Detection of axion dark matter in condensed matter, with a focus on tabletop-scale experiments

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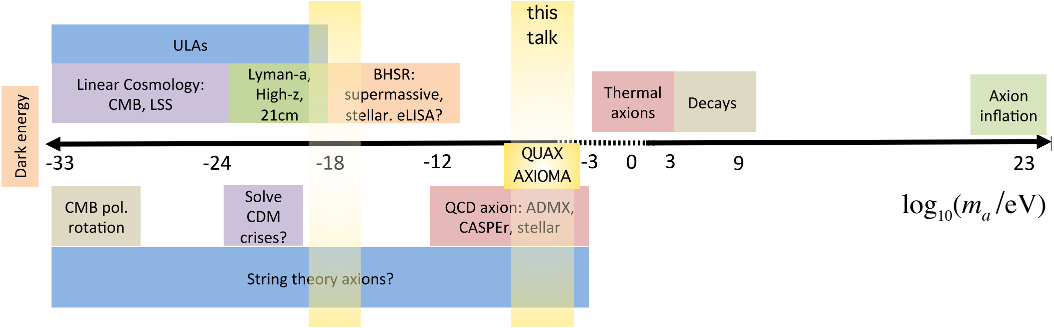
for the QUAX and AXIOMA collaborations

October 25, 2017

AXION & COSMOLOGY



The word *axion* can take on a variety of meanings:

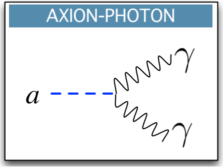
- QCD axion: the Peccei-Quinn solution to the strong-CP problem $m_a \propto 1/f_a$
- ALP: any pseudoscalar Goldstone bosons of spontaneously broken global chiral symmetries, giving a two parameter model (m_a, f_a)
- ST&SUGRA: either matter or pseudoscalar fields associated to the geometry of compact spatial dimensions

RELEVANT AXION INTERACTIONS WITH SM PARTICLES WHEN $v/c \ll 1$

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a\, \partial^\mu a + \frac{1}{2}m_a^2 a^2$$

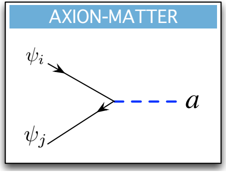
An almost *model-independent axion mass*:

$$m_a \simeq 0.6 \times 10^{-4}\,\text{eV}\left(\frac{10^{11}\text{GeV}}{f_a}\right)$$



$$\mathcal{L}_{a\gamma\gamma} = -\frac{\alpha}{2\pi} f_a^{-1} g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

Primakoff effect:
axion detection by their decay into microwave photons in an external magnetic field **B**



$$\mathcal{L}_a = f_a^{-1} g_{aij} \bar{\psi}_i \gamma^\mu \gamma^5 \psi_j \partial_\mu a$$

In DFSZ axion models couplings with fermions are not suppressed at tree level

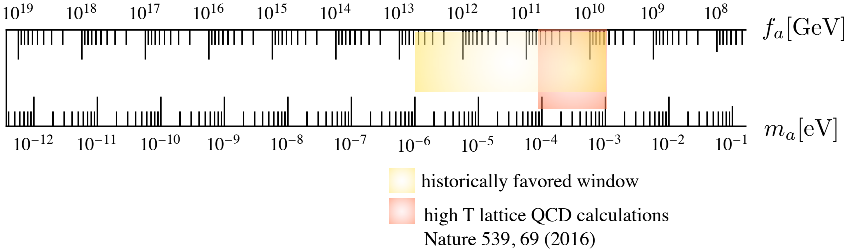
AXION MASS

An almost *model-independent axion mass*:

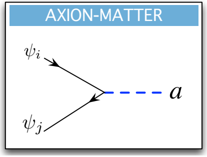
$$m_a \simeq 0.6 \times 10^{-4}\,\text{eV}\left(\frac{10^{11}\text{GeV}}{f_a}\right)$$

$$\omega \propto m_a$$

$$B_a \propto \rho_{a\,\text{DM}}$$



AXIONS AS EFFECTIVE OSCILLATING MAGNETIC FIELD ACTING ON FERMIONS



$$\mathcal{L}_a = f_a^{-1} g_{aij} \bar{\psi}_i \gamma^\mu \gamma^5 \psi_j \partial_\mu a$$

In DFSZ axion models couplings with fermions are not suppressed at tree level

$$H_{\rm int} = \frac{g_{aee}}{f_a}\left(\vec{\nabla} a \cdot \vec{\sigma} + \partial_t a \frac{\vec{p}\cdot\vec{\sigma}}{m_e}\right)$$

$$i\hbar \frac{\partial \varphi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_p \hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla} a\right]\varphi$$

$$-\frac{g_p \hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla} a \equiv -2\frac{e\hbar}{2m}\boldsymbol{\sigma}\cdot\left(\frac{g_p}{2e}\right)\boldsymbol{\nabla} a$$

$-2\mu_B\boldsymbol{\sigma},$

μ_B the Bohr magneton

$$B_a \equiv \frac{g_p}{2e}\boldsymbol{\nabla} a$$

effective magnetic field

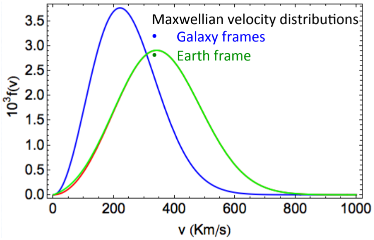
The interaction term has the form of a spin−magnetic field interaction with ∇a playing the role of an oscillating (ω frequency) effective magnetic field

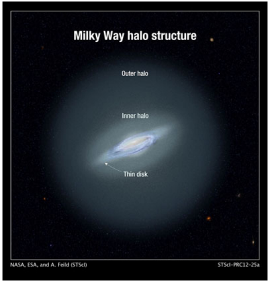
$$\omega \propto m_a$$

$$B_a \propto \rho_{a\,\rm DM}$$

AN AXION WIND

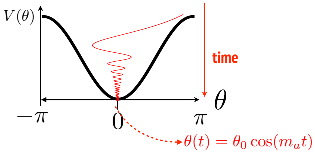
RELEVANT PROPERTIES FROM Λ−CDM COSMOLOGY





- cold DM $\longleftrightarrow$ coherent axion field filling the Universe (hp: axionic DM)
- cosmic axion density $\rho_{DM} \sim 300\,\mathrm{MeV/cm^3} \longrightarrow n_a \sim 3\times 10^{12}\,(10^{-4}\,\mathrm{eV}/m_a)$ axions/cm^3
- axion velocities are distributed according to a Maxwellian distribution
  $f(v) = 4\pi\left(\frac{\beta}{\pi}\right)^3/2v^2\exp(-\beta v^2)$, with $\beta = \frac{3}{2\sigma_v^2}$, σ_v velocity dispersion [Turner]
- + motion of E in the galaxy $\longrightarrow$ they can be seen as a wind with $v \sim 10^{-3}\,c$

MATCHING TO THE AXION LINEWITH



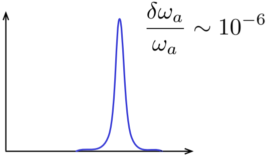
a_0 is a very small number ($B_a \sim 10^{-21}$ T) but coherent oscillations allow for detection

COHERENCE TIME

$$\tau_{\nabla a} = 0.68\tau_a \simeq 34\,\mu\text{s}\left(\frac{10^{-4}\text{eV}}{m_a}\right)$$

CORRELATION LENGTH

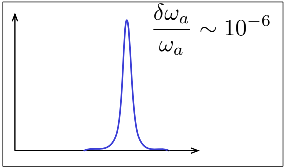
$$\lambda_{\nabla a} = 0.74\lambda_a \simeq 10.2\,\text{m}\left(\frac{10^{-4}\text{eV}}{m_a}\right)$$

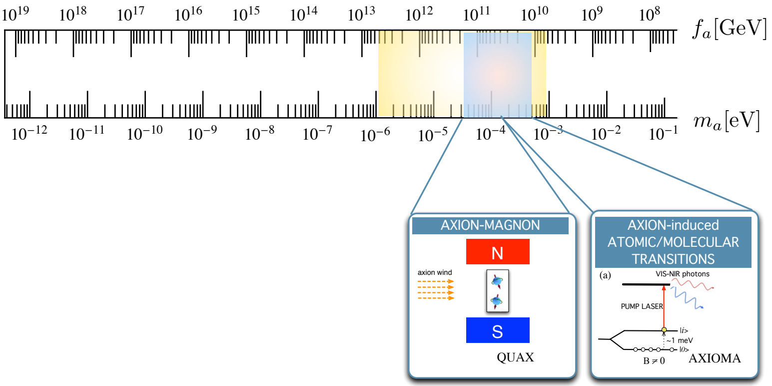


- relaxation time of the magnetized materials/lifetime of the involved atomic levels must not exceed the coherence time
- huge number of channels

A COMPLEMENTARY RESEARCH EFFORT

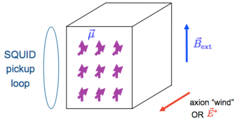
10^9 channels in the favored window!





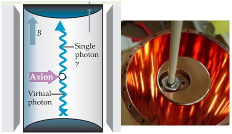
A BLOOMING OF TABLETOP-SCALE EXPERIMENTS

Oscillating neutron EDM/wind

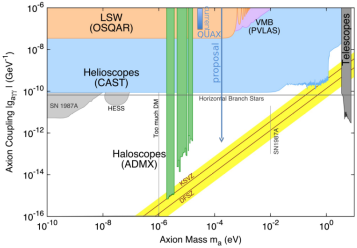


CASPER-wind, CASPER-E

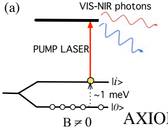
AXION-PHOTON



ADMX, CAPP, ...

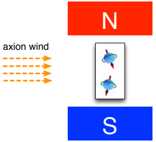


AXION-induced ATOMIC/MOLECULAR TRANSITIONS

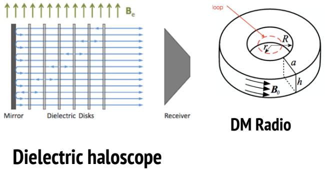


AXIOMA

AXION-MAGNON

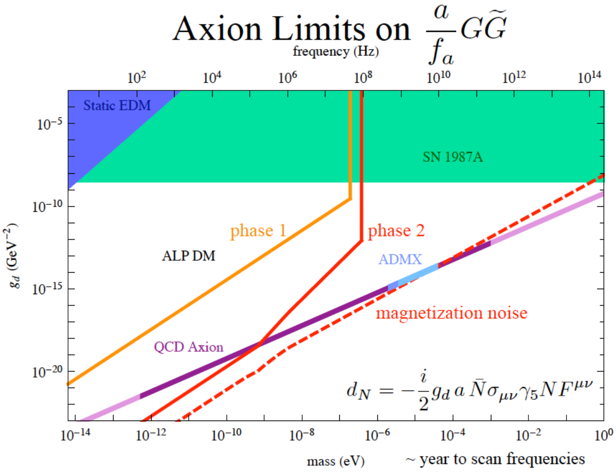


QUAX



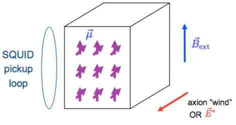
AND MORE...

Casper in the exclusion plots



A BLOOMING OF TABLETOP-SCALE EXPERIMENTS

Oscillating neutron EDM/wind



CASPER-wind, CASPER-E

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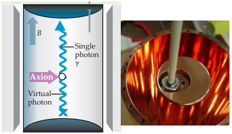
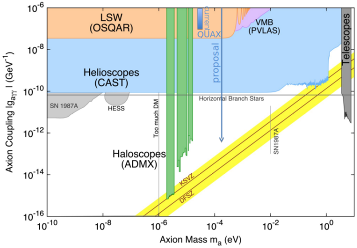
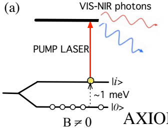


ADMX, CAPP, ...

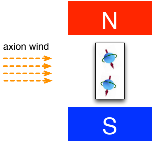


AXION-induced ATOMIC/MOLECULAR TRANSITIONS

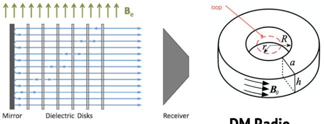


AXIOMA

AXION-MAGNON



QUAX



DM Radio

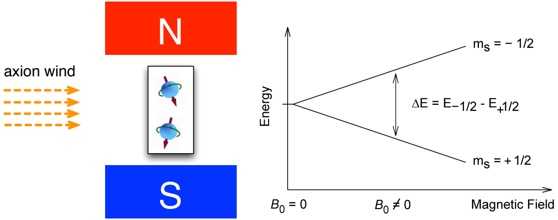
Dielectric haloscope

AND MORE...

QUAX

INTERACTION OF THE AXION FIELD WITH A MAGNETIZED SAMPLE

- axion-electron coupling
- the axion DM acts as as **effective RF magnetic field** on the electron spin
- the magnetized sample behaves as an RF receiver tuned at the Larmor frequency
- the equivalent magnetic RF field excites a **transition** in the magnetized sample $\longrightarrow$ **variation in the magnetization**



L. M. Krauss, J. Moody, F. Wilczek, D.E. Morris, *Spin coupled axion detections* (1985)

R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B **226**, 357 (1989)

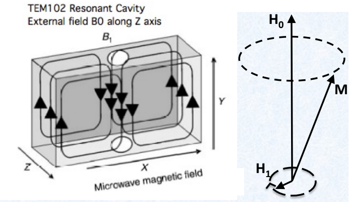
A.I. Kakhizde, I.V. Kolokolov, Sov. Phys, JETP **72** 598 (1991)

THE EXPERIMENTAL TECHNIQUE: EPR/ESR – FMR

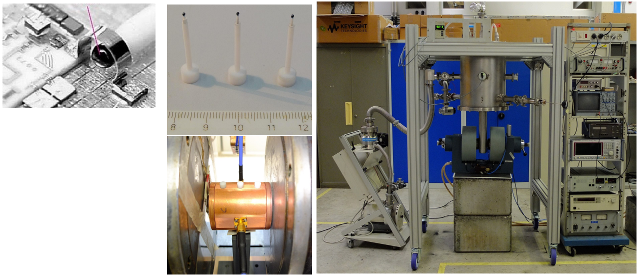
Magnetic resonance arises when energy levels of a quantized system of electronic moments are **Zeeman split** ($\Longleftrightarrow$ the magnetic system is placed in a uniform magnetic field B_0) and the system absorbs EM radiation in the microwave range.

An experimental geometry with **crossed magnetic fields** is needed:

- B_0 along z
- a microwave field is applied to the xy plane
  sum of two counter-rotating fields $2A\cos\omega t = A(e^{i\omega t} + e^{-i\omega t})$
- resonance occurs when the Larmor precession of the magnetic moment is synchronized with the clockwise or anticlockwise component
- no resonance occurs when the AC field is parallel to B_0



QUAX



AXION-FERMION interaction

Axions are converted to:

- *magnons* in QUAX
- *photons* (VIS-NIR) in AXIOMA

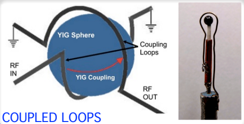
- magnetized material with spin density $2 \times 10^{28}\,\mathrm{m}^{-3}$ and FMR linewidth $\sim 150\,\mathrm{kHz}$ ($\tau_2 \sim 2\,\mu$s)
- necessary magnetized sample volume $\sim 100\,\mathrm{cm}^3$ to be hosted in $\sim$ 50 GHz frequency cavities
- $\sim 10^6$ Q-factor cavity/cavities
- ppm level uniformity and high stability of the 2 T magnetic field
- signal detection beyond SQL with linear amplifiers $\Longrightarrow$ single-photon microwave detectors
- 100 mK working temperature of the complete apparatus
- frequency tunability

Phys. Dark Universe 15, 135141 (2017)

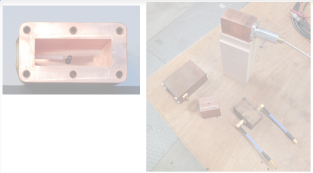
RADIATION DAMPING

The dynamics of the magnetic sample is well described by its magnetization **M**, whose evolution is given by the Bloch equations with dissipations and radiation damping.

The **damping term** related to τ_r affects the *maximum allowed coherence* hence the integration time of the magnetic system with respect to the axion driving input.



COUPLED LOOPS



MICROWAVE CAVITY 7, 8, 12, 16 GHz rectangular cavities

MATERIAL **IN FREE SPACE**

$$\frac{dM_x}{dt} = \gamma(\mathbf{M}\times\mathbf{B})_x - \frac{M_x}{\tau_2} - \frac{M_x M_z}{M_0 \tau_r}$$

$$\frac{dM_y}{dt} = \gamma(\mathbf{M}\times\mathbf{B})_y - \frac{M_y}{\tau_2} - \frac{M_y M_z}{M_0 \tau_r}$$

$$\frac{dM_z}{dt} = \gamma(\mathbf{M}\times\mathbf{B})_z - \frac{M_0 - M_z}{\tau_1} - \frac{M_x^2 + M_y^2}{M_0 \tau_r}$$

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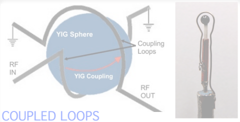

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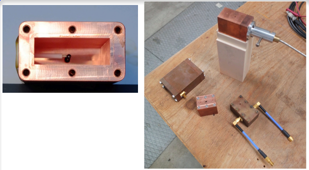


MICROWAVE CAVITY 7, 8, 12, 16 GHz rectangular cavities

MATERIAL **IN A CAVITY**

$$
\begin{aligned}
\frac{dM_x}{dt} &= \gamma M_y B_0 - \frac{M_x}{\tau_2} \\
\frac{dM_y}{dt} &= \gamma (M_z K I - M_x B_0) - \frac{M_y}{\tau_2} \\
\frac{dM_z}{dt} &= -\gamma K' I M_y - \frac{M_0 - M_z}{\tau_1} \\
L \frac{dI}{dt} &= K \frac{dM_x}{dt} - RI - \frac{1}{C} \int^t I dt + V_{\mathrm{rf}}
\end{aligned}
$$

N. Bloembergen and R. V. Pound, Phys. Rev. **95**, 8 (1954)

HYBRIDIZED MODE $\Longleftrightarrow$ STRONG COUPLING REGIME

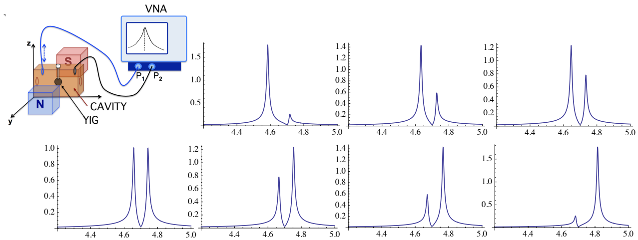
In QUAX the axion interaction excites the magnon-photon oscillator

In the solutions for $\tau_r \ll \tau_c$ we find the dynamics of two coupled oscillators with the complex frequency of the two modes

$$\omega_\pm = \omega_L \pm \frac{1}{2}\sqrt{\frac{4}{\tau_c}\left(\frac{1}{\tau_2}+\frac{1}{\tau_r}\right) - \left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)^2}$$

and with the same decay time:

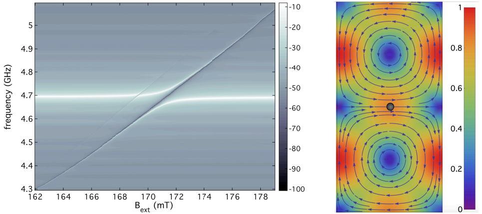
$$\tau_\pm = \bar{\tau} = \left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)^{-1}$$



Real part of the transmission function of the standard input-output formalism:

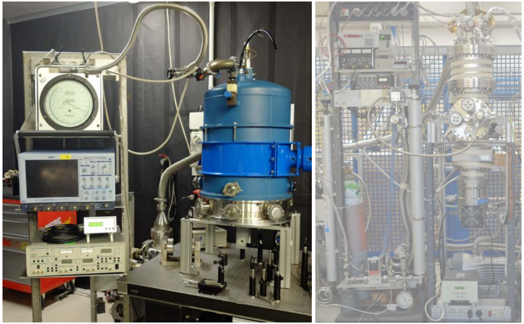
$$S_{21}(\omega) \simeq \frac{1}{i(\omega-\omega_c) - \frac{k_c}{2} + \frac{|g_m|^2}{i(\omega-\omega_m)-k_m/2}}$$

$k_c = 1/\tau_c$ (cavity), $k_m = 1/\tau_2$ (FMR)
$k_h = \frac{1}{2}(k_c + k_m)$ hybridized mode width
g_m coupling strength



Phys. Rev. Lett. 118, 107205 (2017)

AXION DETECTION IN RE-DOPED CRYSTALS



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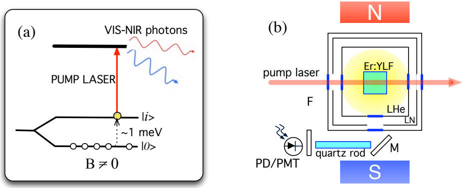
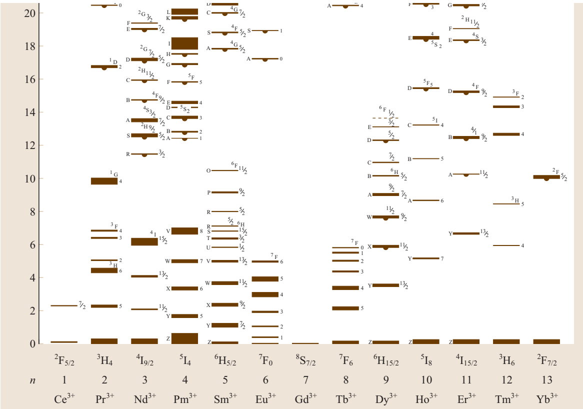
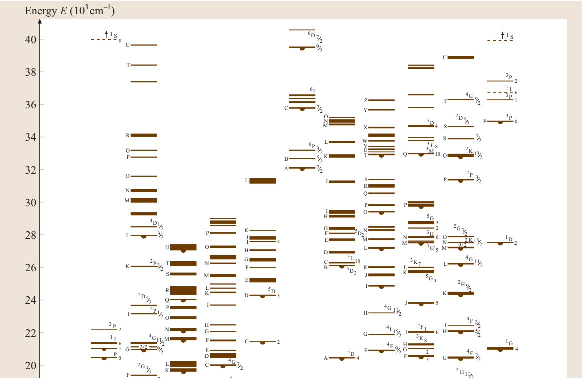


- axion-induced transitions take place between Zeeman-split ground state levels in rare-earth doped materials
- transitions involve electrons in the $4f$ shell
- a tunable laser pumps the excited atoms to a fluorescent level
- crystal immersed in LHe and superfluid He

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)

AXION DETECTION IN SOLID CRYSTALS OF INERT GASES

AXION-FERMION interaction

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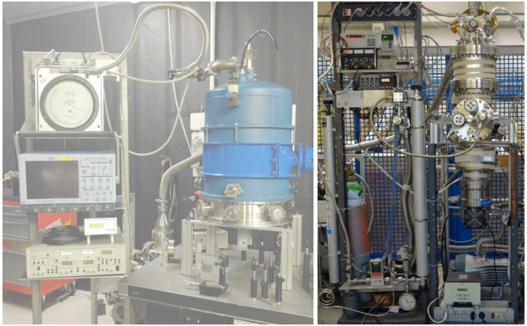
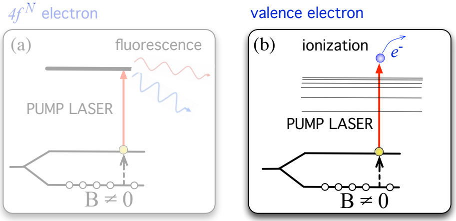




- axion-induced transitions take place between Zeeman-split ground state levels in alkali-doped solid crystals of inert gases
- a tunable UV laser pumps ionizes the excited alkali atom
- transitions involve valence electrons
- single electron detection (MCPs)

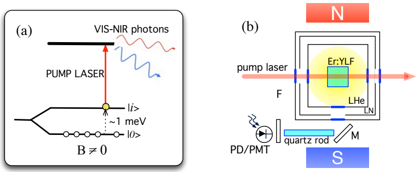
AXION DETECTION IN RE-DOPED MATERIALS

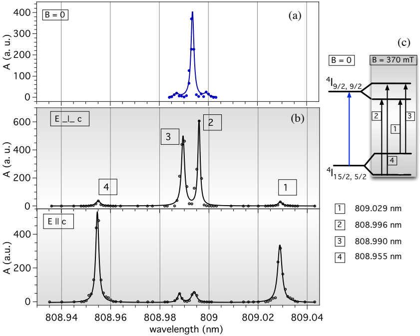
For one mole of target atoms (RE-dopant) in the ground state $|0\rangle$, the transition rate to the level $|i\rangle$ by axion absorption on resonance (P. Sikivie PRL (2016))

$$N_A R_i = 8.5 \times 10^{-3} \left(\frac{\rho_a}{0.4\,\mathrm{GeV/cm^3}}\right)\left(\frac{E_a}{330\,\mu\mathrm{eV}}\right)^2 g_i^2 \left(\frac{\overline{v^2}}{10^{-6}c^2}\right)\left(\frac{\min(t,\tau,\tau_{\nabla a})}{10^{-6}\,\mathrm{s}}\right)\ \mathrm{Hz}$$

where R_i is the transition rate of a single target atom, N_A is the Avogadro number, $E_a = h\nu_a$ is the axion energy

→ spectroscopic properties at "high" RE concentration (0.1 %, i.e. $\gtrsim 10^{19}$ *axion target electrons*/cm^3) in ∼ 1 l- active volume





the linewidth of the transition driven by the laser must be narrower than the energy difference between the atomic levels $|0\rangle$ and $|i\rangle$

AXION DETECTION IN RE-DOPED MATERIALS: WORKING T

fundamental noise limit → thermal excitation of the Zeeman excited level

$$N_A R_t = \bar{n}/\tau$$

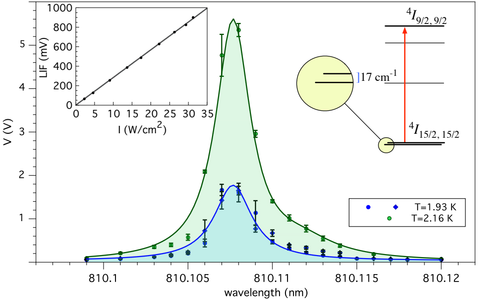
$\bar{n} = N_A \exp(-E_a/kT)$ average number of excited ions in the energy level E_a
SNR= 3, statistically significant number of counts within $t_m = 1\,\mathrm{h}$
→ thermal excitation rate $R_t = 6 \times 10^{-3}\,\mathrm{Hz}$

$\tau = 1\,\mathrm{ms}$ level lifetime → $\bar{n} \leqslant 5 \cdot 10^{-6}$

Axions with mass greater than 80 GHz can be searched, provided the active crystal is cooled down to at least 57 mK.

⟹ ultra-cryogenic ($T \sim 100\,\mathrm{mK}$) optical apparatus

Laser-related backgrounds ($\sim 10\,\mathrm{W/cm^2}$)?



The pump laser does not affect the thermal population of the Zeeman excited level at least up to a few $\mathrm{W/cm^2}$ intensity

THE QUAX AND AXIOMA COLLABORATIONS

Phys. Dark Universe 15, 135141 (2017) → the QUAX proposal
Phys. Rev. Lett. 118, 107205 (2017) → magnon-photon mode and calibration
arxiv.org/abs/1707.06103v1 (2017) → atomic transitions in RE-doped crystals
New J. Phys. 17 113025 (2015) → molecular transitions

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