Magnetized Media as Detectors for Galactic Axions

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for the AXIOMA collaboration

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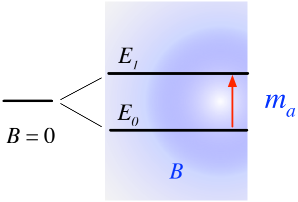
AXION COUPLING

AXION-FERMION interaction

detection of atomic transitions
$|0\rangle \to |i\rangle$ in which axions are absorbed

- AXIOMA $\Longrightarrow$ detection of VIS-NIR *photons* in rare-earth doped materials
- QUAX $\Longrightarrow$ axions are converted to *magnons* in a ferri-/para-magnet



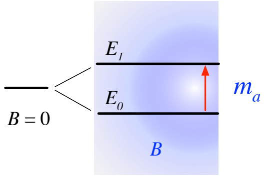
QUAX and AXIOMA

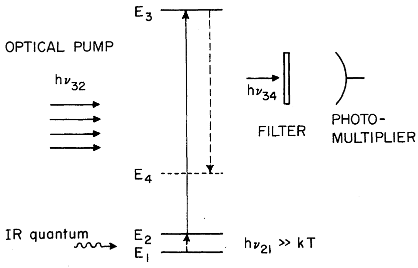
AXIOMA - AN UPCONVERSION SCHEME

AXION-FERMION interaction

detection of atomic transitions
$|0\rangle \rightarrow |i\rangle$ in which axions are absorbed

- QUAX $\Longrightarrow$ axions are converted to *magnons*
- AXIOMA $\Longrightarrow$ axions are converted to VIS-NIR *photons*

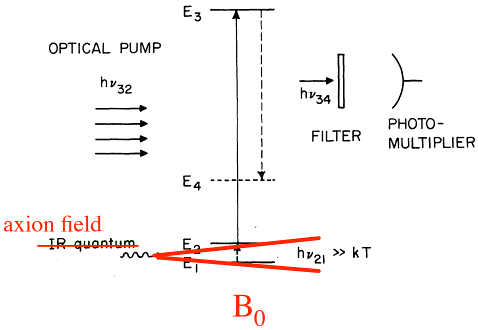




- pump laser resonant with transition $2 \rightarrow 3$
- material transparent to the pump until an IR photon is absorbed ($1 \rightarrow 2$)
- level 3 is fluorescent $\Longrightarrow$ detection can be accomplished via conventional detectors (PMT or PD)
- such energy level scheme can be realized in wide bandgap materials doped with trivalent rare-earth ions

N. Bloembergen, *Phys. Rev. Lett.* **2**, 84 (1959)

AXIOMA - AN UPCONVERSION SCHEME



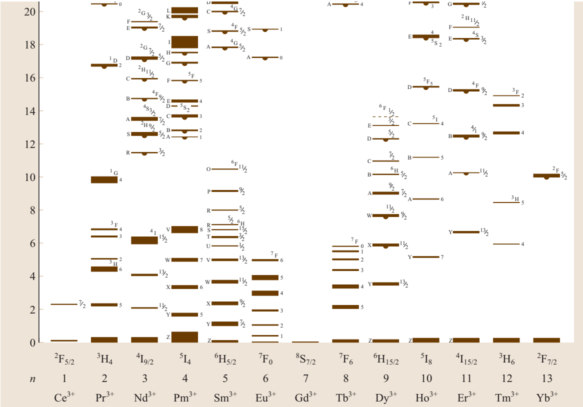
- material transparent to the pump until an AXION is absorbed (1 $\rightarrow$ 2)
- transition 1 $\rightarrow$ 2 takes place between GS ZEEMAN–SPLIT LEVELS to allow for tunability (B_0 field) in the interesting axion mass range
- level 3 is fluorescent $\Longrightarrow$ detection can be accomplished via IR single photon detectors
- dopant (rare-earth ion) concentration compatible with transition rate by axion absorption R_i for a MOLE of target atoms:

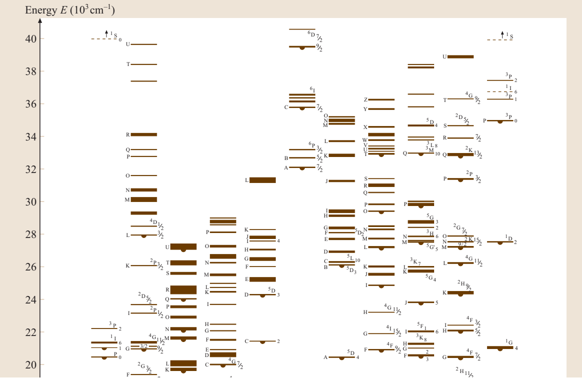
$$N_A R_i = g_i^2 N_A \bar{v}^2 \frac{2\rho_a}{f_a^2} \min(t, t_1, t_a)$$
$$= \frac{2.13 \times 10^3}{\text{sec}} \left(\frac{\rho_a}{\text{GeV/cm}^3}\right) \left(\frac{10^{11}\ \text{GeV}}{f_a}\right)^2 \cdot g_i^2 \left(\frac{\bar{v}^2}{10^{-6}}\right) \left(\frac{\min(t, t_1, t_a)}{\text{sec}}\right)$$

P. Sikivie, PRL **113**, 201301 (2014)

$1\% \longleftrightarrow \sim 10^{20}$ target atoms/cm$^3 \longleftrightarrow\ \gtrsim 1$ liter ACTIVE VOLUME

Energy level diagram of RE^{3+} in $LaCl_3$



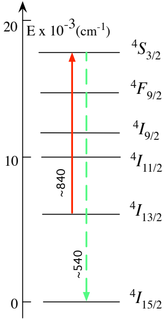


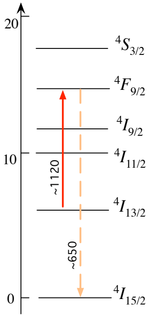
– 4f electrons
– electrostatic interaction 10^4 cm^{-1}

– further splitting by spin-orbit interaction 10^3 cm^{-1}
– crystal field (Stark splitting)

RE in inorganic matrices

Possible upconversion schemes in Er^{3+} and detector intrinsic threshold



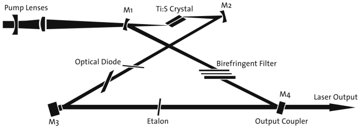


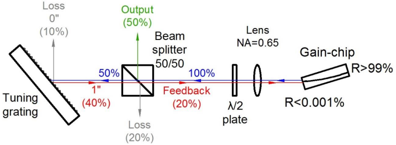
(A) pump at $^4I_{13/2} \to ^4 S_{3/2}$ ($\lambda \sim 840$ nm)
$\to$ fluorescence at 540 nm

(B) pump at $^4I_{15/2} \to ^4 F_{9/2}$ transition ($\lambda \sim 1120$ nm)
$\to$ fluorescence at $\sim$ 650 nm

$\Longrightarrow$ intrinsic threshold $\sim$ 0.7 eV

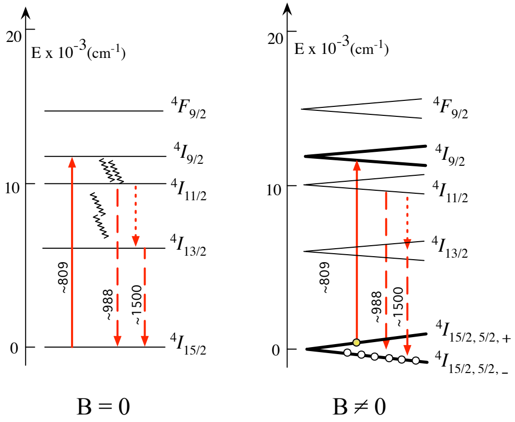
TUNABLE PUMP LASERS





RE IN INORGANIC MATRICES

IMPROVING THE DETECTOR INTRINSIC THRESHOLD

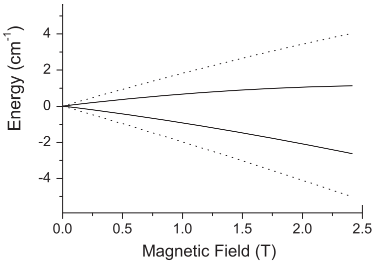


pump laser tuned to $^4I_{15/2,5/2,+} \rightarrow ^4 I_{9/2,9/2,+}$ transition ($\lambda \sim 809$ nm)

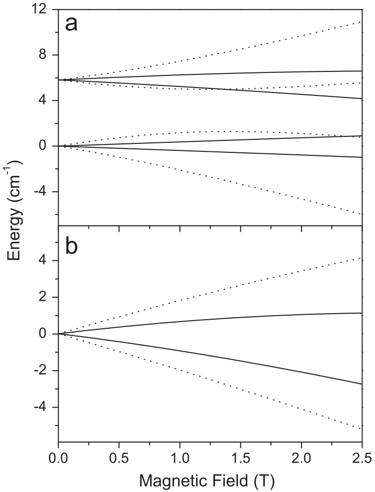
$\rightarrow$ IR fluorescence

$0.5\,\mathrm{T} < B_0 < 2.5\,\mathrm{T}$
$20\,\mathrm{GHz} < \nu_a < 110\,\mathrm{GHz}$

$83\,\mu\mathrm{eV} < m_a < 0.45\,\mathrm{meV}$ (“dressed” e^-)



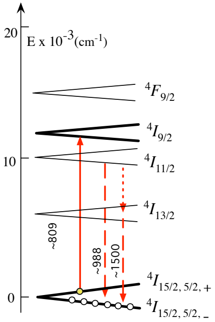
A DRESSED ELECTRON



The Er^{3+}, 4f shell electrons are dressed of their interaction with the matrix.
Calculated Zeeman level energies as a function of B_0 magnetic field parallel to c (solid lines) or to a (dashed lines) in Er:YLF.
(a) ${}^4I_{13/2}(0)$ and ${}^4I_{13/2}(1)$
(b) ${}^4I_{15/2}(0)$

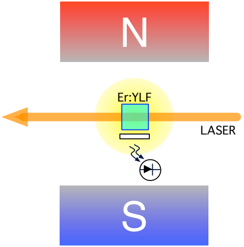
LASER-INDUCED IR FLUORESCENCE AND AXION TRANSITION

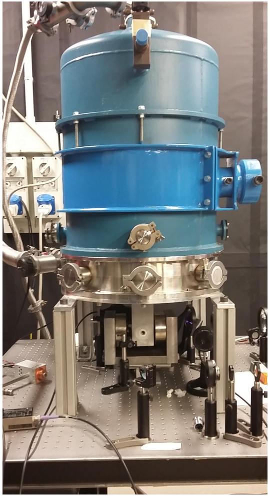
- Er:YLF (0.01%, 1% doping), oriented
- immersed in liquid He (4.2 K)/superfluid He (1.51 K)
  $\Longrightarrow$ axion transition saturated
- tunable laser (Ti:Sa)
- infrared (1.5 μm) fluorescence scheme
- $B_0 = 370\,\mathrm{mT}$ (permanent magnet)



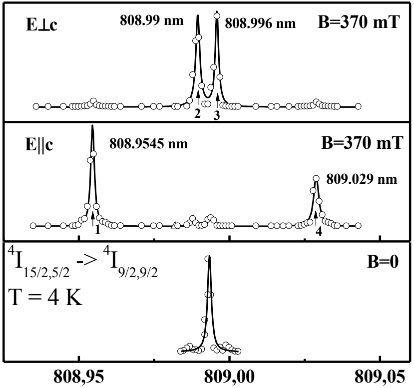
$B \neq 0$

- identify Zeeman splitting
- investigate laser-induced noise (in a LIF scheme that involves phonon generation)

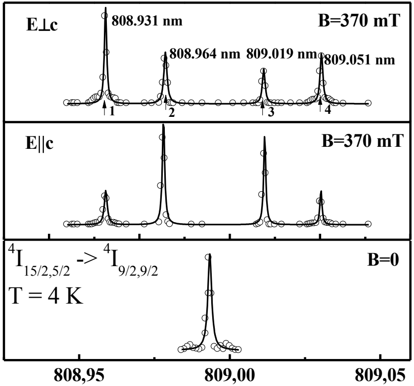




$B \parallel c$



$B \perp c$



$\lambda_3 - \lambda_1 = 41.3\,\text{pm} \rightarrow 78.2\,\mu\text{eV} \rightarrow 18.9\,\text{GHz}$

$\lambda_3 - \lambda_1 = 88\,\text{pm} \rightarrow 166.7\,\mu\text{eV} \rightarrow 40.3\,\text{GHz}$

$\lambda_4 - \lambda_3 = 32.99\,\text{pm} \rightarrow 62.5\,\mu\text{eV} \rightarrow 15.2\,\text{GHz}$

$\lambda_4 - \lambda_3 = 32\,\text{pm} \rightarrow 60.5\,\mu\text{eV} \rightarrow 14.7\,\text{GHz}$

By comparison with data in the literature we are able to identify the splitting of the ground state in the (A) upconversion scheme with $B \parallel c$.

$B \parallel c$

$$\boxed{\lambda_3 - \lambda_1 = 41.3\,\text{pm} \rightarrow 78.2\,\mu\text{eV} \rightarrow 18.9\,\text{GHz}}$$

$$\lambda_4 - \lambda_3 = 32.99\,\text{pm} \rightarrow 62.5\,\mu\text{eV} \rightarrow 15.2\,\text{GHz}$$

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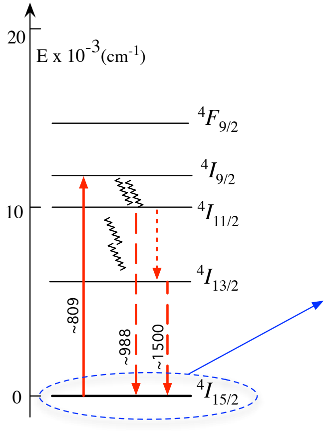
NO ATOMS IN THE EXCITED STATE REQUEST

$N_A e^{-(m_a/T)} < 0.1 \leftrightarrow T = 12\,\text{mK}\left[\frac{m_a(eV)}{0.6\cdot 10^{-4}}\right] = 15.6\,\text{mK} \Longrightarrow \Uparrow B_0$ field (thus m_a) to operate at $T \sim 200\,\text{mK}$

LASER-INDUCED BACKGROUNDS

Is the laser **heating** the crystal? / At which level is the **transparency condition** not satisfied?
Measure the temperature of the active volume of the detector via LIF from the Stark levels.



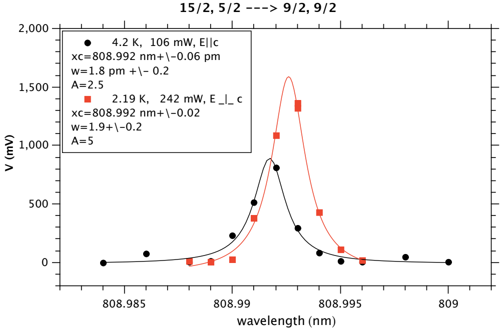
Stark splitting of the free ion terms

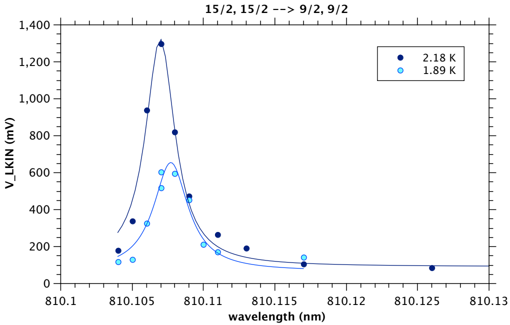
$^{2S-1}L_J$ level	$\lvert M_J \rvert$	E_{exp} (cm^{-1})
$^4I_{15/2}$	5/2	0
	15/2	17
	3/2	28
	1/2	57
	9/2	255
	7/2	290
	11/2	320
	13/2	355

LASER-INDUCED BACKGROUNDS

Measure the temperature of the active volume of the detector via LIF from the Stark levels:
LIF from (15/2,15/2) at two different temperatures scales as the ratio of the Boltzmann factors P(E)

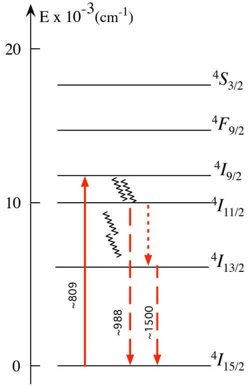
T [K]	kT [meV]	kT [cm-1]	P(E) GS	P(E) 1S
1.67	0.144	1.162	1.0000	4.40e-07
2.00	0.172	1.391	1.0000	4.93e-06
4.20	0.362	2.921	0.9970	0.00296
10.0	0.862	6.955	0.9053	0.0786
67.0	5.78	46.60	0.4459	0.310

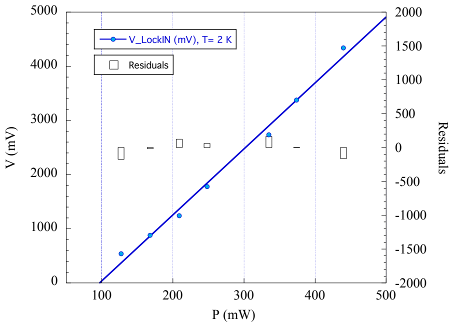




LASER-INDUCED BACKGROUNDS

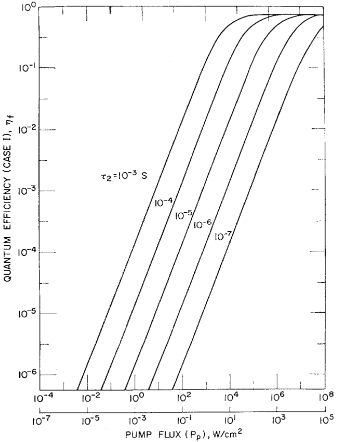
Measure the temperature of the active volume of the detector via LIF from the Stark levels:
LIF from (15/2,15/2) is linear with laser power

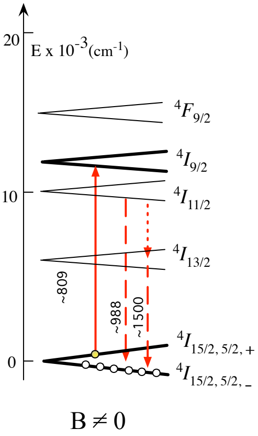




Matching the axion linewidth

The linewidth $\Delta f = 1/\pi\tau_+$ (τ_+ lifetime of the upper Zeeman level) of the transition between the GS Zeeman-split levels should be matched to $Q_a \sim 2 \cdot 10^6$ (axion linewidth)





$\tau_+ \sim 300\,\mu$s at 1T (20 GHz/1kHz) is compatible with an efficient upconversion process

CONCLUSIONS

AXIOMA

- results for a gas system New J. Phys. **17** (2015) 113025
- upconversion in RE-doped crystals Appl. Phys. Lett. **107** (2015) 93501
- solid crystals of inert gasses: demonstrated apparatus that allows high purity crystals growth and verified electrons emission through the solid-vacuum interface in s-Ne and s-CH4

Currently investigating:

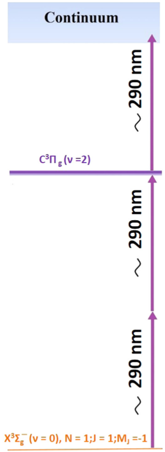
- laser-induced noise
- matching Q_a with the Zeeman transition (τ_m)
- upconversion efficiency and lifetime of the excited state

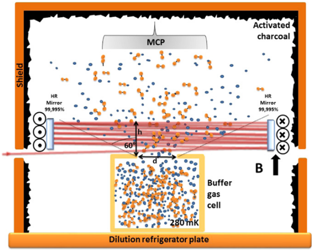
BACKUP SLIDES

AXION DETECTION IN A GAS SYSTEM

- BGC (buffer gas cooling). $^{16}O_2$ cooled by collisions with a helium-3 thermal bath at temperature $T_{He} \simeq 280\,\mathrm{mK} \Longrightarrow W_{ba}(B_{\min}) = 11\,\mathrm{cm}^{-1}$ (1.4 eV)
- magnetic field region:
  W_{ba} saturates for $B > B_{\max} = 18\,\mathrm{T}$
  $1.4\,\mathrm{eV} < m_a < 1.9\,\mathrm{eV}$
- detection: REMPI (resonance-enhanced multi-photon ionization spectroscopy)
- $N_{\mathrm{refl}} = 13500$ to maximize the fraction of molecules that interacts with the laser beam $\mathcal{F} = (N_{\mathrm{refl}}\,\pi\,w^2)/(h\,d + h^2 \tan\theta)$

(2+1)REMPI
2 ph to intermediate state
+1 ph to ionize





New J. Phys. **17** (2015) 113025

GAS SYSTEM: ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

In 1 s, the number of oxygen molecules that have been exposed to the axion field is

$$N_{\mathrm{molec}} = \frac{n_{\max}}{4}\pi(d/2)^2 v_m,$$

where $v_m = \sqrt{(8\,k_B\,T)/\pi\,m}$
and $n_{\max} \simeq (1/30)\,n_{\mathrm{He}} = 10^{15}\,\mathrm{cm}^{-3}$ max molecular density that can be cooled to T_{He}

$\Longrightarrow$ the axion-induced absorption event number

$$N = N_{\mathrm{molec}}\frac{\bar{h}}{v_m}\mathcal{R}_{ab}\mathcal{F}(n_{\mathrm{days}}\cdot 24\cdot 3600)$$

In the worst case $\mathcal{R}_{ab} = 1\,\mathrm{Hz}/N_A \rightarrow N \simeq 1$ for an acquisition time of 10 days

...is it possible to increase the density?