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Polarized Targets as Dark Matter Detectors

Abstract

The strong electron paramagnetic resonance (EPR) of polarized targets can be used to search for axions as dark matter candidates in the range of $(1-100)$ GHz. Once the axions are absorbed they can provide the communications gate for spin thermal equilibrium between different nuclei that were kept artificially at different temperatures.

Y. K. Semertzidis[3], G. Baum[1], P. Berglund[6], S. Bültmann[1], C. M. Dulya[2], P. Hautle[5], N. Hayashi[8], S. Ishimoto[8], A. Kishi[6], Y. Kisselev[7], D. Krämer[1], J. Kyynäräinen[3], J.-M. Le Goff[4], A. Magnon[4], T. Niinikoski[3]

[1]) Universität Bielefeld, Fakultät für Physik, D-33615 Bielefeld, Germany
[2]) University of California, Department of Physics, Los Angeles, 90024 CA, USA
[3]) CERN, PPE Division, CH-1211 Genève 23, Switzerland
[4]) DAPNIA, C. E. Saclay, 91191 Gif-sur-Yvette, France
[5]) ETH, 8093 Zürich, Switzerland
[6]) Helsinki University of Technology, Low Temperature Laboratory, Otakaari 3A, 02150 Finland
[7]) JINR, Laboratory of Super High Energy, Dubna, Russia
[8]) Nagoya University, Department of Physics, Furo-Cho, Chikusa-Ku, 464 Nagoya, Japan

The axions appeared first as a solution to the strong CP problem, the fact that the QCD Lagrangian was violating the charge parity (CP) symmetry whereas the experimental limit for the electric dipole of the neutron did not support it. Peccei and Quinn [1] first introduced a symmetry (named after them) and Weinberg and Wilczek [2] showed that from the breakdown of this symmetry appears a particle, the axion.

The microlensing events reported by EROS, MACHO, and OGLE [3] stimulated a lot of discussion as to whether different kinds of cold dark matter (CDM) are worth seeking for in our galaxy. Gates and Turner [4] claim that microlensing is not a sensitive probe for local dark matter (LDM) and that the best motivated CDM candidates are the axion with a mass around 10^{-5} eV and neutralinos (a superposition of photino, zino and two higgsinos) with mass between 10 GeV and 1 TeV.

There are several experiments which searched for axions, that couple to two photons, as LDM as well as making attempts for a direct production in a limited mass region. [5, 6, 7, 8, 9] The coupling constant versus mass exclusion regions from them are given in Fig. 1 (from reference [7]) where some astrophysical bounds are also given.

Axions can also couple directly to fermions and to the spin of the electrons [10, 11, 12, 13, 14] a feature we will try to exploit in this paper. Polarized target materials contain a large amount of paramagnetic centers [15] which help in the nucleon polarization buildup. Those centers are essentially semi-free electron spins which exhibit strong EPR lines in high magnetic fields and low enough temperatures. The axions are pseudoscalars (0^-) and behave effectively very similarly to M1 photons; they can induce an electron spin flip when their mass coincides with the EPR frequency. Their de Broglie wavelength is $(10 - 100)$ m and their kinetic energy very small (since they are bosons they can all be in the same energy state) making their energy fractional width Γ_a very small ($Q_a = m_a/\Gamma_a = 10^6$). In order to provide the closure of the universe their local density must be around $\rho_a = 0.3$ GeV/cm^3.

The axion absorption rate can be inferred from Eq. 12 of reference [14] and is:

$$N_a = (4/q^2)\rho_a V(m_e g_e/F)^2 Q_f \chi_0 u_\perp^2 \tag{1}$$

where q is the electron charge, $V = 2340$ cm^3 the volume of the polarized target, m_e the electron mass, g_e model dependent dimensionless constant of order one, Q_f the quality factor of the EPR resonance (which here we will assume to be limited by the magnetic field inhomogeneity i.e. about 10^4), χ_0 the static susceptibility, $u_\perp^2 = 10^{-6}c^2$ the axion velocity orthogonal to the direction of the electron spins (which is equal to the virial velocity of the galaxy), and F the breaking scale of the Peccei-Quinn symmetry, and related to the axion mass by:

$$m_a = 6 \times 10^{-6} eV(10^{12} GeV/F) \tag{2}$$

We can now calculate the axion absorption rate at say $B = 2.5$ T and $T = 50$ mK which are routinely attainable during the physics run of the spin muon collaboration (SMC) [16]. First we need to calculate χ_0:

$$\chi_0 = \mu_0 \frac{N\hbar^2\gamma^2 I(I+1)}{3kT} \approx 10^{-2} \tag{3}$$

where $\mu_0 = 4\pi \times 10^{-7}$ V s/A m, $N = 7 \times 10^{25}$ spins/m^3 the electron spin density, $\gamma = 2\pi f/B$ with f the EPR frequency, I the electron spin, and k the Boltzmann's constant. From Eq. (1) we have that $N_a \approx 0.35 \times 10^{-2}$ axions/s. The estimated background at 50 mK from the thermal photons of the copper microwave cavity (emissivity $\approx 10^{-3}$), surrounding the polarized target, is less than 10^{-4} photons/s with frequency which peaks around 1 GHz and therefore is totally negligible. In reality the polarized target is kept at 50 mK whereas the cavity is at 3 K with vacuum between the two systems. However, in principle, the cavity temperature can be kept very close to that of the target.

Since axions behave like microwave photons we can calibrate the system by turning on the microwaves in the polarized target and setting their frequency to be close to the EPR line. In our polarized target there are different nuclear species that are not in thermal contact when the microwaves are off. However, when the microwaves are switched on, the various spin species establish thermal contacts and tend to obtain the same final spin temperature. Last year this prospect motivated the work on the cross relaxation between protons and ^{13}C-nuclei [17] where we had saturated the ^{13}C polarization by RF and observed the polarization buildup with and without microwaves. There is certainly an enhancement of the thermal spin contact with the microwaves present. This year the material is deuterated [15] with the contents of the protons being much more than that of the ^{13}C, and the proton signal being much stronger, we might assume that we can observe 1 nJoule of microwave energy. Assuming a total run of 10^6 s for scanning the EPR frequency between $1 - 70$ GHz by moving the magnetic field, the experiment could approach the solar limit shown in Fig. 1.

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Figure captions

Figure 1. Axion coupling to two photons versus axion mass limits from past experiments and star models. Axions with mass in the $(5 \times 10^{-6} - 5 \times 10^{-4})$ eV range are excellent candidates for LDM.