horizontal direction. The molecules are then placed in a linear superposition of two states $|\Psi_L\rangle_a$ and $|\Psi_L\rangle_o$, where the nuclear spin is either aligned or anti-aligned with the molecular axis respectively (see figure 1). This superposition can be created using traditional NMR techniques. The energy shift caused by the dark matter axion in the two states is of opposite sign and hence a phase difference will accrue between them. This phase difference will continuously accrue over several axion oscillations if the nuclear spin precesses at a frequency equal to the axion mass. This precession can be achieved by applying a magnetic field of suitable magnitude in the direction perpendicular to the molecular axis (*i.e.* the vertical direction in figure 1). The phase difference between the states $|\Psi_L\rangle_a$ and $|\Psi_L\rangle_o$ is measured after several axion oscillations. A non-zero phase difference would indicate the existence of time varying energy shifts in the molecule at the precession frequency of the nuclear spin, which would be the effect of the axion induced time varying CP odd nuclear moments interacting with the internal molecular fields.

The electric and magnetic fields necessary to realize the above setup are feasible. The preparation of the initial state, where the nuclear spins are perpendicular to the molecular axis can be achieved through the application of magnetic fields ~ 1 T (for molecules at a milli kelvin) and electric fields $\sim 100\,\frac{\text{kV}}{\text{cm}}$. The strength of the required field is correspondingly smaller if lower molecular temperatures can be achieved. The magnetic field necessary to precess the nuclear spin depends upon the unknown axion mass. For axions with decay constants f_a between the GUT and Planck scales, the axion mass ranges between MHz to kHz respectively. The magnetic field necessary to precess the nuclei at these frequencies is $\sim 0.1\text{ T}\left(\frac{10^{16}\text{ GeV}}{f_a}\right)$. Since the axion mass is unknown, the experiment will scan through various precession frequencies in search of the axion. This can be achieved by dialing this magnetic field.

Significant new technological developments are required in order to build an instrument that has the sensitivity to detect axion dark matter. Current molecular interferometers are between two to four orders of magnitude less sensitive than the requirements of this experiment. The experiment

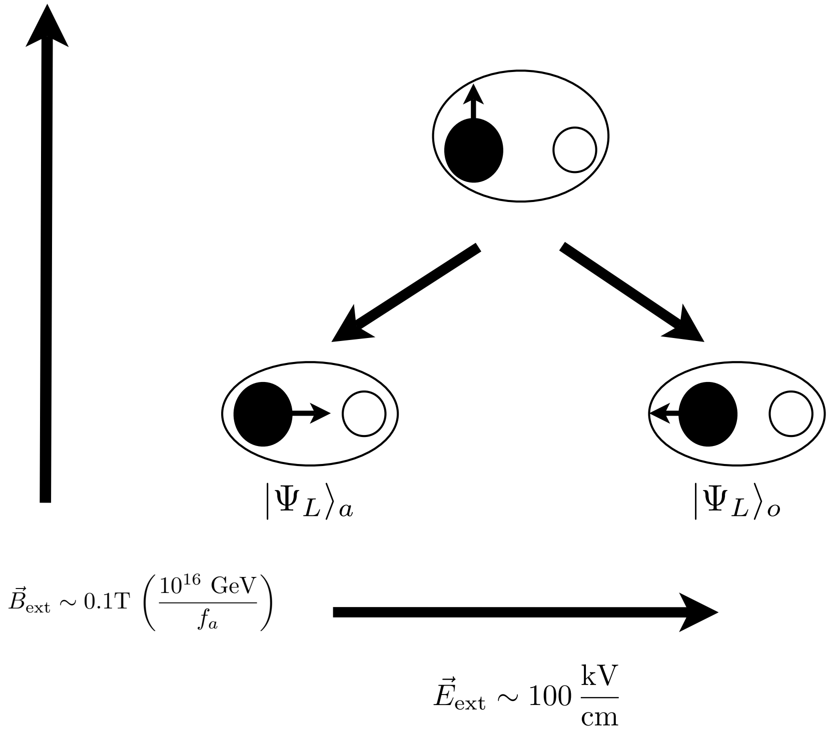

Figure 1: The molecules are polarized by an external electric field $\vec{E}_{\rm ext} \sim 100\,\frac{\mathrm{kV}}{\mathrm{cm}}$. They are then placed in a linear superposition of the two states $|\Psi_L\rangle_a$ and $|\Psi_L\rangle_o$, where the nuclear spin is either aligned or anti-aligned with the molecular axis respectively, leading to a phase difference between them in the presence of the axion induced nuclear dipole moment d_n. The external magnetic field $\vec{B}_{\rm ext} \sim 0.1\ \mathrm{T}\left(\frac{f_a}{10^{16}\mathrm{GeV}}\right)$ causes the spins to precess, so that the phase difference can be coherently accrued over several axion oscillations. The frequency can be scanned by dialing this magnetic field $\vec{B}_{\rm ext}$ until it is resonant with the axion frequency.

requires highly sensitive molecular interferometers that contain a light Actinide. There are two major, scalable technological paths that can be pursued in order to achieve these sensitivity goals.

First, the sensitivity of molecular interferometers can be improved through improved molecular cooling techniques. Considerable progress has been recently achieved in cooling molecular beams, thereby increasing the sensitivity of molecular interferometers. For example, the magnetic Feshbach resonance has been recently used to create $\sim 3 \times 10^5$ polar bialkali molecules of KRb cooled to sub microkelvin temperatures. These techniques could potentially be used to create bialkali molecules containing the actinide Francium, which belongs to the same chemical group as K and Rb. Innovative extensions of laser cooling techniques have also been successfully employed to create sub millikelvin ensembles of SrF, with possible applications to other molecular structures. The molecular structure that allows for the successful laser cooling of SrF should also apply to other alkaline-earth monohydrides and monohalides. These techniques could prove particularly useful in dealing with molecules of the actinide Radium which is also an alkaline earth element. Furthermore, it may also be possible to use squeezed molecular states to significantly enhance the shot noise limits of the interferometer. Such enhancements have been proposed for atomic interferometers and an $\mathcal{O}(5)$ enhancement has been recently demonstrated. It is important to note that these techniques are scalable and significant enhancements to the sensitivity of molecular interferometers seem possible in the near future.

In addition to developments in molecular interferometry, this proposal requires the use of actinide nuclei which give rise to enhanced Schiff moments. These nuclei are radioactive and special techniques are needed to use them in the laboratory. Such techniques are currently being developed in order to use these nuclei to search for static nucleon electric dipole moments. In particular, successful laser trapping and cooling of Radium and Francium atoms have been demonstrated. However, molecular states containing these actinides have not been used in laboratory studies. Further work is necessary to establish if the actinide nuclei produced by the above techniques can be successfully used to produce molecular states of interest.

The detection of the dark matter axion field requires the harnessing of advances in both molecular interferometry and the ability to manipulate actinide nuclei. The current technological status in each of these areas is scalable and advances seem possible in the near future. Each of these areas are under very active development. Advances in each area are individually useful for a variety of physics searches, in particular the search for static nucleon electric dipole moments. However, the combination of these techniques will advance not only these dipole moment searches but also allow for the unique opportunity to search for the dark matter axion field.

3 Accelerator or Lab Facility

This experiment is currently at the stage of a proposal. Its natural home would be a facility that has expertise in atomic and molecular technology as well as expertise in the production and handling of actinides or other elements with large Schiff moments. The Argonne National Lab, which is currently the home of a Radium EDM experiment is one example of a natural home for this kind of experiment.

4 Physics Reach

This experiment can search for axion dark matter where the axion decay constant f_a lies between the Planck scale and the grand unification (GUT) scale $\sim 10^{16}$ GeV) and possibly as low as $\sim 10^{15}$ GeV, as in Figure 2. A discovery in such an experiment would not only reveal the nature of dark matter and confirm the axion as the solution to the strong CP problem, it would also provide a glimpse of physics at the highest energy scales, far beyond what can be directly probed in the laboratory.

5 Status and Schedule

This is a proposed experiment.

6 Future Plans

The experiment requires significant technology development as discussed earlier. The technological advances are scalable and have applications to multiple physics goals.

7 Collaborating Institutions and Collaborators

The proposal was conceived by Dr. Surjeet Rajendran and Prof. Peter Graham of Stanford University.

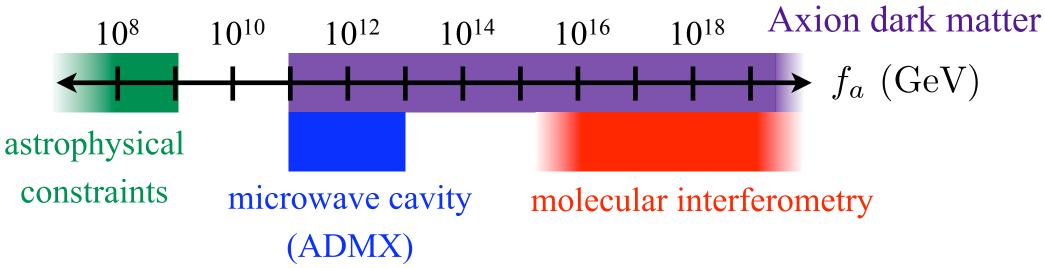

Figure 2: The parameter space of the axion in f_a (GeV). Values of $f_a < 10^9$ GeV are ruled out by astrophysical constraints (green). Values of $f_a \gtrsim 10^{11}$ GeV allow the axion to be the dark matter (purple). The (blue) region labelled "microwave cavity" shows the region of parameter space that is potentially observable with microwave cavity experiments, e.g. ADMX. The (red) region labelled "molecular interferometry" shows the range of f_a which is potentially observable with the experiment proposed here. The lower limit on this region may in fact be lower than shown, depending on technological advances.

8 Written Materials (e.g. references)

The proposal was published in Physical Review D 84:055013, 2011. References to the various technologies alluded to in this document can be found in this paper.

9 Any other info?