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New ideas on prospective low energy threshold detectors for dark matter searches

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Low energy threshold detectors are necessary in many frontier fields of experimental physics. In particular, these are extremely important for probing possible dark matter (DM) candidates. We present a novel detection approach that exploits the energy levels of atoms maintained at cryogenic temperature. We exploit laser-assisted transitions that are triggered by the absorption of the incident particle in the material and lead to the emission of a fluorescent photon or an electron. In this approach, the incident particle will in fact excite the first low-lying energy level that is then up-converted using an opportune narrow-band laser system. Two different detection schemes are thus possible in our active material: one is based on a photon signal while the other takes advantage of high efficiency in-vacuum charge detection.

Keywords: Dark matter detection; low energy threshold; rare gas crystals.

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1. Introduction

An extraordinary result of modern cosmology is that the major part of the mass content of the universe is unknown. This amount of matter, which interacts almost only through the gravitational force, is called dark matter (DM). In particular, astrophysical considerations related to the rotational curves of galaxies, gravitational lensing, galaxy clustering and cosmic microwave background (CMB) anisotropies give the following result:[1]

$$\begin{aligned} \Omega_{\text{(ordinary matter)}} &= 0.0456 \pm 0.0015 \\ \Omega_{\text{(dark matter)}} &= 0.228 \pm 0.013 \\ \Omega_{\text{(dark energy)}} &= 0.726 \pm 0.015 \end{aligned} \tag{1}$$

where Ω is defined as

$$\Omega_x = \frac{8\pi G \rho_x}{3H^2} = \frac{\rho_x}{\rho_c} \tag{2}$$

and G is the gravitational constant, H is the Hubble constant, and $\rho_c = 3H^2/8\pi G$ is the critical density of the universe.

This means that when considering the matter present in the universe, only 20% is made of ordinary matter, while almost 80% is composed of non-visible and unknown matter, the so-called dark matter (DM). Numerous theories and models have been proposed in the last decades to solve this lack of comprehension. The favored solution to this problem seems to be that DM would be composed of particles that do not belong to the Standard Model (SM).[2] In particular, most of the searches for DM are focused on weakly interacting massive particles (WIMPs) and axion-like particles (ALPs). WIMPs are massive particles that can interact through the weak force and can thus be detected in large calorimeters with low background. The axion, and also ALPS, are pseudo-Nambu–Goldstone bosons arising from extensions of the SM; in particular the axion is a particle introduced by R. Peccei and H. Quinn in the '70s to solve the charge–parity (CP) problem in the strong interaction. According to theory, axions and ALPs can interact with ordinary matter such as photons, fermions or hadrons through different effects, for instance the Primakoff or the axio-electric effect.

Many experiments, most of them in underground laboratories, are currently running and taking data. A WIMP interaction cross section limit in the range [1–10^4] GeV/c^2 is given by the Xenon experiment (the best value is $\sigma_{\text{WIMP–Xe}} = 4.1\cdot10^{-47}$ cm^2 at $m_{\text{WIMP}} = 30$ GeV/c^2),[3] while axions are instead excluded in the range [19–24] μeV by the ADMX experiment.[4] Numerous other collaborations are searching for DM in the mass range of μeV to GeV. Unfortunately, up to now, no experimental evidence of dark matter has been found. Other experimental detection schemes are thus of paramount importance in this endeavor.

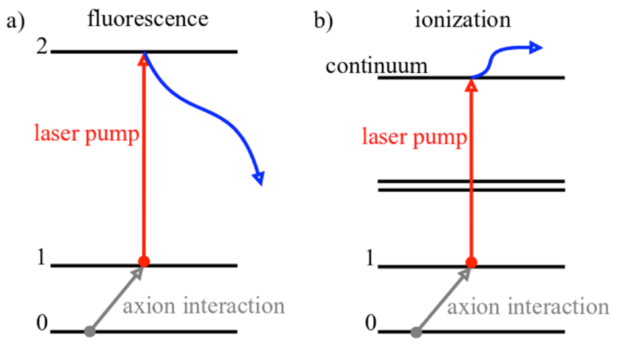

Fig. 1. Schematic representation of the two approaches that we are pursuing: a) the LIF scheme; and b) the LII scheme. These schemes are explained in the text.

2. Our Scheme

We propose to take advantage of innovative schemes that exploit electronic energy levels of atoms combined with laser spectroscopy techniques that are used as probes for this system. A similar approach is also at the basis of the Infrared Quantum Counter (IRQC) concept that was proposed by N. Bloembergen in the 1950s for detection with high efficiency Infrared (IR) light.[5] In such a system, the axion–electron coupling allows us to define a novel kind of detector that is complementary to the detectors already in operation. The term of interaction of the direct axion–electron coupling[6] is

$$\frac{g_{ae}}{2e}\vec{\nabla}a\cdot\vec{\mu}, \tag{3}$$

where g_{ae} is the coupling constant, e is the electric charge, μ is the electron magnetic moment and a is the axion field, which plays the role of an effective magnetic RF field. Considering the axion mass (m_a) and its momentum (p_a), a resonant condition is furthermore met when the axion energy $\sqrt{m_a^2c^4+p_a^2c^2}$ matches a fixed energy transition ΔE, which can be tuned continuously by exploiting the Zeeman effect. In this way, the axion will promote resonant transitions from the ground state (0) to the first excited level (1) as shown schematically in Fig. 1. It is also worth noting that, since axions are usually assumed non-relativistic, from the dispersion relation $E_a \approx m_a$, and p_a is thus negligible.

In the framework of the AXIOMA and DEMIURGOS projects at Legnaro National Laboratory, we are applying this scheme to cryogenic crystals and investigating different observables such as Laser Induced Fluorescence (LIF) and Laser Induced Ionization (LII) in rare-earth and alkali-doped crystals of oxides, fluorides or rare gases (RG) matrices.[7] Figure 1 shows the axion excitation in LIF and LII processes respectively on the left and on the right side. The axion is absorbed from the ground state (level 0) to the first excited Zeeman (level 1) whose energy ΔE can be tuned using an external static magnetic field B in the range (10^{-2}–10) T. The narrow bandwidth laser pump must be tuned to the transition between the first excited level and respectively an upper level in the LIF or the continuum in the LII scheme. In opportune materials, where non-resonant absorption can be neglected, laser absorption is triggered only when the first transition between 0 and 1 occurs and thus laser flux does not represent a limitation. Depending on the two different approaches, a fluorescent photon or an electron is then the signal. The operating temperature of the crystals can be calculated comparing the thermal excitation rate (R_{th}) and the expected axion interaction rate (R_a). R_{th} in the material is given by:[8]

$$R_{th} = e^{\frac{-\Delta E}{K_b T}} \cdot \frac{1}{\tau} \tag{4}$$

where K_b is the Boltzmann constant and τ is the lifetime of the first excited level. The rate R_a of the interaction between axion and a single target atom in the ground state can instead be calculated following Ref. 9, and it is the following:

$$R_a = 1.4 \cdot 10^{-26} g_i^2 \left(\frac{\rho_a}{0.4\text{GeV/cm}^3}\right)\left(\frac{E_a}{330\mu\text{eV}}\right)^2 \left(\frac{v/c}{10^{-3}}\right)^2 \left(\frac{\tau_s}{10^{-6}\text{ s}}\right) [\text{Hz}], \tag{5}$$

where g_i is the coupling strength of axion to target atoms, ρ_a is the axion density, $E_a = h\nu_a$ is the axion energy, v is the mean velocity of the axion in the galaxy halo and τ_s is the shortest time between axion coherence time, lifetime fluorescence and the integration time of the measurement. Assuming standard values for the quantity in R_a, the crystal temperature must be lower than $\sim$ 57 mK.

3. Preliminary Results

Concerning the LIF scheme, we did some preliminary measurements in a fluoride crystal for infrared detection, exploiting a scheme similar to the IRQC. The core of the set-up is a pulse-tube refrigerator, which allows a minimum temperature of 10 K. IR photons in the (1.2–4.5) μm band are delivered by a quartz–tungsten–halogen lamp, whose beam is collimated and focused onto the crystal. These photons are absorbed in Er^{3+} atoms between the ground state and the first excited level where they can be upconverted. A tunable titanium–sapphire (Ti:Sa) laser system is used to pump the crystal, while a visible photomultiplier tube (PMT) allows the detection of fluorescent photons in the orthogonal direction with respect to the laser.

The fluorescence measurements of Er^{3+}:YLF at 10 K allowed us to identify the transitions of electrons in the 4*f* manifold of the trivalent rare earth. Furthermore, we applied an external magnetic field, and we measured the Zeeman splitting of the levels. The amplitude of the fluorescence light at the PMT ($\lambda \sim 540$ nm) as a function of the excitation wavelength is shown in Fig. 2. Experimental data both with and without external magnetic field (B) at 290 mT are shown. A splitting of the level of $\approx \delta E = \mu_B \cdot B \approx 6$ GHz was correctly found. Further results are presented in Ref. 8. We are currently investigating the limitations to the sensitivity of this scheme that may arise from spurious laser absorption or due to impurities in the crystals. Furthermore, the sensitivity of the measurement is related to the laser flux, the absorption cross section and the lifetime of the level. In the present measurements, laser flux has been set at 50 W/cm^2. Such a value is sufficient to attain an efficiency of ~40% in the up-conversion of 1.5 μm photons in an Er^{3+}:YLF crystal.

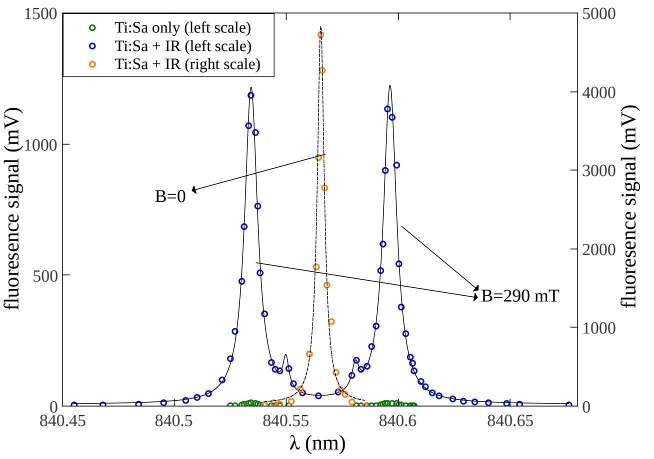

Fig. 2. Fluorescence of the Er^{3+}:YLF crystal at 10 K pumped with Ti:Sa laser system. The wavelength in the x-axis is the excitation wavelength. The splitting of the line due to the magnetic field is shown by the blue points. Black lines are the fit functions using a Lorentzian equation.

Table 1. Melting and boiling point of Rare Gases.

Rare Gas	T_{melt} (K)	T_{boil} (K)
Ne	24.57	27.09
Ar	84.0	87.29
Kr	116.2	119.79
Xe	161.4	165.03

The Laser Induced Ionization scheme is instead based on the possibility to extract electrons through the solid-vacuum interface and to efficiently detect them using low noise, high gain charge detectors. This extraction process is favored in matrices where electrons have a positive ground state energy with respect to the vacuum. Examples are the rare gas (RG) solid crystals. These matrices are also important because they represent a good environment for embedding different species such as alkali or rare earth. Perturbations of the atomic level structure of guest atoms are very low in RG matrices due to their feeble interactions. Rare gases condense into colorless solids at cryogenic temperature as listed in Table 1.

To embed guest atoms in the condensed phase, according to the Matrix Isolation Technique, we have assembled a cryogenic facility at the Legnaro National Laboratory.[10] As shown in Fig. 3, a pulse-tube cryocooler provides the low temperature cold finger where crystals can be grown. We also developed a gas purification system based on activated charcoal traps and Oxysorb commercial filters that clean the gas reaching an impurity level lower than ppb.

Preliminary measurements concerning neon and argon crystals doped with alkali are currently underway and will be presented in a future article.

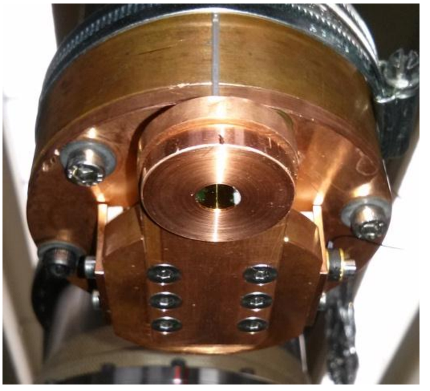

Fig. 3. Picture of the cold finger at ~4K. This copper part is attached to the pulse tube refrigerator and represents the growth plate for RG crystals.

4. Conclusions

Novel detectors characterized by a low energy threshold in a large active volume are necessary in the study of the physics beyond the Standard Model. In particular, complementary detectors for the search of dark matter are necessary to scan the larger mass range possible. We propose a novel scheme with two approaches, one using Laser Induced Fluorescence and one using Laser Induced Ionization. Interaction between dark matter particles and electrons of the low-lying energy levels of atoms can in fact lead in an excess of population that can be probed using laser spectroscopy techniques. Preliminary results using Er^{3+}:YLF and RG crystals were briefly discussed.

Acknowledgments

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