Dark matter search with coherent atoms

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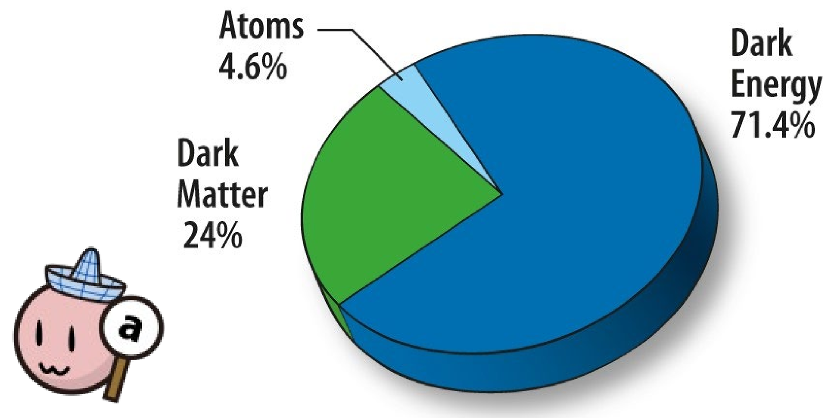
Ⅰ. Introduction

- ❑ Nature of Dark Matter (DM) is still a big mystery.
- ❑ Dark matter candidates

  WIMPs, sterile neutrino…

  Axion and dark photon are also promising candidates



- ❑ Axion

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} = g\frac{\alpha}{\pi f_a}$$

- ❑ Dark photon

$$\mathcal{L}_{\mathcal{DP}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_{\mu\nu}X^{\mu\nu} + j_\mu A^\mu$$

Axion/Dark photon direct detection with atomic transition

But interaction is rather weak !

Ⅱ. Amplification scheme

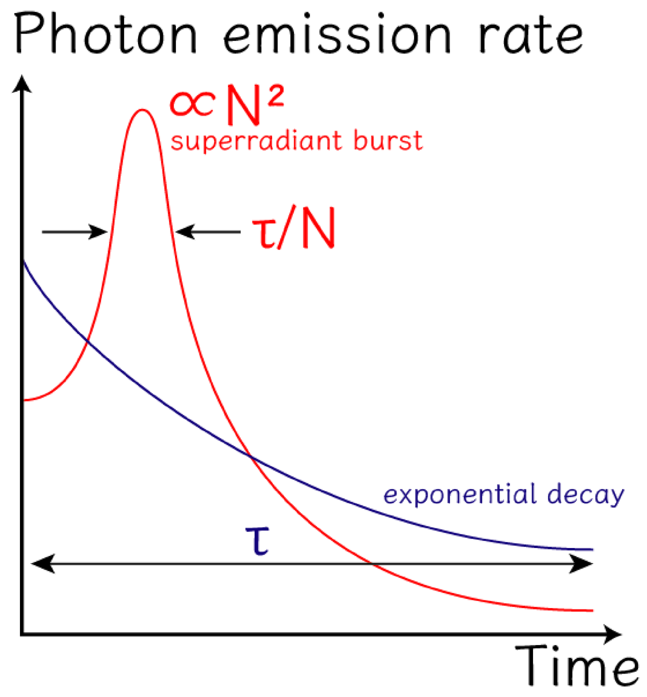
❑Super-Radiance[R. H. Dicke Phys. Rev. 93, 99–110 (1954)]

De-excitation via single-photon emission.

$$R \propto \left|\sum_{m=1}^{N_T} \mathrm{Exp}\left(i\vec{k}_\gamma \vec{x}_m\right) M(\vec{x}_m)\right|^2 \propto N_T^2$$

$\mathrm{Exp}[0] = 1$

$[\because M(\vec{x}_m) = M(0), |\text{ target size }| \ll \lambda]$

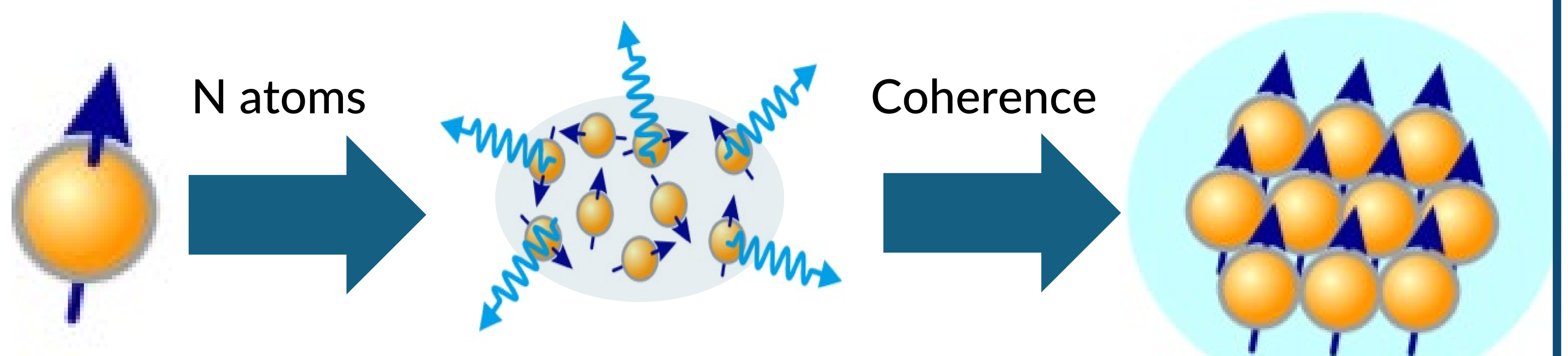


❑Macro-coherent amplification

Multi-photon involved transition.

$$R \propto \left|\sum_{m=1}^{N_T} \mathrm{Exp}\left(i\Delta\vec{k}x_m\right) M(\vec{x}_m)\right|^2 \propto N_T^2$$

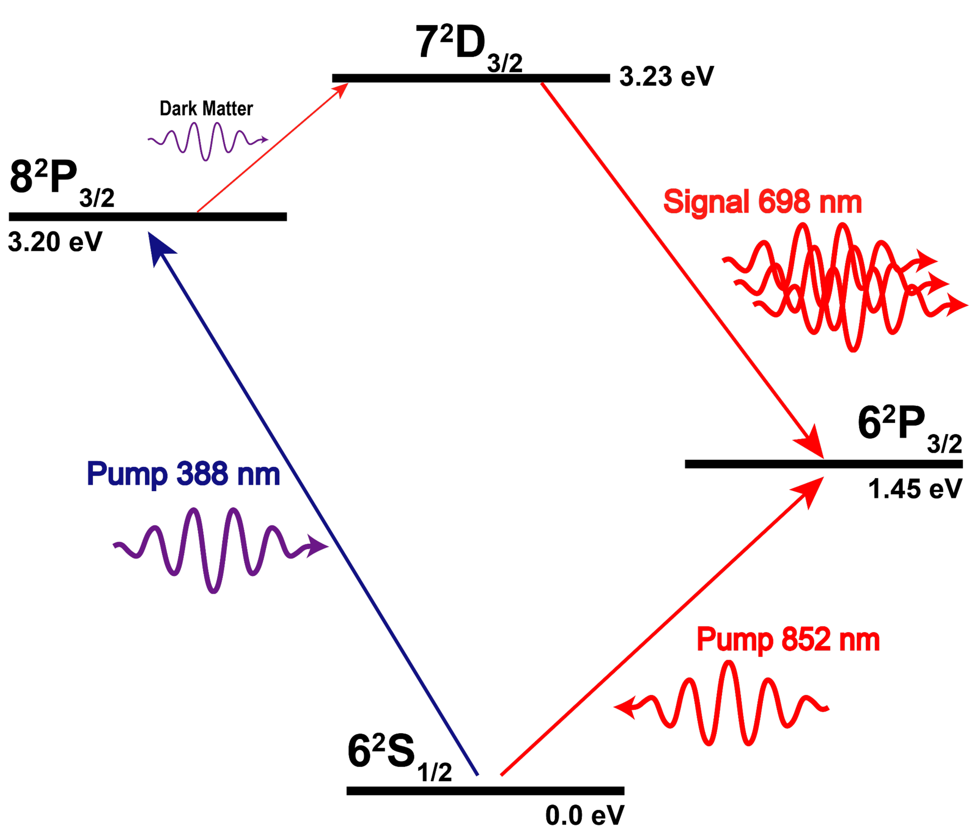
$$\left[\because M(\vec{x}_m) = M(0), \Delta\vec{k} = -\vec{k}_{\gamma 1} + \vec{k}_{\gamma 2} + \ldots = 0\right]$$



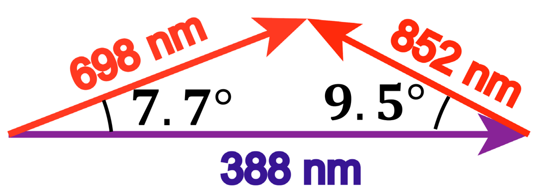
[Miyamoto et al. Prog. Theor. Exp. Phys.081C01 (2015)]

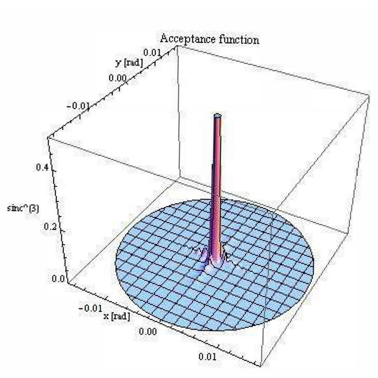
Ⅲ. Dark matter detection scheme

❑DM absorption by cesium atom [Sasao et al. Eur. Phys. J. C (2018) 78:949]



❑To satisfy $\Delta\vec{k} = 0$





$$F_{QC} = N_T|\rho_{fi}|\sqrt{A(\Delta\vec{k})}$$

❑Signal rate estimation using Fermi's Golden Rule for N atoms system

$$d\Gamma = \frac{2\pi}{\hbar}\delta(\hbar(\omega_{fi} + \omega_s - \omega_d))|M_0 F_{QC}|^2 \frac{V}{(2\pi)^3}d^3\vec{k}_s$$

❑Assuming following parameters $N_T|\rho_{fi}| = 10^{10}$, $\int Ad\Omega = 10^{-7}$, $T = 4\,\mathrm{K}$,

❑For dark photon, $\chi = 10^{-12}$ $\quad \rho_{DM} = 0.3\,\mathrm{GeV/cm^3}$, $B_{ext} = 1\,\mathrm{T}$, $m_{dm} = 32\,\mathrm{meV}$

$$E_d = 3.3 \times 10^{-9}\mathrm{V/m} \quad \Gamma_{\mathrm{Dark}} \simeq 12.6\mathrm{Hz}$$

❑For Axion, $g_{a\gamma\gamma} = 10^{-12}\mathrm{GeV}^{-1}$, need to increase N_T by 10^4

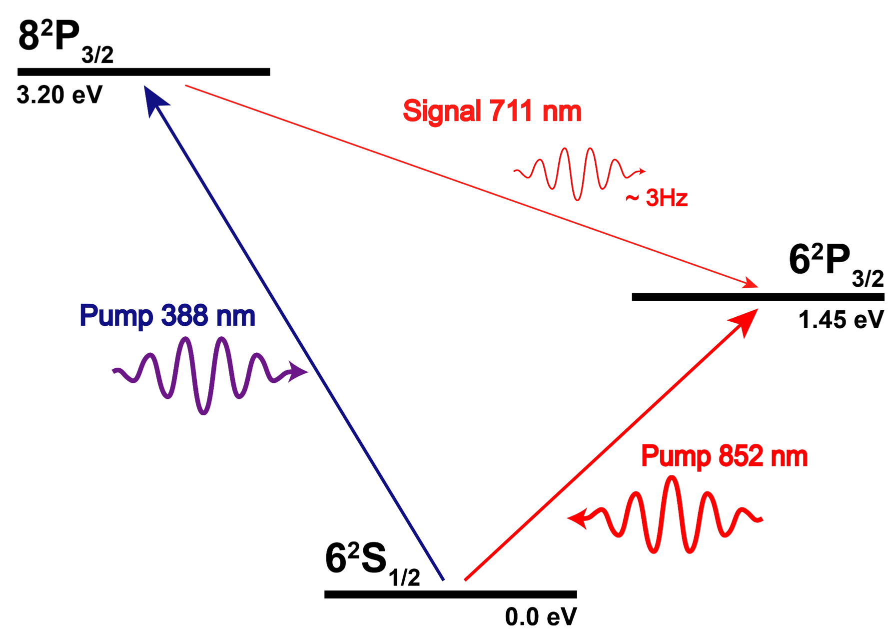
$$E_d \simeq 10^{-13}\mathrm{V/m} \quad \Gamma_{\mathrm{Axion}} \simeq 10\mathrm{Hz}$$

Ⅳ. Coherence generation

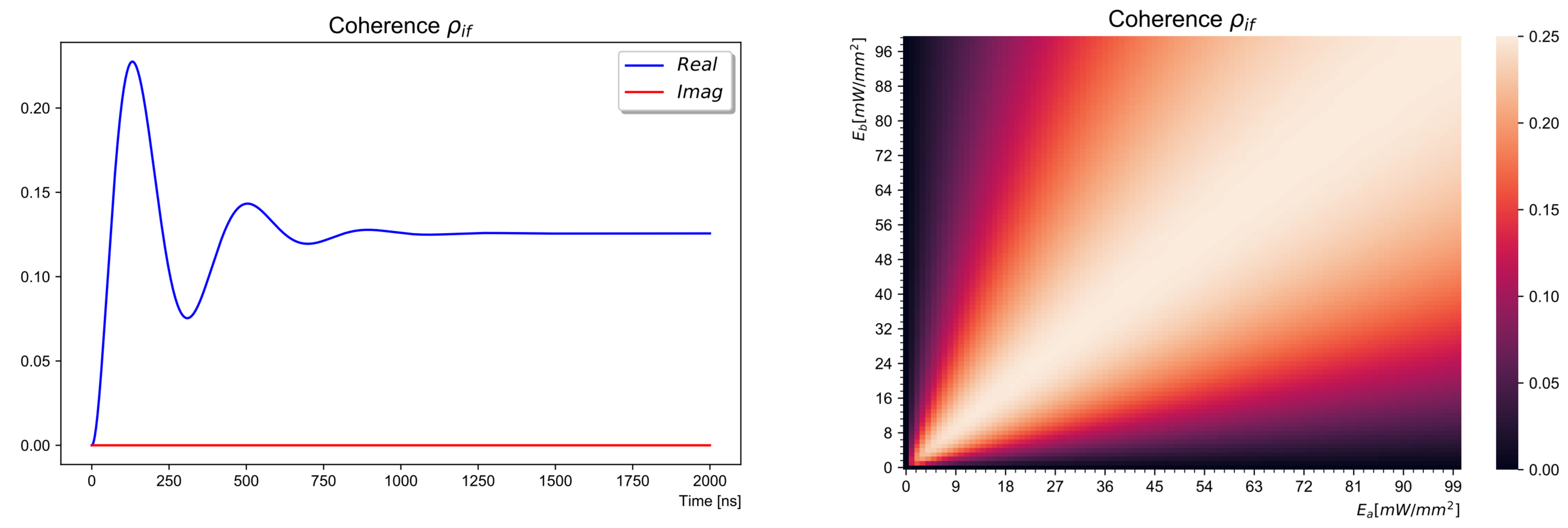
❑Generate atomic coherence between $8P_{3/2}$ and $6P_{3/2}$ using two pump lasers

❑Coherence simulation using the Von Neumann equation

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] + G\hat{\rho}G^\dagger - \frac{1}{2}\{G^\dagger G, \hat{\rho}\}$$



❑Inject two pump continues wave lasers: system reach steady state

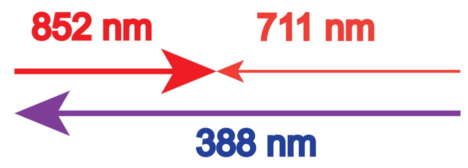


❑Laser power requirements

$$P_a = \frac{10^{10} \times 3.198\mathrm{eV}}{274\ \mathrm{ns}} \sim 20\ \mathrm{mW} \qquad P_b = \frac{10^{10} \times 1.5\mathrm{eV}}{35\ \mathrm{ns}} \sim 70\ \mathrm{mW}$$

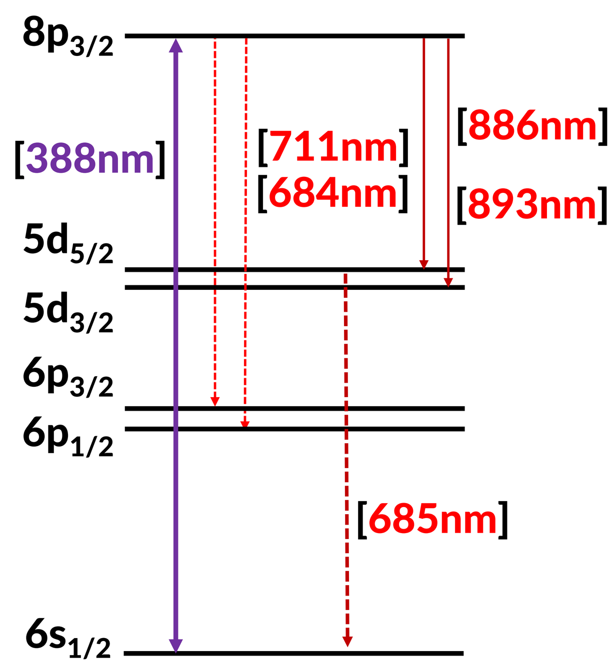
❑Coherence can be monitored using Cesium 8P → 6P E2 transition

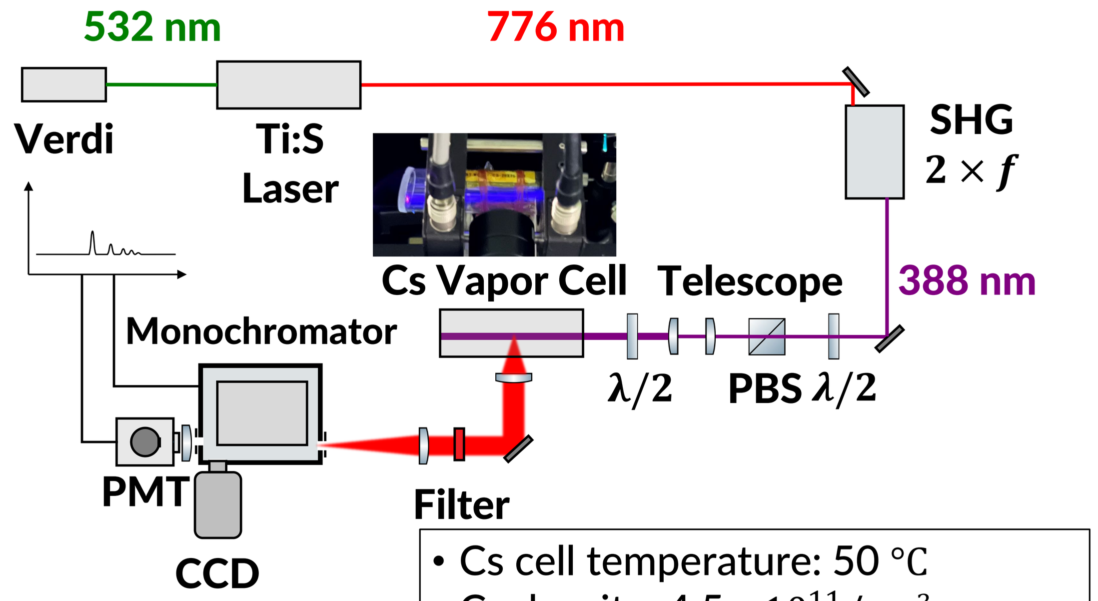
❑E2 transition is expected to be amplified when lasers satisfy $\Delta\vec{k} = 0$



8P → 6P spontaneous emission rate is necessary

Ⅴ. 8P → 6P transition measurement



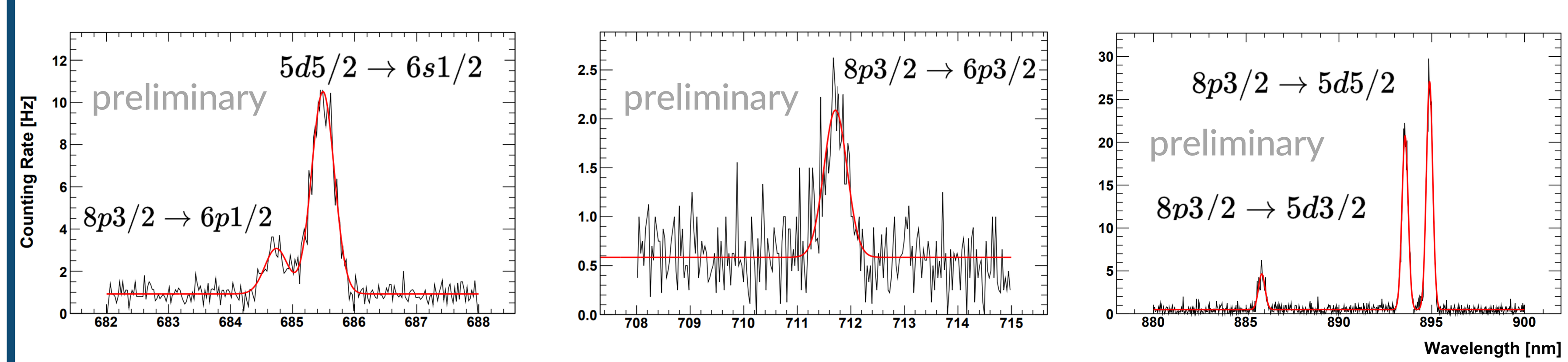


- Cs cell temperature: 50 ℃
- Cs density: 4.5× 10^{11}/cm³
- 388 nm laser intensity: 0.5 W/cm²

❑Compare the emission rate from same excited state

❑Photomultiplier Tube (PMT Hamamatsu R13456P) is cooled down to -30 ℃ to reduce the dark count rate (~1 Hz)

❑Spectrums by scanning the monochromator



❑Forbidden transitions are successfully observed

❑Calibration of the setup is ongoing …

Ⅵ. Summary

❑ New method of dark matter search.
- ❖Amplification by macroscopic coherence is KEY

❑ Coherence measurement experiment with Cs E2 transition
- ✓Determine E2 transition rate
- ❖Coherence measurement experiment

❑ Dark matter search in meV region