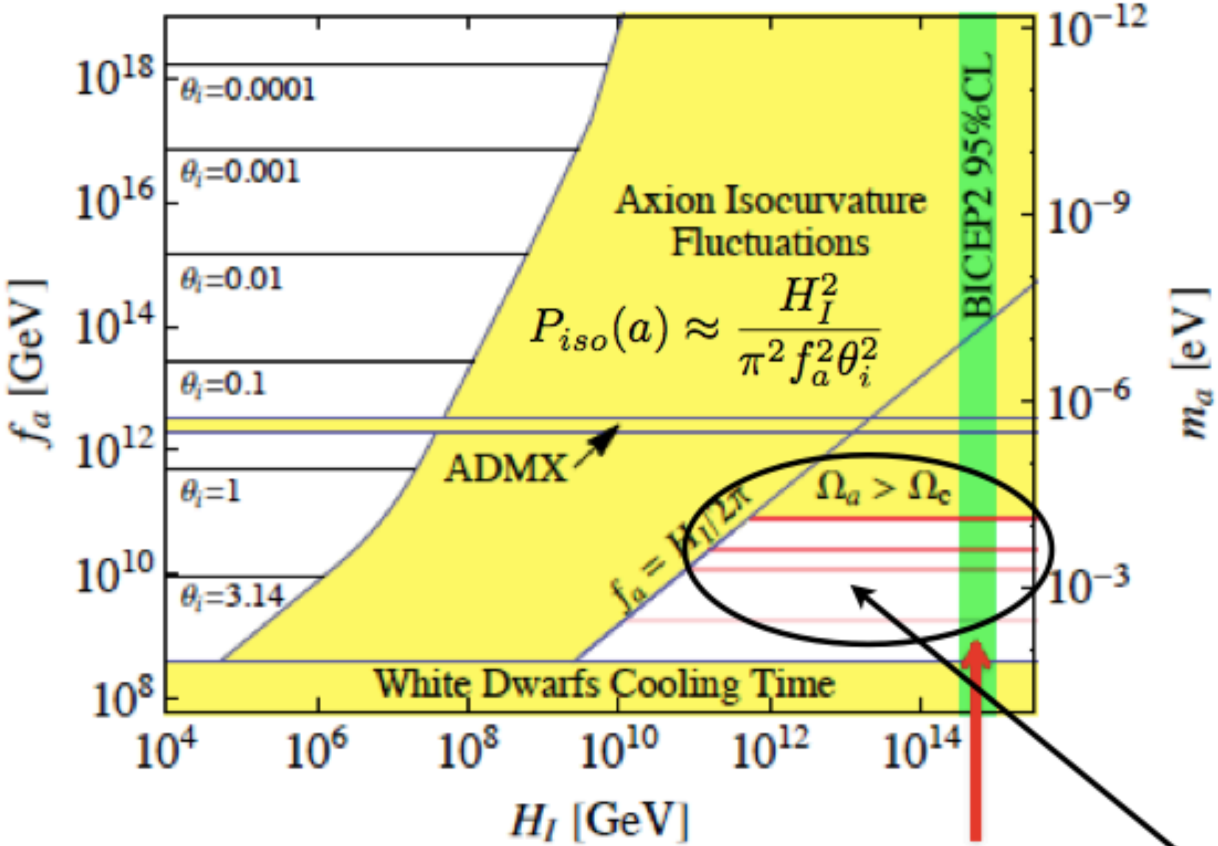
FROM BARBIERI TALK JAN.2015

QCD Axions in cosmology

$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$

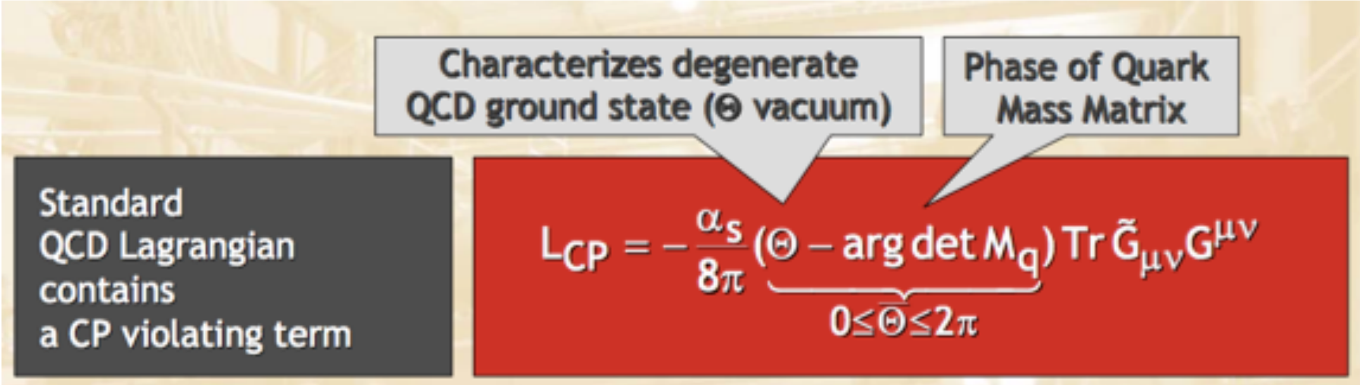


$$\Omega_a h^2 \approx 0.16\left(\frac{m_a}{10^{-5} eV}\right)^{-1.18} \theta_i^2 \qquad \theta_i = \frac{a_i}{f_a} \qquad \theta_i^2 = \frac{\pi^2}{3}$$

(Axion Like Particles: m and f unrelated)

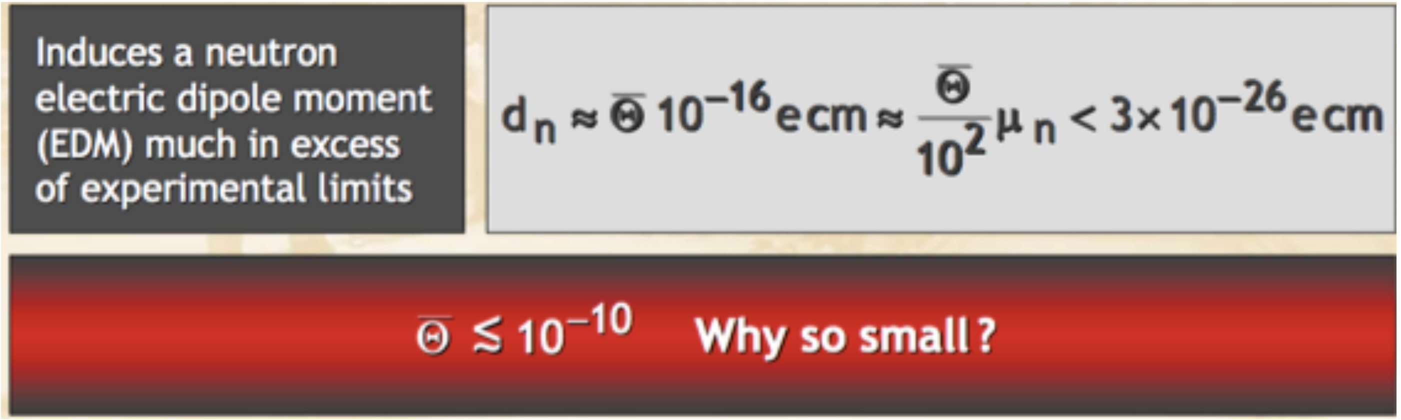
The strong CP problem

- The QCD lagrangian contains a term that foresees CP violation



The parameter θ is unprescribed by the theory, it is expected to be θ ~ 1. QCD interaction actually depends on θ through its difference with the **phase of the quark mass matrix**:

$$\bar{\theta} = \theta - \arg\det(m_1, m_2, \ldots, m_n)$$

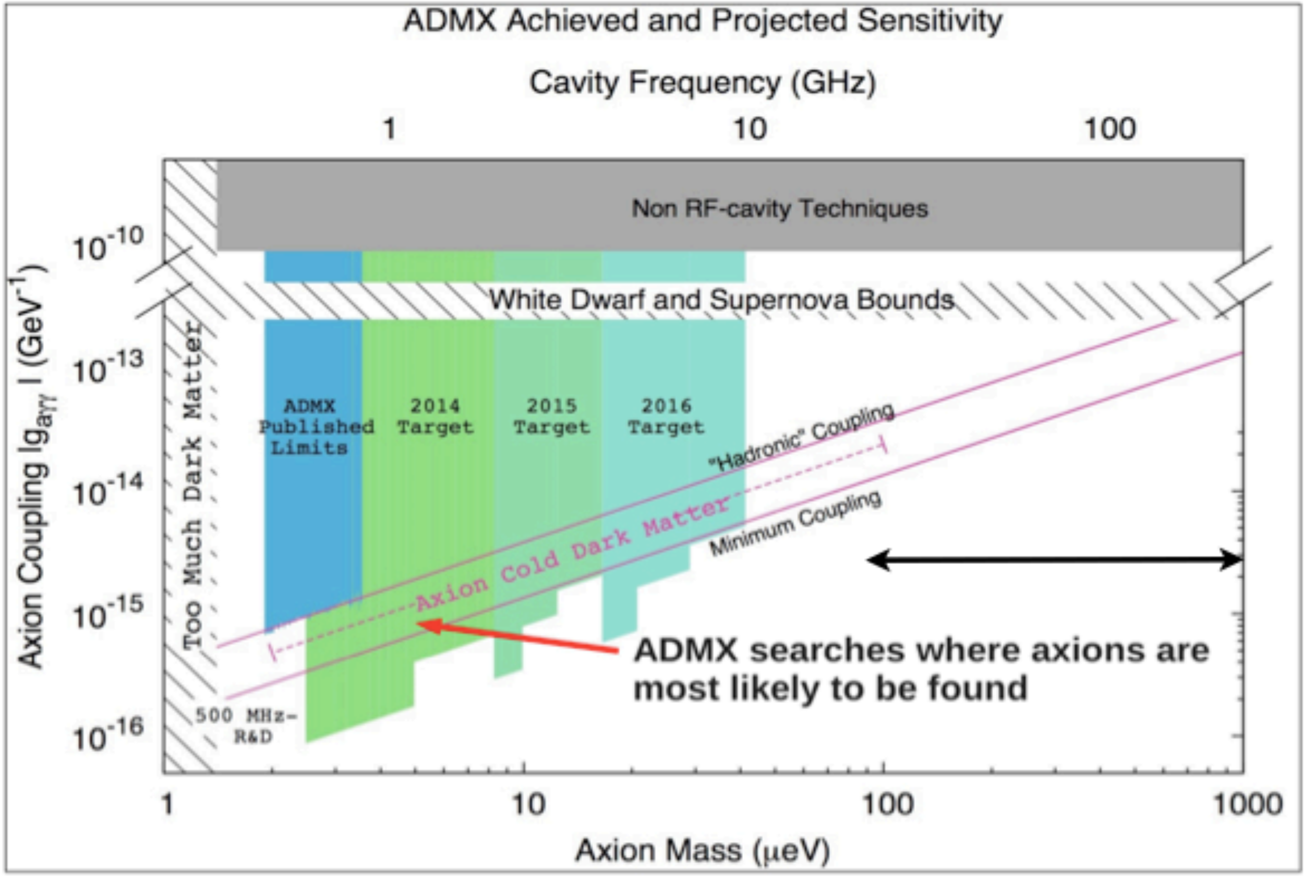


VERY FINE TUNING! -> STRONG CP PROBLEM

FROM BARBIERI TALK JAN> 2015

The classic search

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$



Not easy to explore the most relevant region

$$10^{-4} \lesssim m_a/eV \lesssim 10^{-3}$$

Rybka ADMX

Axion electron interaction

- The interaction of the axion with the a spin ½ particle

$$L = \bar{\psi}(x)(i\hbar\not{\partial}_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

- In the non relativistic approximation

$$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

The interaction term has the form of a **spin - magnetic field interaction** with $\vec{\nabla}a$ playing the role of an effective magnetic field

$$H_a = -\vec{S}\cdot\left[\frac{g_p}{m_e}\nabla a\right]$$

$$B_a = \frac{1}{\gamma}\frac{g_p}{m_e}\sqrt{\frac{\rho_a\hbar^3}{m_a c}}\frac{p_s}{\hbar} = 9.2\cdot 10^{-23}\left(\frac{m_a}{10^{-4}\,\mathrm{eV}}\right)$$

FROM BARBIERI TALK JAN. 2015

The coupling to spin

$$L = \bar{\psi}(x)(i\hbar\not{\partial}_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

$$g_p = A_\Psi \frac{m_\Psi}{f_a} \quad (g_s = 10^{-(12\div 17)} g_p \frac{GeV}{m_\Psi})$$

DFSZ $g_p(e) \approx 1$

KSVZ $g_p(e) \approx 10^{-3}$

NRL: $$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

$$\gamma\vec{B}_{eff}\cdot\vec{\sigma}$$

$$\gamma = \frac{e}{2m_\Psi}$$

A coupling to the spin <u>and</u> to the Electric field

$$L \approx \frac{\alpha_S}{4\pi}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \Rightarrow \quad d\,\vec{\sigma}\cdot\vec{E}$$

$$d \approx 10^{-16}\frac{a}{f_a}(e\cdot cm)$$

Experimental parameters

Axion mass $10^{-4}\,eV \le m_a \le 10^{-3}\,eV$

Equivalent RF magnetic field $10^{-22}\,Tesla \le B \le 10^{-21}\,Tesla$

Working frequency $20\ GHz \le \nu \le 200\ GHz$

Electron Larmor Frequency

$$\nu_{larmor} = \gamma_e B_0 \quad ; \quad \gamma_e = 28GHz/T$$

$$0.7\,T \le B_0(T) \le 7\,T$$

Magnetizing field

Measurement at the quantum limit

$$T_{spin} \le \frac{\mu_b B_0}{K_b}, T_{lattice} \le \frac{\hbar\nu}{K_b}$$

$$100mK \le T(K) \le 1K$$

Working temperature

Detection issues

The working frequency lies in a region at the interface of two different regimes for best detection sensitivity

Frequency

Below 40 GHz

FIELD DETECTION
(Linear detection)

- EPR Magnetometry
- MASER Amplifier

Above 40 GHz

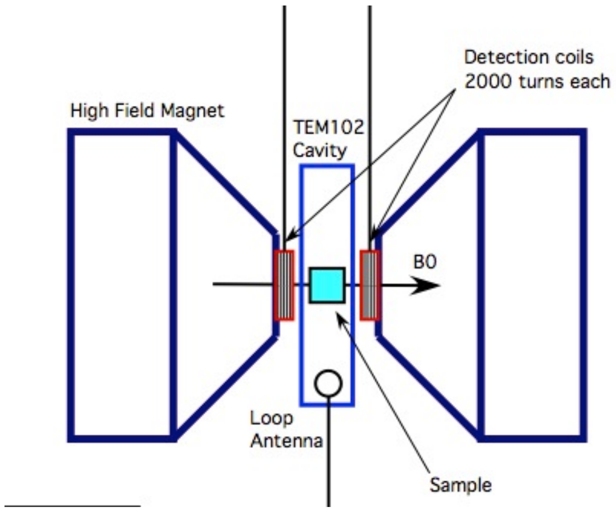
ENERGY DETECTION
(Square detection)

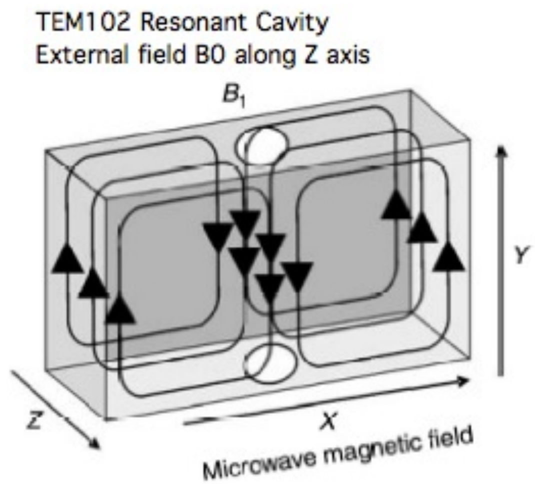
- QUANTUM COUNTER
(ZEEMAN Transitions)

In either case to reach quantum limit sensitivity 1/100 -1 mole of a magnetized sample at cryogenic temperature is necessary

ESR / MR Magnetometry

- We exploit the Magnetic Resonance (MR) inside a magnetized material (Electron Spin Resonance - ESR)





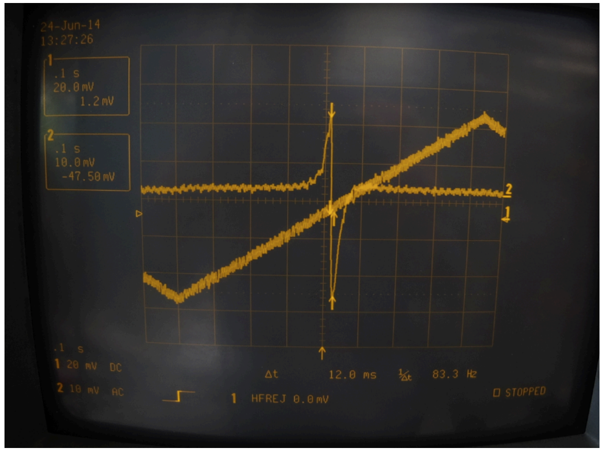
ESR/MR resonances inside a magnetic media can be tuned by an **external magnetizing field** and lies in the **multi GHz range** (radio frequency)

Bohr magneton $\mu_B = \frac{e\hbar}{2m_e} = 9.27 \cdot 10^{-24}$ J T^{-1}

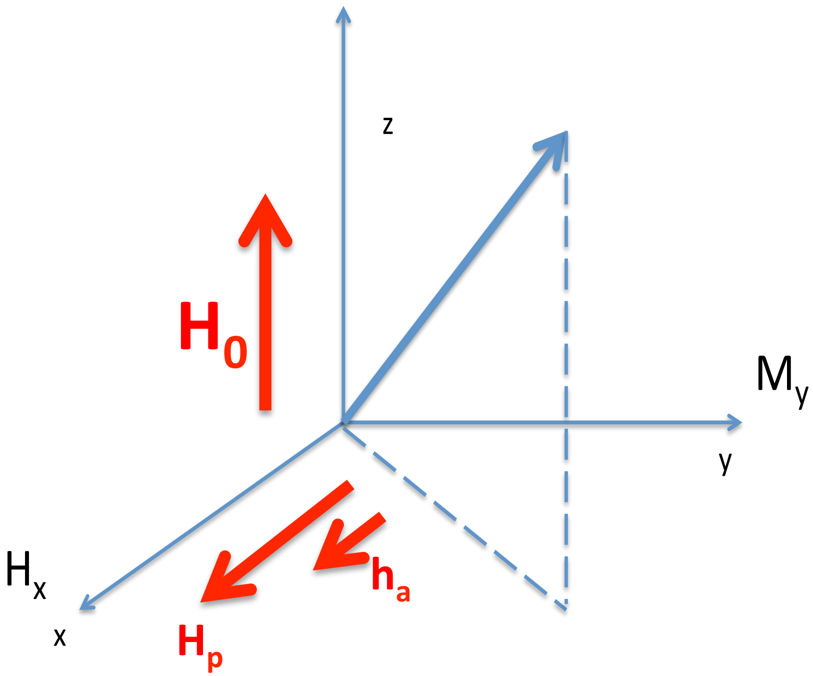
Gyromagnetic ratio $\gamma_e = ge/(2m) = g_e\mu_B/\hbar = 1.76 \cdot 10^{11}$ rad s^{-1} T^{-1}

Larmor frequency $\omega_L = \gamma_e B_0$

1 T -> 28 GHz



Longitudinal Detection of axion field



- We magnetize the sample along the z-axis and orient the sample in order to have the equivalent **axion field h_a** in the transverse direction
- **H_0 amplitude** matches the searched value of the **axion mass**
- We drive the sample with a **pump field H_p** at the Larmor frequency

The total driving radio-frequency field is then

$$H_x = H_p \cos \omega_p t + h_a \cos \omega_a t \qquad \omega_p \cong \omega_a \cong \omega_{\mathrm{Larmor}} = \gamma H_0$$

$$\omega_p - \omega_a \cong \omega_D \neq 0 \qquad \omega_p + \omega_a \cong 2\omega_p$$

Also Present

Longitudinal Detection of axion field

We can define some sort of gain G_m for the **low frequency field component** $\mu_0\, m_z$ with respect to the **high frequency** one h_a

$$\mu_0 m_z(t) = \frac{1}{2}\mu_0 M_0 \gamma^2 T_1 T_2 H_p h_a \cos\omega_D t$$
$$= G_m h_a \cos\omega_D t$$

$$G_m = \frac{1}{2}\mu_0 M_0 \gamma^2 T_1 T_2 H_p$$

If we put some relevant numbers (already published)

$T_1 = 10^{-3}$ s
$T_2 = 3 \times 10^{-7}$ s
$M_0 = 200$ A/m

→ We obtain $G_m > 1$

for a pump field of $H_p \sim 1$ nT

Can we get enough gain G_m to be able to reach a measurable low frequency value from the axion field $h_a \sim 10^{-22}$ T?

→

- **find the right material**
- **power dissipated in the cryogenic system**
- **noises in the system**

MASER AS LOW RF MICROWAVE FIELD AMPLIFIER AND NEUTRAL PARTICLE DETECTOR

Bloembergen Paramagnetic Maser 4 Level System

Exploiting Electron – Phonon Coupling Through Lattice

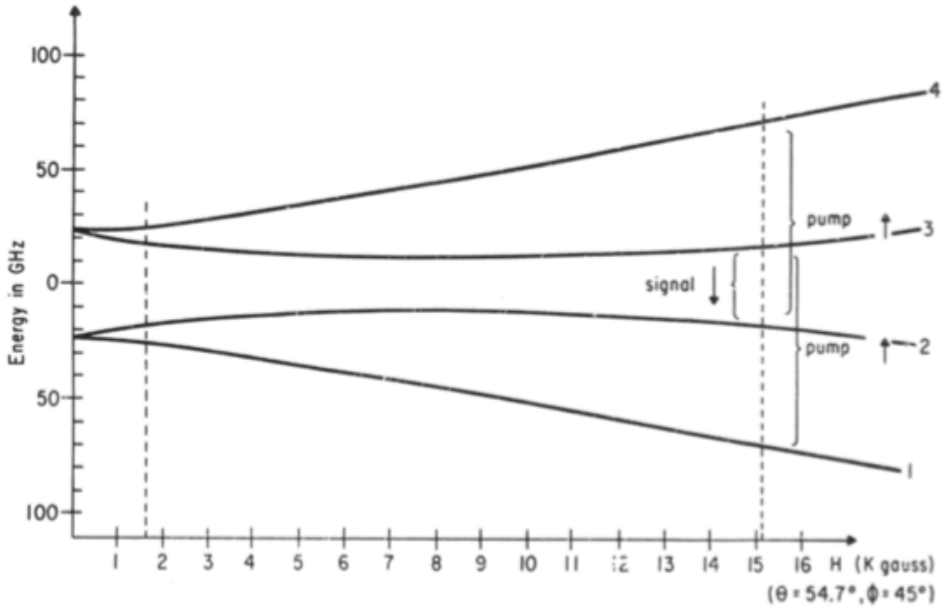
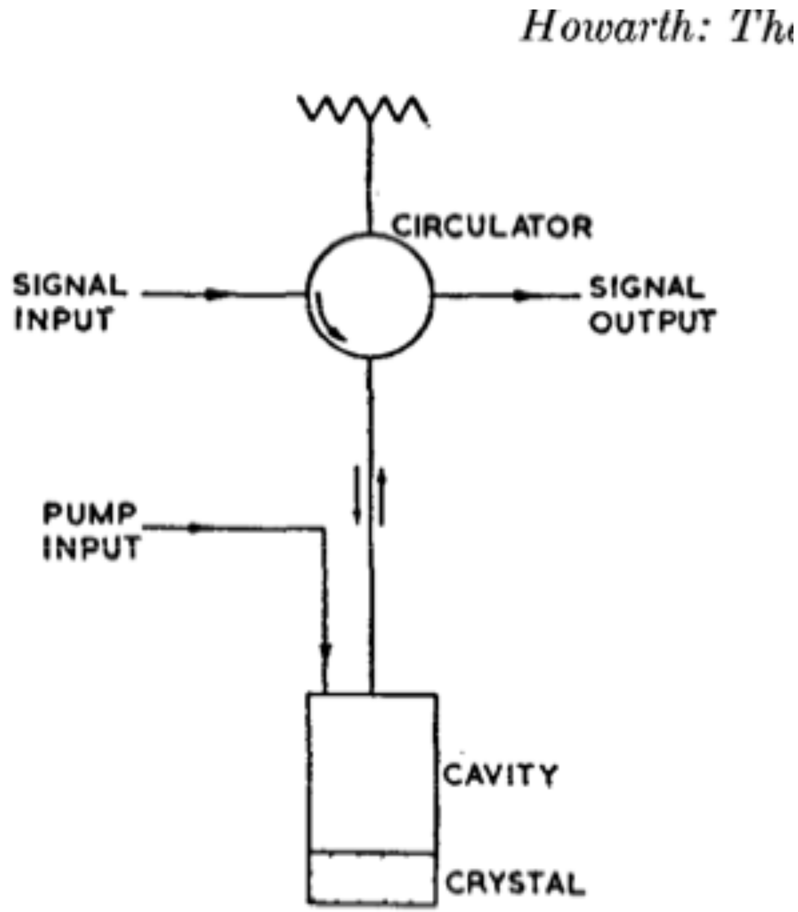


Figure 5 - Push-pull Energy Levels in Rutile



$$P_{diss}(W) = \frac{1}{2\mu_0}\omega_p H_p^2 M_0 \gamma T_2 V_S$$

Power Stimulated Emission : $\frac{N_{32}}{6KT} h^2 (\nu_{31} - 2\nu_{32}) B_{32} \rho_{32} \nu_{32}$

$P = \frac{N\hbar^2 \nu_{32}}{3KT} (\nu_{21} - \nu_{32}) W_{32}$ **Where** $W_{32} = \gamma^2 B_{ax}^2 T_2$

Quantum Maser Noise : $P_{masernoise} = \hbar \nu_{32} \Delta \nu_{32}$ **or** $P_{masernoise} = \hbar \nu_{32} T_2^{-1}$

Minimum Detectable B field: $\frac{B}{Hz^{1/2}} = \frac{10^{-19} T}{\sqrt{Hz}}$

Minimum Cross Section Attainable: $\sigma_{\min}(cm^2) \approx \frac{e^{-\frac{\hbar \nu_{12}}{KT}}}{\Phi}$

WEAK CROSS SECTION SEEMS ATTAINABLE 10-43 cm2

Axion Dark Matter Detection Using Atomic Transitions

P. Sikivie
Department of Physics, University of Florida, Gainesville, Florida 32611, USA
(Received 9 September 2014; published 14 November 2014)

Dark matter axions may cause transitions between atomic states that differ in energy by an amount equal to the axion mass. Such energy differences are conveniently tuned using the Zeeman effect. It is proposed to search for dark matter axions by cooling a kilogram-sized sample to millikelvin temperatures and count axion induced transitions using laser techniques. This appears to be an appropriate approach to axion dark matter detection in the 10^{-4} eV mass range.

$$\mathcal{L}_{a\bar{f}f} = -\frac{g_f}{2f_a}\partial_\mu a\ \bar{f}(x)\gamma^\mu\gamma_5 f(x)$$

$$H_{a\bar{f}f} = +\frac{g_f}{2f_a}\left(\vec{\nabla}a\cdot\vec{\sigma} + \partial_t a\,\frac{\vec{p}\cdot\vec{\sigma}}{m_f}\right)$$

ZEEMAN TRANSITION RATE With 1 Mole of Polarized Electrons

$$N_A R_i = g_i^2 N_A v^2 \frac{2\rho_a}{f_a^2}\min(t, t_1, t_a)$$

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

Hz Rate

Axion Dark Matter detection by laser spectroscopy of ultracold molecular oxygen

P. Sikivie's idea: dark matter axions may induce magnetic dipole (M1) transitions between atomic or molecular states that differ in energy by an amount equal to the axion mass.

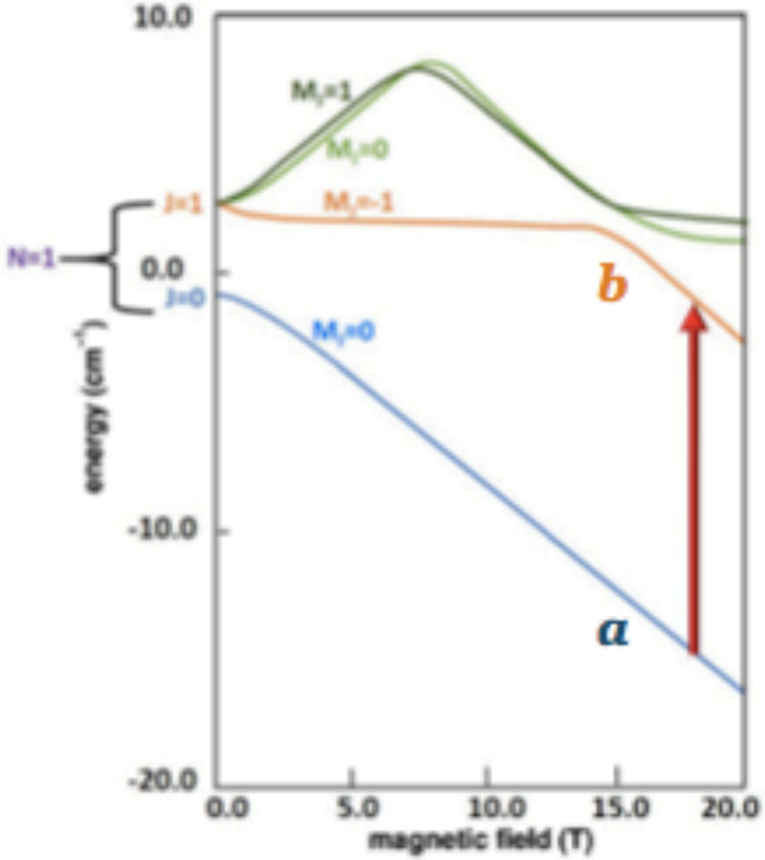
Following this suggestion, we propose an experiment which aims at detecting molecular transitions in a gas system in the 10^{-3} eV mass range.

Experimentally, this involves the preparation of a sub-Kelvin, mole-sized molecular gas sample through a buffer-gas-cooling (BGC) process in a He-3 environment. In addition, the molecular species should be sensitive enough to the application of an external magnetic field and well-suited to a single-particle spectroscopic interrogation technique as well.

→ **$^{16}O_2$**

- **Already cooled by BGC (with He-4)**
- **Paramagnetic (magnetic moment=$2\mu_B$)**
- **Well-suited to resonace-enhanced multi-photon ioniozation (REMPI) spectroscopy**

The axion transition



Zeeman effect in the X $^3\Sigma_g^-$ (υ=0) ground state

N = rotational angular-momentum quantum number

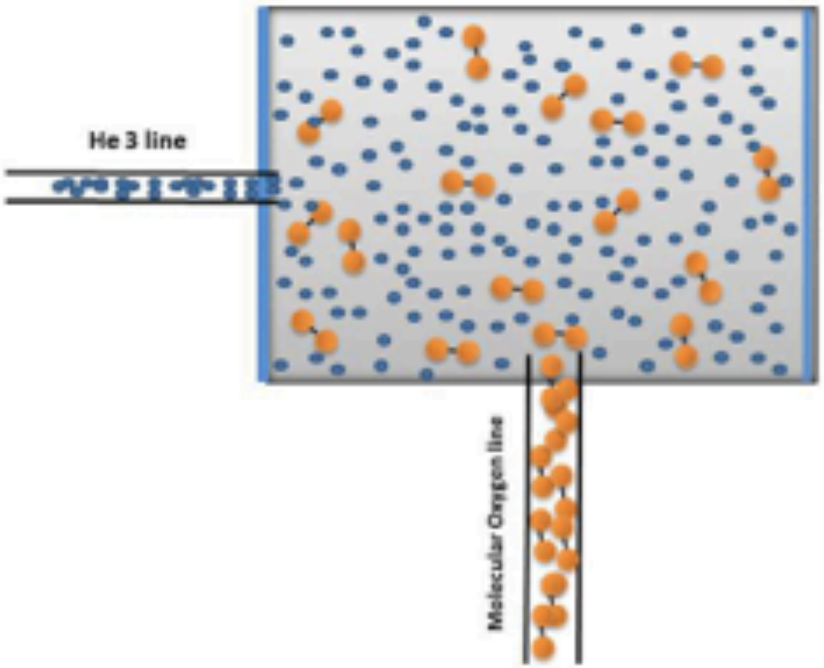
J = spin-rotational component

M_J = magnetic quantum number

M1 selection rules: $\Delta J = 0, \pm 1$ ($J = 0 \nleftrightarrow 0$), $\Delta M_J = 0, \pm 1$, and $\pi_b = \pi_a$, where π_a (π_b) denotes the parity of the transition's lower (upper) level.

At this point in the discussion, we choose the rotational level $(N = 1, J = 0, M_J = 0) \equiv a$ and $(N = 1, J = 1, M_J = -1) \equiv b$ as the lower and upper level of the axion transition, respectively. In this way, the energy difference $W_{ba}(B) \equiv W(b,B) - W(a,B)$ ranges from 11 cm^{-1} for $B = 12$ T to 15.5 cm^{-1} for $B = 18$ T. Correspondingly, for a temperature of $T = 280$ mK, the quantity $Q = N_A \exp[-W_{ba}(B)/(k_B T)]$ ranges from 0.17 to $1.5 \cdot 10^{-10}$, with k_B being the Boltzmann constant and N_A the Avogadro number. This quantitative statement expresses the fact that, when a mole of $^{16}O_2$ is considered, all the N_A molecules occupy the axion transition's lower level (a), whereas level b is in fact depopulated

Buffer-gas-cooling source



Here, both translational and internal degrees of freedom of the desired molecular species, at initial temperature T_0, are cooled in a cryogenic cell via collisions with a thermal bath of helium-3 (buffer gas) at temperature T_{He} and density n_{He}.

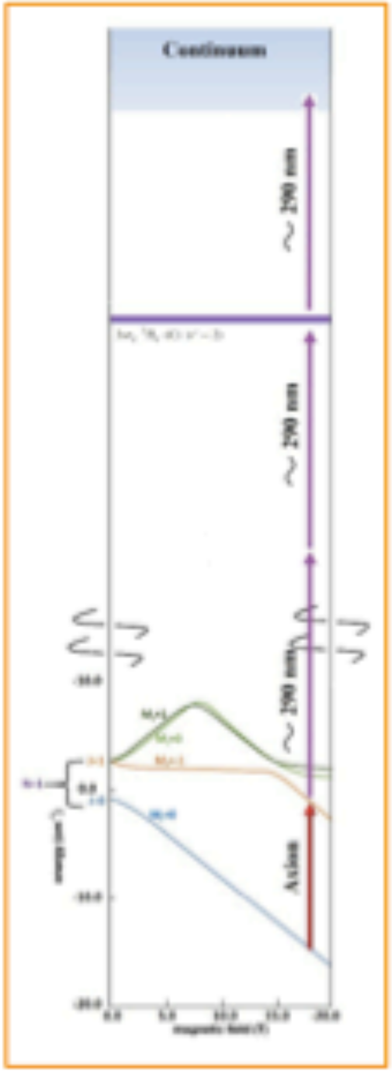
T_{He}=280 mK,

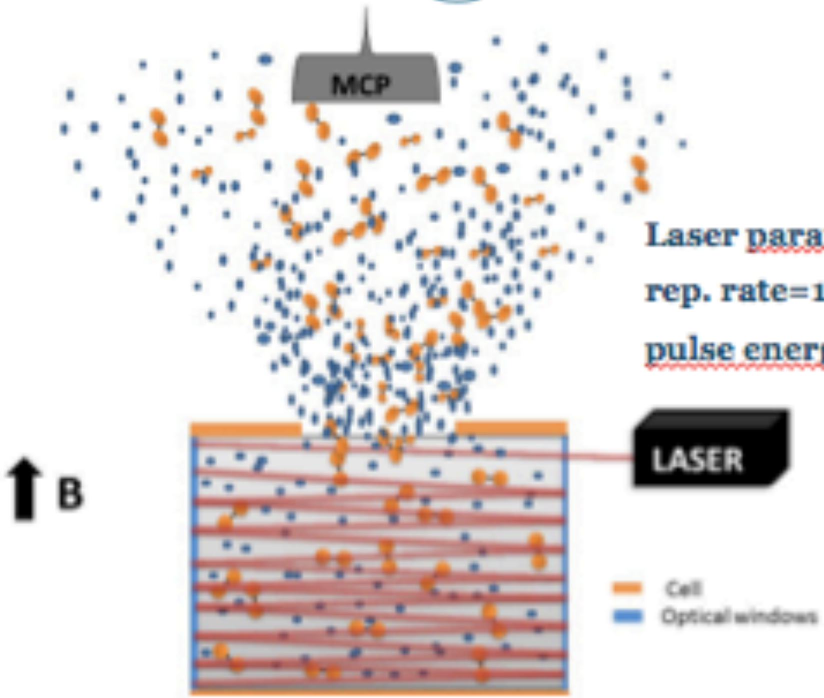
corresponding vapor

density $n_{He}=3*10^{16}$ cm^{-3}

Assuming that the maximum molecular density that can be cooled down to T_{He} is $n_{max}=(1/30)\, n_{He}=10^{15}$ cm^{-3}, a 10-liter-volume cell is needed to provide $N_{BGC}=10^{19}$ oxygen molecules in level a

REMPI detection





Laser parameters:

rep. rate=10 Hz; pulse duration=10 ns,

pulse energy=200 mJ, line width=0.3 cm^{-1}

Through multiple reflections, the laser beam interacts with one third of the buffer-gas-cell volume. Thus, with an acquisition time of t=3 hours,, it is possible to realize one mole of oxygen molecules that have been exposed to the axion field:

The axion as a source of an effective $\vec{B}$

1. By the Dark Matter wind

$$\vec{B}_{eff} = \frac{g_p}{e}\vec{\nabla}a = \frac{g_p}{e}m_a\vec{v}\, a_0 \cos m_a t$$

$m_a \approx 10^{-4} eV$ (as reference) $\omega = m_a \approx 100\ GHz$

$f_a \approx 10^{11} GeV$

$m_a\, a_0 \approx \sqrt{\rho_{DM}} \approx 0.3\ GeV/cm^3$ $v \approx 10^{-3}$

coherence length $\lambda_a^C \approx \frac{1}{m_a v} \approx 3\ m$

coherence time $\tau_a \approx \frac{2\pi}{m_a v^2} \approx 10^{-4}\ sec$

$$B_{eff} \approx 10^{-22}\ Tesla \frac{m_a}{10^{-4} eV}$$

(on electrons)

(1000 bigger on nucleons)