Coherence amplification

using atoms (ions) for fundamental physics

Akihiro YOSHIMI

on behalf of SPAN collaboration

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Research Institute for Interdisciplinary Science

For crystal projects

H. Hara, Y. Miyamoto, Junseok Han,
Y. Imai, N. Sasao, K. Yoshimura, M. Yoshimura

Introduction

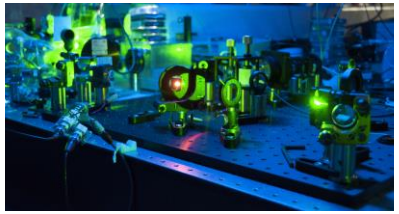
Precision measurement

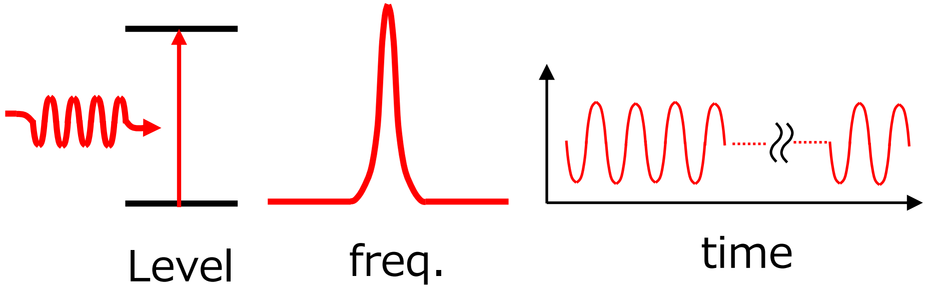
Nuclear clock

Muonium spectroscopy

EDM

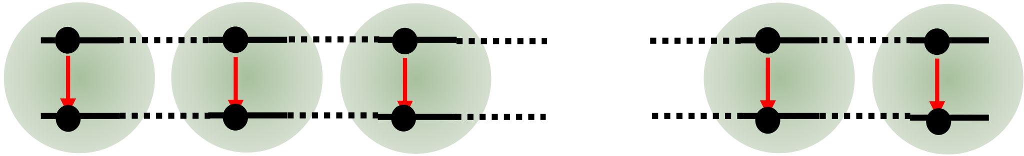
Cold molecule ・・・

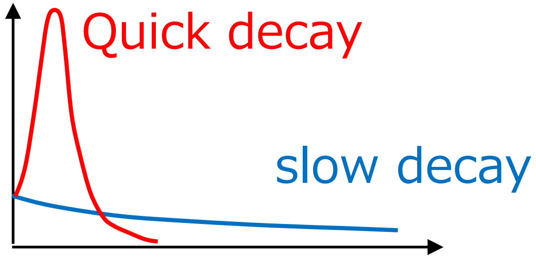




Amplification of “weak” process

using quantum coherence





Neutrino mass spectroscopy

Dark matter (Axion, DP, ..) search

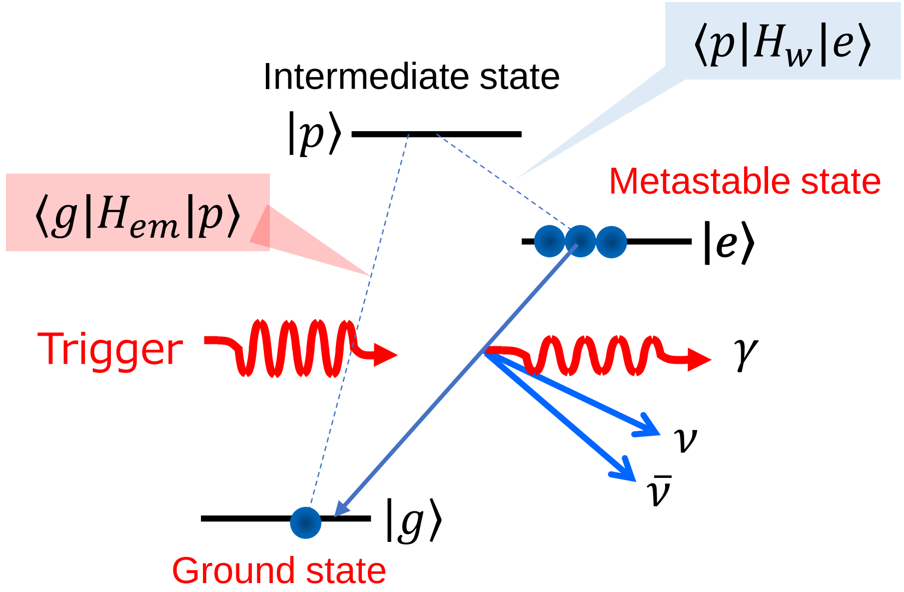
Origin of CP violation

beyond Standard Model

What should be amplified

Radiative emission of neutrino pair (RENP)

Atomic transition



$$H_w = \frac{G_F}{\sqrt{2}} \sum_{ij} \bar{\nu}_i \gamma^{\alpha}(1-\gamma_5)\nu_j \, \bar{e}(\gamma_\alpha c_{ij} - \gamma_\alpha \gamma_5 b_{ij})e$$

PHYSICAL REVIEW D **75,** 113007 (2007)

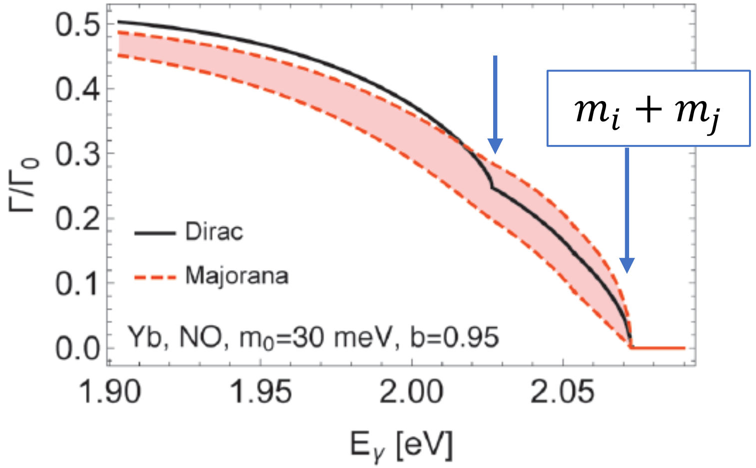
Neutrino pair emission from excited atoms

M. Yoshimura

Center of Quantum Universe and Department of Physics, Okayama University, Tsushima-naka 3-1-1, Okayama 700-8530, Japan

(Received 24 December 2006; revised manuscript received 4 April 2007; published 25 June 2007)

photon spectrum



$$\omega_{ij} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}}.$$

- Neutrino absolute mass (mass eigen state)
- Dirac / Majorana
- NH/IH

Energy scale eV ~ meV : neutrino mass scale

Low RENP rate @ E ~ eV

$$\Gamma_{RENP} \sim \alpha G_F^2 E^5 = 1.5 \times 10^{-33}\ [s^{-1}]$$

Neutrino Physics

- Absolute mass ?
- Dirac-type or Majorana-type ?
- CP-violating parameters ?

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Cosmology

Why No antimatter in Universe ?

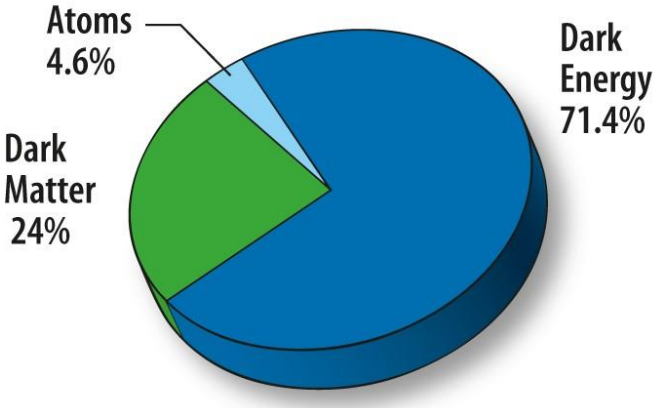
Particle Physics

Why so small mass of neutrinos ?

➡ Leptogenesis   Heavy right-handed neutrino

Majorana neutrino $\nu \neq \bar{\nu}$

Dark matter



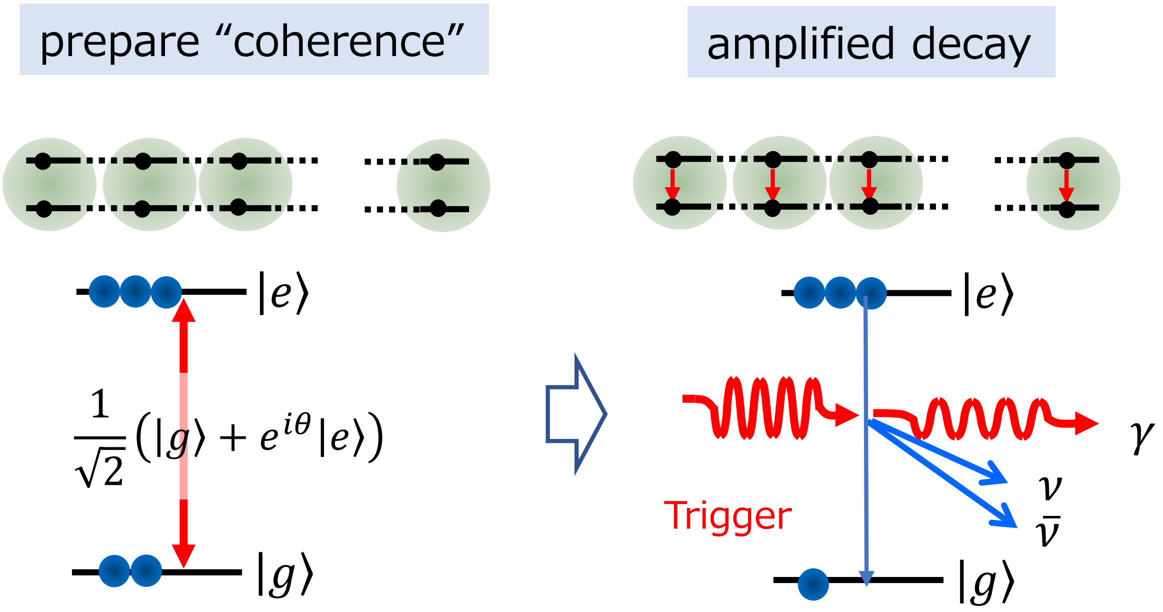
Axions

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

Dark photon

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

Coherence amplification



$$\Gamma_{\mathrm{RENP}} \propto \left| \sum_{a}^{N} e^{-i(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)\cdot \boldsymbol{r}_a} \cdot \mathcal{M}_a(r_a,t) \cdot e^{i\boldsymbol{k}_{ex}\cdot \boldsymbol{r}_a} \right|^2$$

Excitation γ

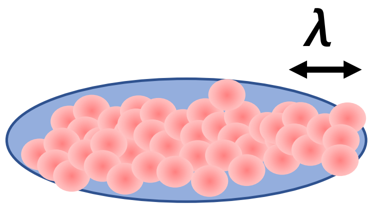
Emitted γ/ν : plane wave

Atoms: Transition matrix

if momentum conservation:

$$\boldsymbol{k}_{ex} - (\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3) = 0$$

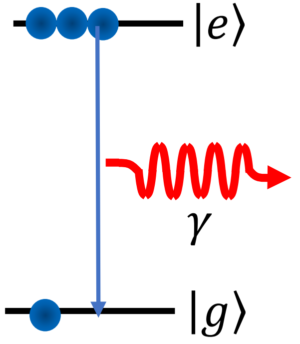
$$\Gamma_{\mathrm{RENP}} \propto \left| \sum_{a}^{N} \mathcal{M}_a(r_a,t) \right|^2 \simeq N^2 |\mathcal{M}_a|^2$$



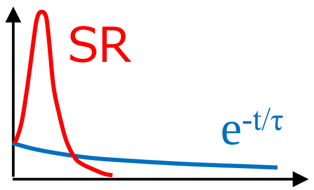
"macroscopic "

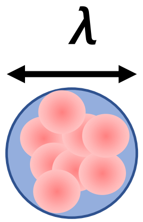
SR beyond λ !

Dicke's Superradiance

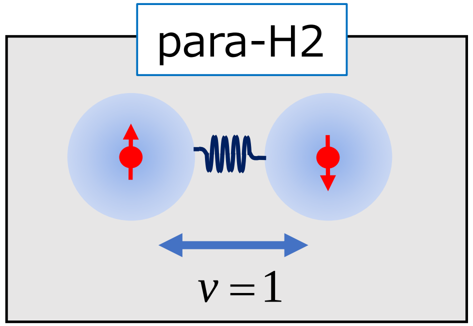


$$\Gamma_\gamma \propto \left| \sum_{a}^{N} e^{i\boldsymbol{k}\cdot \boldsymbol{r}_a} \cdot \mathcal{M}_a(r_a,t) \right|^2 \simeq N^2 |\mathcal{M}|^2$$



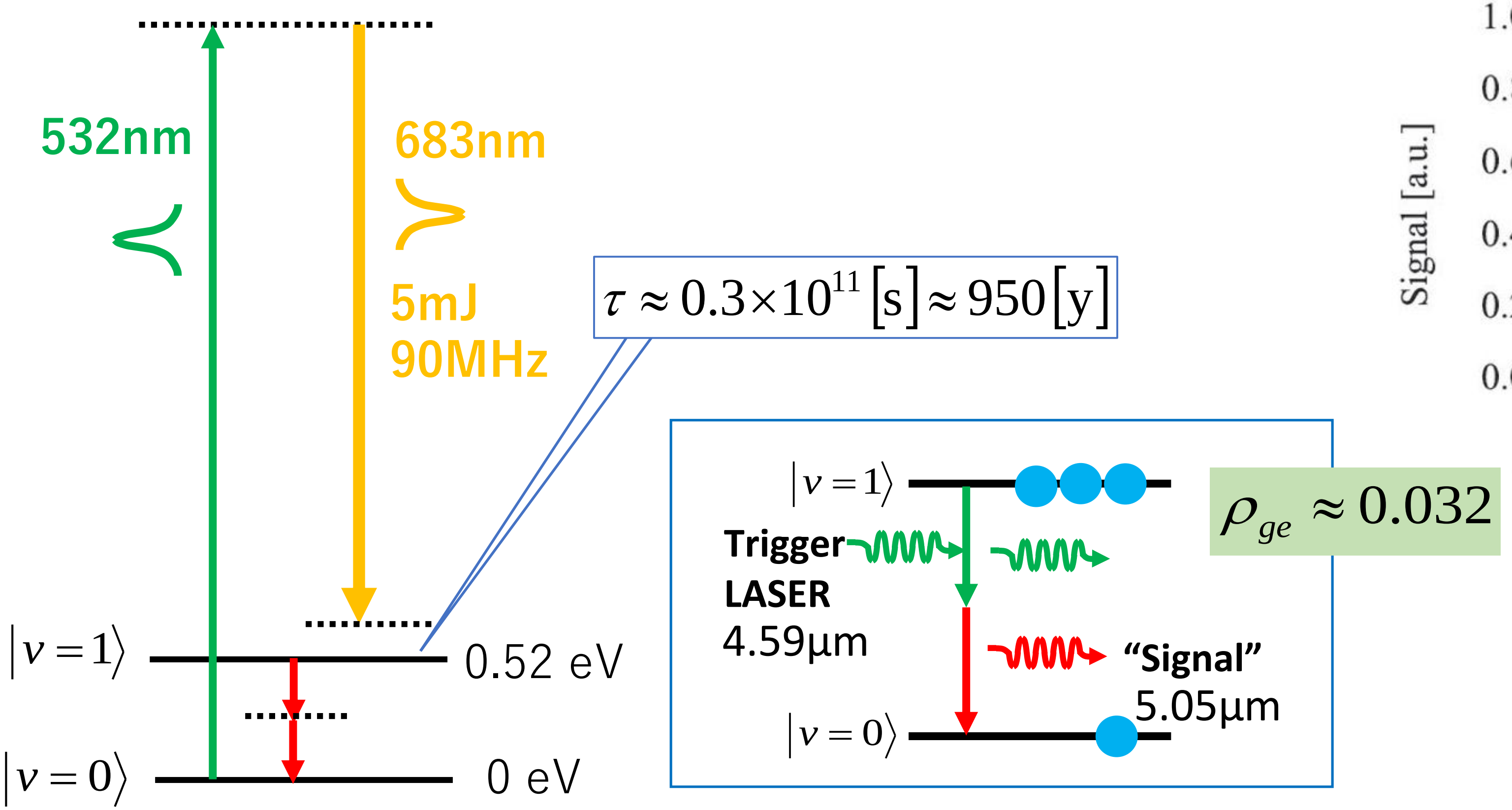


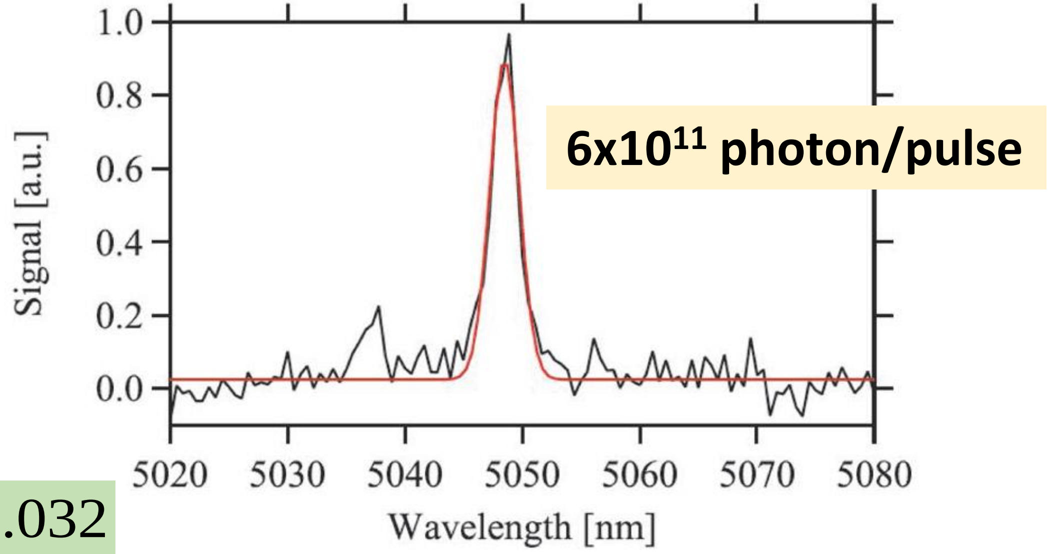
Performed the “basic” experiment of Macro-Coherence-Aamplification



Y. Miyamoto et al.
“Observation of coherent two-photon emission from the first vibrationally excited state of hydrogen molecules”
PTEP 113C01 (2014).

“Externally triggered coherent two-photon emission from hydrogen molecules”
PTEP 081C01 (2015).





$$\text{Enhancement} = \frac{6 \times 10^{11}}{2.4 \times 10^{-7}} \simeq 10^{18}$$

What's next ?

Improvements of amplification

Larger N, Larger coherence ?

two-photon $I_{\mathrm{sig}} \propto \left|E_{\mathrm{sig}}\right|^2 \propto N_i^2 \cdot \left|\rho_{ge}^0\right|^2 \cdot I_{\mathrm{trig}}$

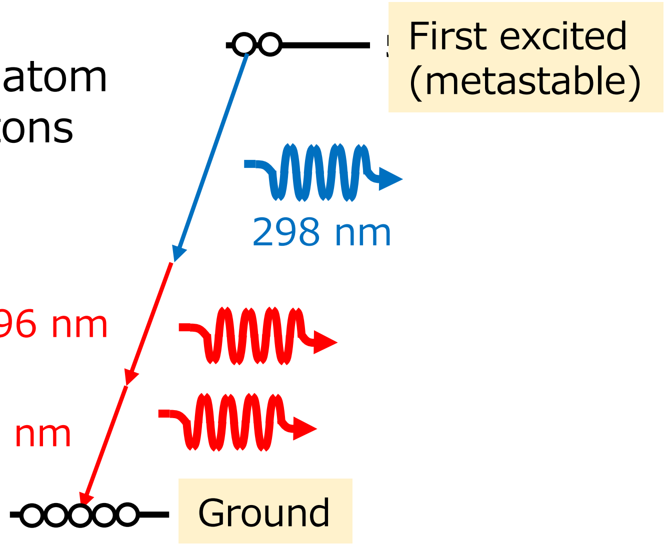
$\rho_{ge} \simeq 0.25$

$n \simeq 1 \times 10^{20}\ [\mathrm{cm}^{-3}]$

$K_{\mathrm{enhance}} \simeq 10^{20}$

Amplification of "weaker"-process

sample: Xe atom
three photons



"Improved" methods

<u>Discrimination of enhanced QED background</u>

three-photon emission $(\boldsymbol{d}_{ep} \cdot \boldsymbol{E}_a)(\boldsymbol{d}_{pq} \cdot \boldsymbol{E}_b)(\boldsymbol{d}_{qg} \cdot \boldsymbol{E}_c)$

sample: Xe atom

$$\Gamma_{3p} \sim 10^{19} Hz \cdot \left(\frac{n}{10^{20} cm^{-3}}\right)^3 \cdot \frac{V}{1\ cm^3} \cdot \frac{\eta_3(t)}{10^{-3}}$$

$$\Gamma_{RENP} \sim 1\ mHz \cdot \left(\frac{n}{10^{20} cm^{-3}}\right)^3 \cdot \frac{V}{1\ cm^3} \cdot \frac{\eta_\omega(t)}{10^{-3}}$$

Discrimination of QED-process

Photonic crystal waveguide

PTEP
Prog. Theor. Exp. Phys. 2017, 043B03 (18 pages)
DOI: 10.1093/ptep/ptx035

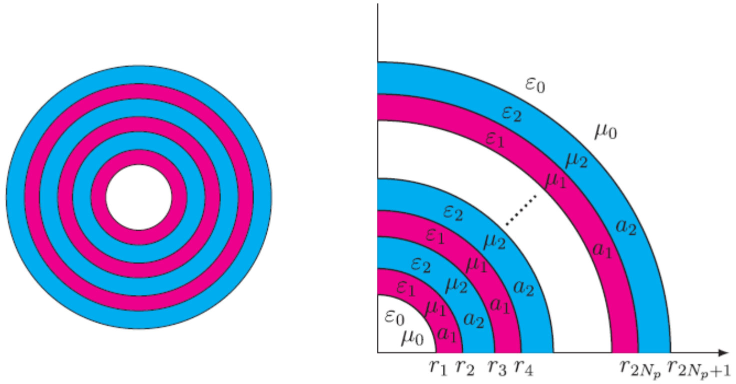
Toward background-free RENP using a photonic crystal waveguide

Minoru Tanaka[1,*], Koji Tsumura[2], Noboru Sasao[3], and Motohiko Yoshimura[3]

Cutoff the mode in a waveguide

Effective photon mass > m_ν

➡ Large suppression of QED

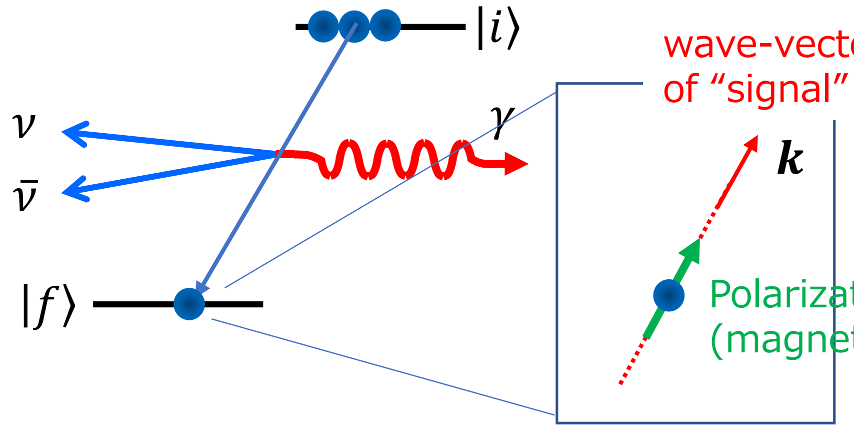


Parity-violating spin component

PHYSICAL REVIEW D **104,** 115006 (2021)

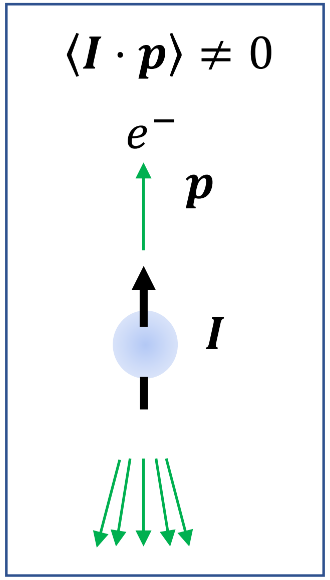
Parity violating magnetization at neutrino pair emission using trivalent lanthanoid ions

Hideaki Hara, Akihiro Yoshimi, and Motohiko Yoshimura
Research Institute for Interdisciplinary Science, Okayama University, Tsushima-naka 3-1-1, Kita-ku, Okayama 700-8530, Japan



⟺

PV in β-decay



$$\langle M\rangle \propto g\mu_B \langle f|\boldsymbol{k}\cdot\boldsymbol{S}|f\rangle \cdot |\langle f|H_W|i\rangle|^2$$

→ Doped ion in crystals

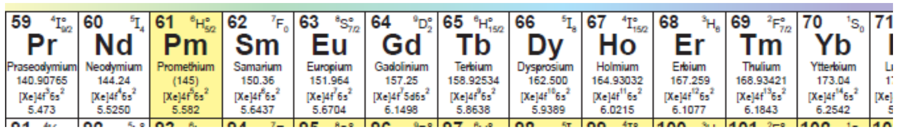
“Parity-mixed” state

➡ **Coherence amplification in Solid state (crystals)**

also good for N^2-amp

Lanthanoid elements doped in crystals

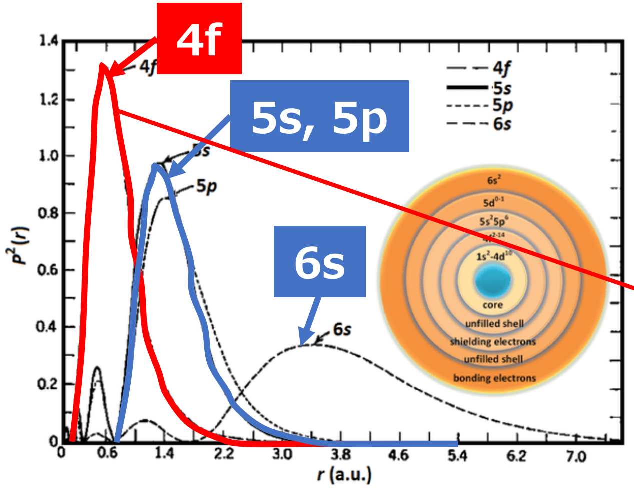
Lanthanoid ions doped in Crystal



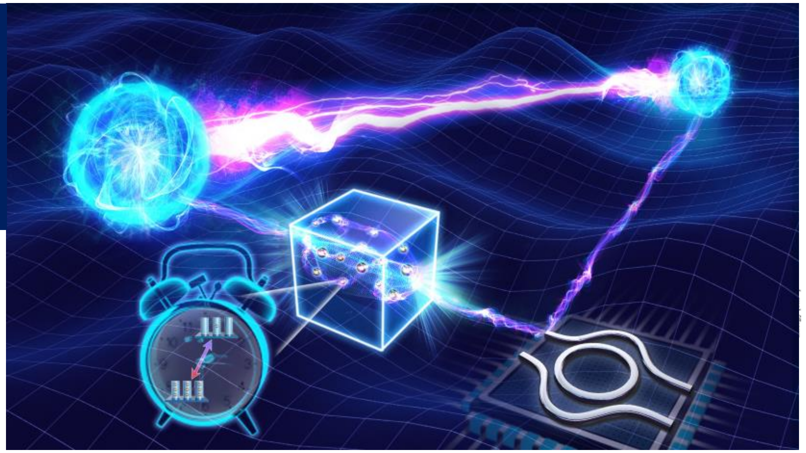
4f-electron

shielded by 5s(5p) electrons

- Narrow linewidth
- Long relaxation time

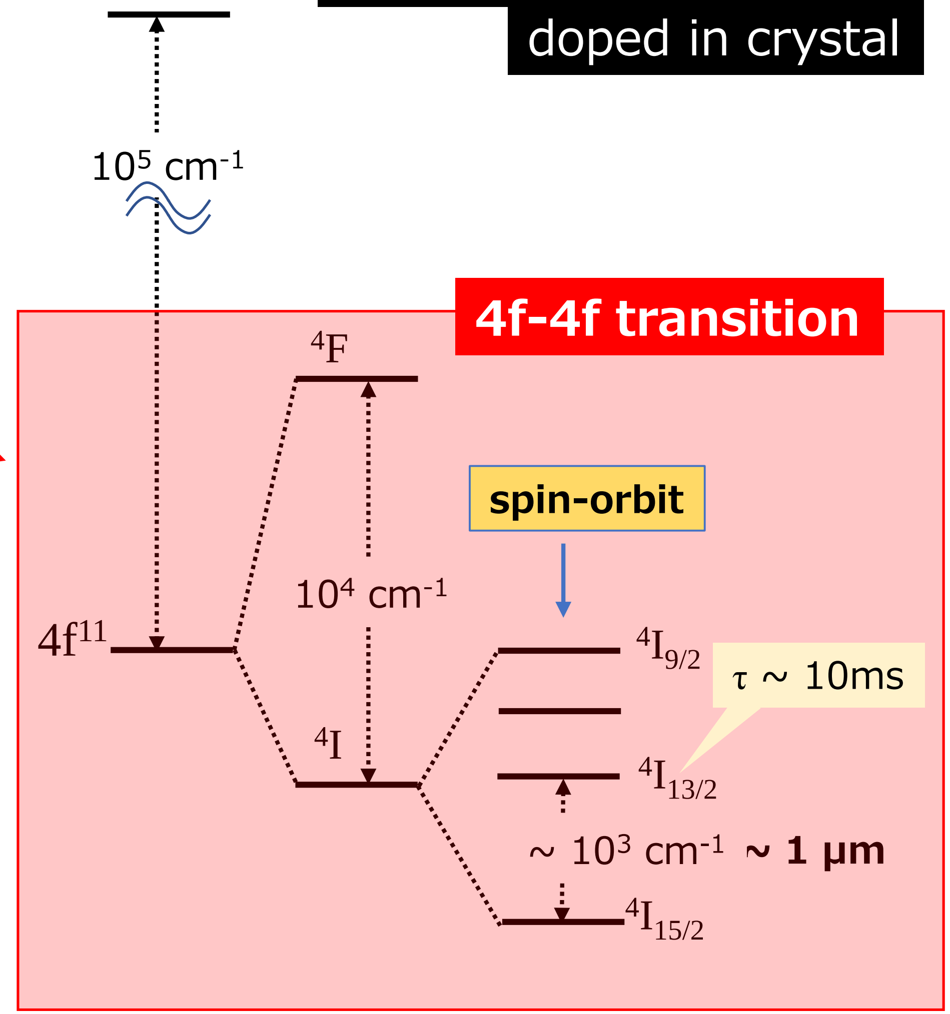


“Quantum storage of entangled photons at telecom wavelengths in a crystal” ($Er:Y_2SiO_5$)



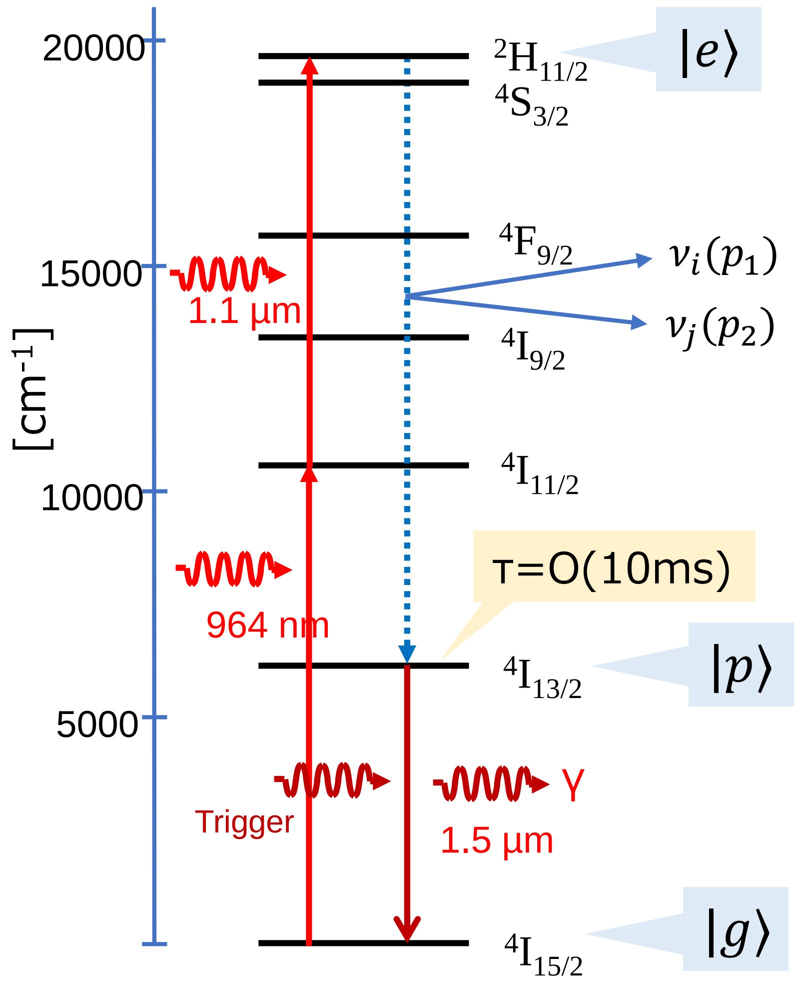
Ming-Hao Jiang et al.
Nature Comm. 14:6995(2023).

The energy level of Er^{3+} doped in crystal



Proposals of MagRENP

proposed scheme with Er^{3+}:$LiYF_4$



Produced magnetization

$\nu_i\nu_j$ emission

$$\Gamma_{Mag} = \frac{2G_F^2}{(2\pi)^3} h_r^2 (nV)^2 |\chi|^2 \cdot g\mu_B n \cdot (\boldsymbol{S}_{ep} \cdot \boldsymbol{v}_{ep}) \cos\theta_s \cdot \sum_{ij} \mathcal{G}_{ij}$$

excitation/coherence

$$\propto \rho_{ee}^3 |\rho_{ep}|^2 = 10^{-2} \sim 10^{-3}$$

$\sim 0.1 - 1\ [nG]$

※ Accumulation time
= 1 ms assumed.
(spin relaxation time)

can be accumulated within spin relaxation.

atomic matrix element

$$\langle p||S||e\rangle = \frac{12}{\mu_B^2} \sum_{m',q} |\langle p,m'|M_q|e,m\rangle|^2 \simeq 3.47$$

$$\langle p||v||e\rangle = \left\langle p \left|\left| \pm i \frac{\boldsymbol{d}_{ep}}{e} \epsilon_{ep} \right|\right| e \right\rangle$$

$$= \frac{12\epsilon_{ep}^2}{e^2} \sum_{m} |\langle p,m'|d_q|e,m\rangle|^2$$

$$\simeq 2.79 \times 10^{-6}$$

"First-step" experiments with crystals

H. Hara,
Y. Miyamoto

PHYSICAL REVIEW RESEARCH **6**, 013005 (2024)

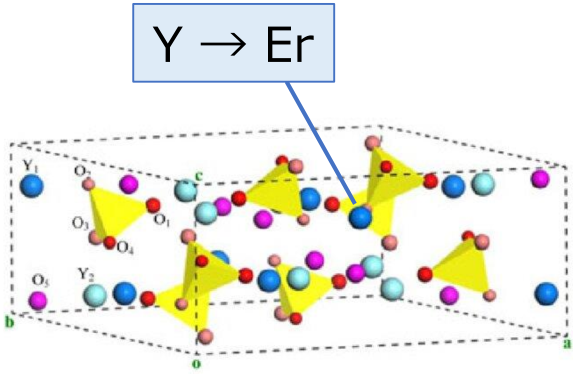
Periodic superradiance in an Er:YSO crystal

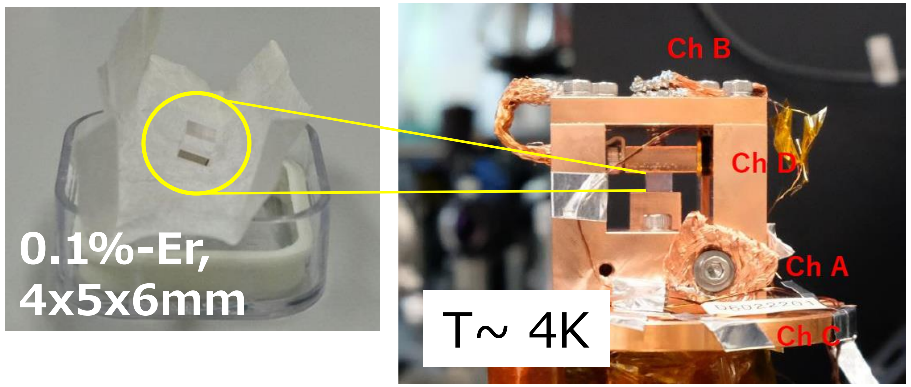
Hideaki Hara,[1,*] Junseok Han,[1,2] Yasutaka Imai,[1] Noboru Sasao,[1] Akihiro Yoshimi,[1] Koji Yoshimura,[1] Motohiko Yoshimura,[1] and Yuki Miyamoto[1,†]
[1]*Research Institute for Interdisciplinary Science, Okayama University, Okayama 700-8530, Japan*
[2]*Department of Physics and Astronomy & Institute of Applied Physics, Seoul National University, Seoul 08826, Korea*

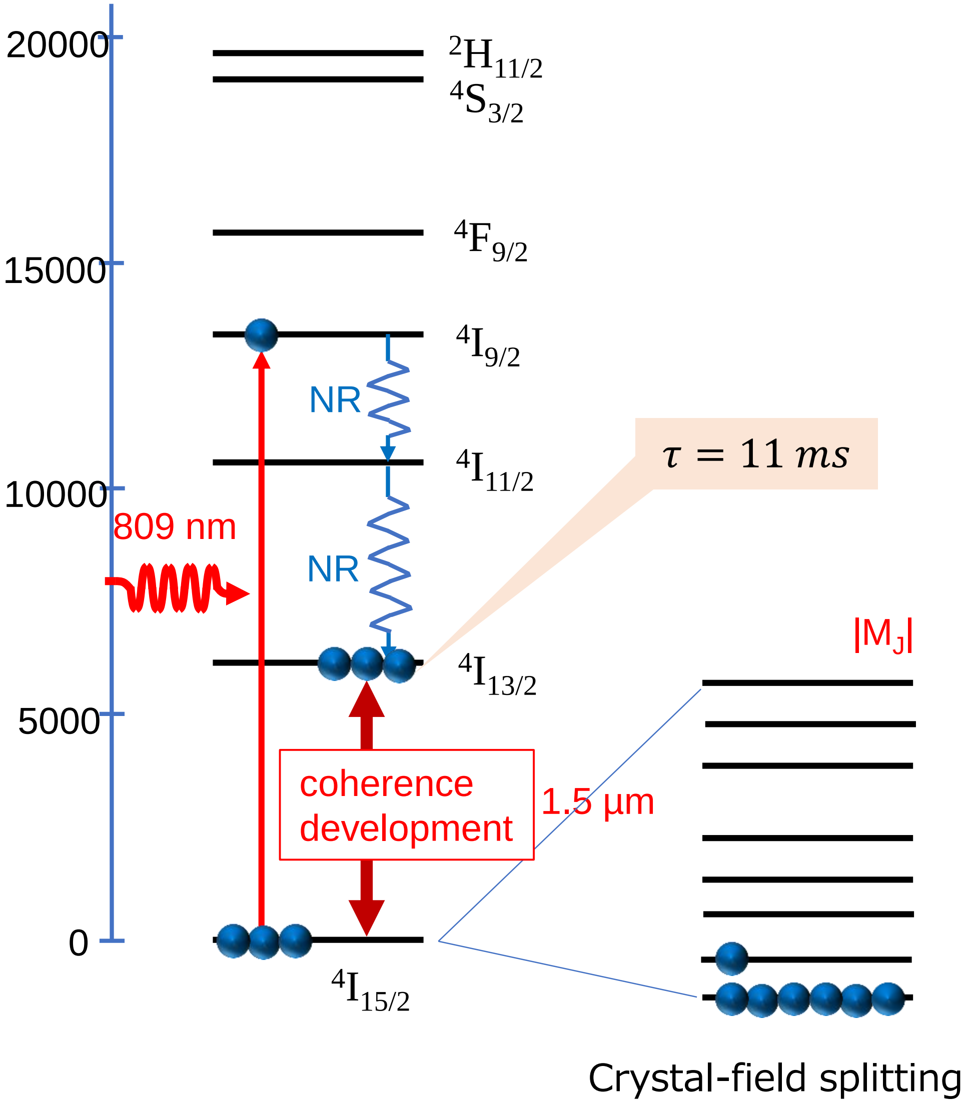
Superradiance in crystal

Er^{3+}:Y_2SiO_5: good condition for "4f-e"-coherence

→ Coherence developed in the crystal environment



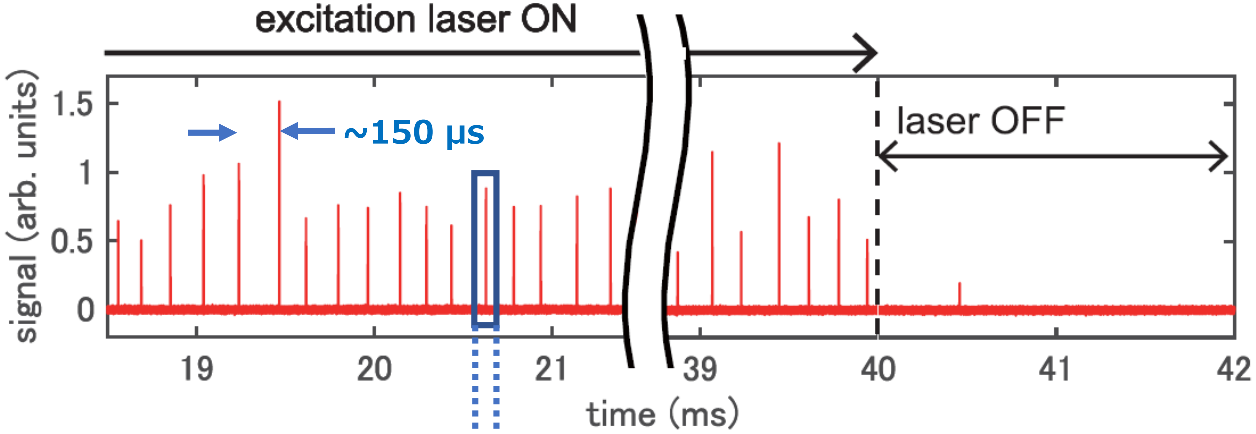


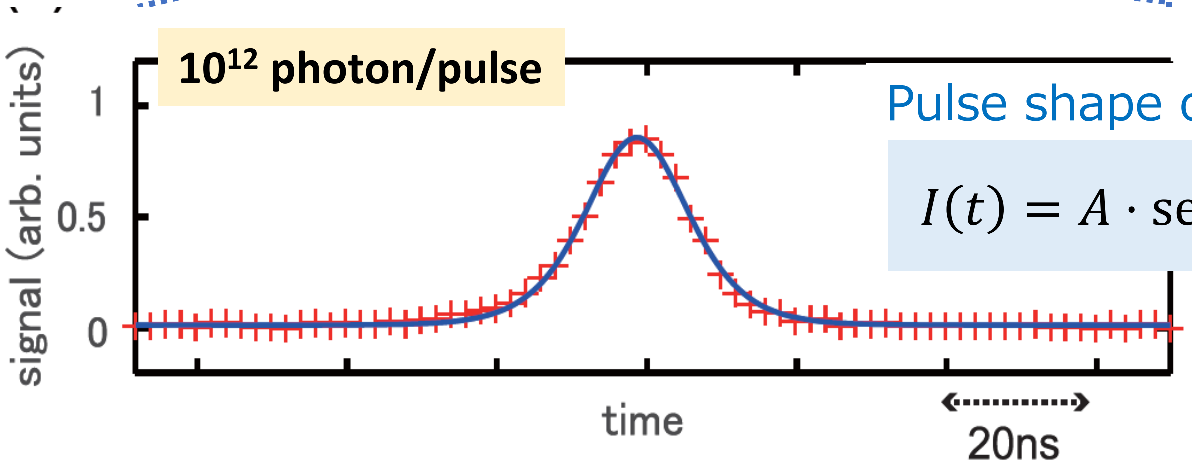


“First-step” experiments with crystals

CW excitation to metastable level

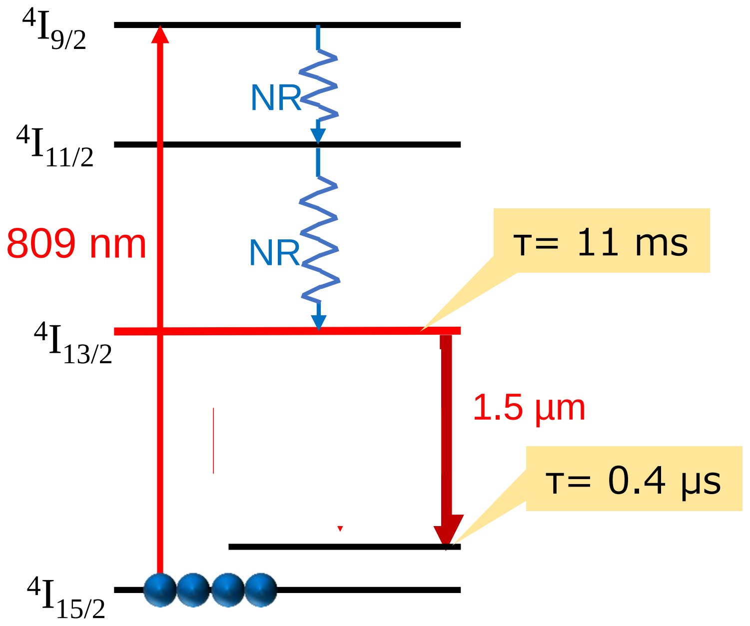
Output pulse of λ=1.5 μm





Pulse shape of SR-emission

$$I(t) = A \cdot \mathrm{sech}^2 \frac{t - t_0}{B}$$



Spontaneous formation of atomic coherence

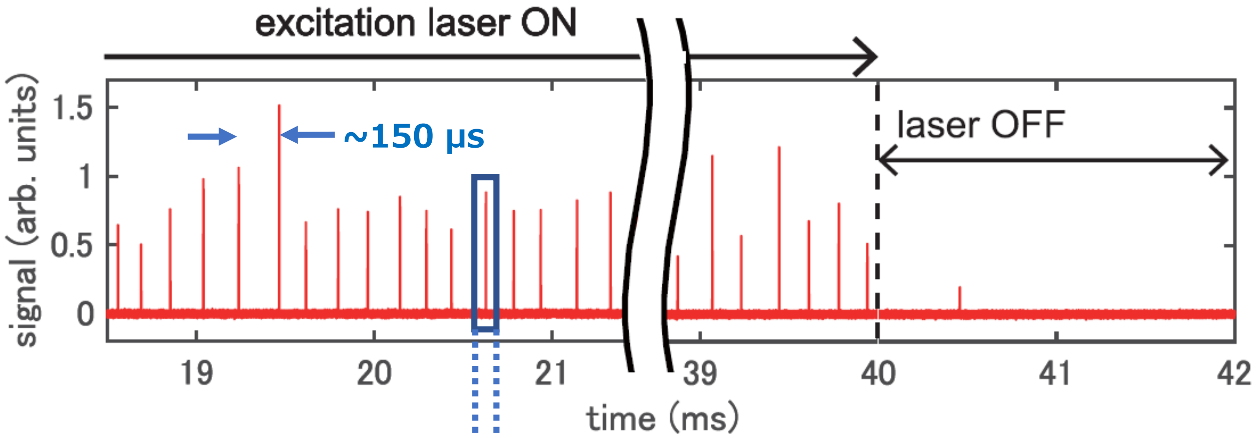
with inhomogeneously broadened (~ 1 GHz) Er-ion

More controllable SR?

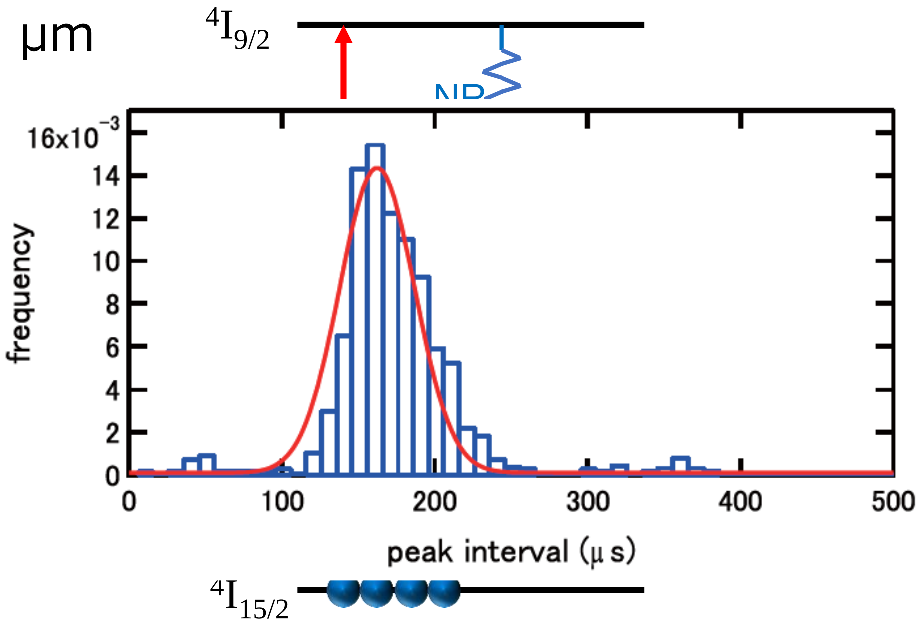
for example, “triggered SR”

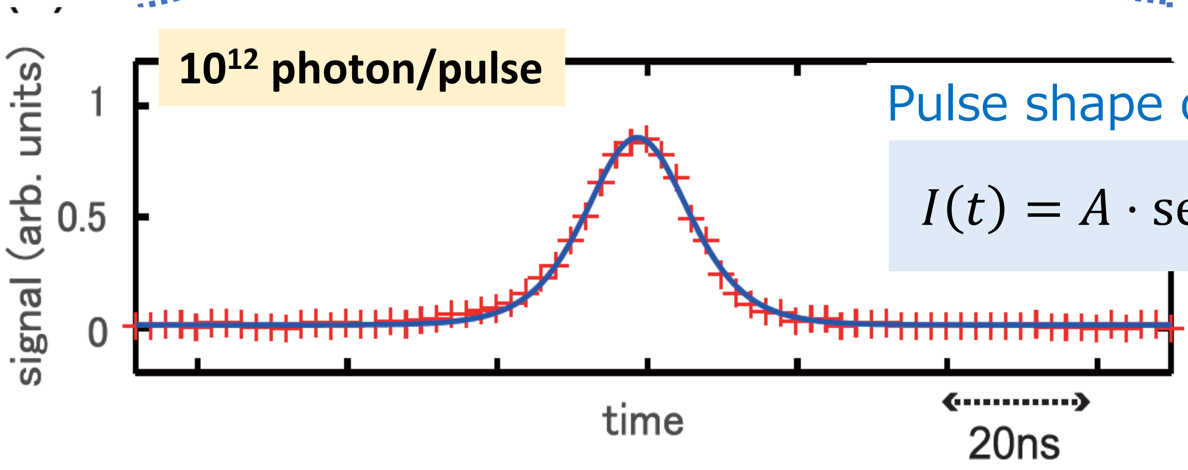
“First-step” experiments with crystals

CW excitation to metastable level



Output pulse of λ=1.5 μm





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Spontaneous formation of atomic coherence

with inhomogeneously broadened (~ 1 GHz) Er-ion

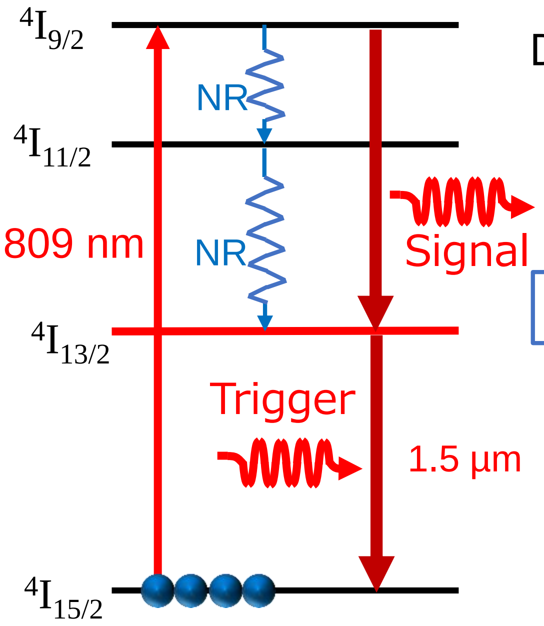
More controllable SR?

for example, “triggered SR”

On-going experiments with crystals

For coherence generation in Er:YLF

Junseok Han



Dispersion of refractive index

$$n_3^o \omega_3 \neq n_1^o \omega_1 + n_2^o \omega_2$$

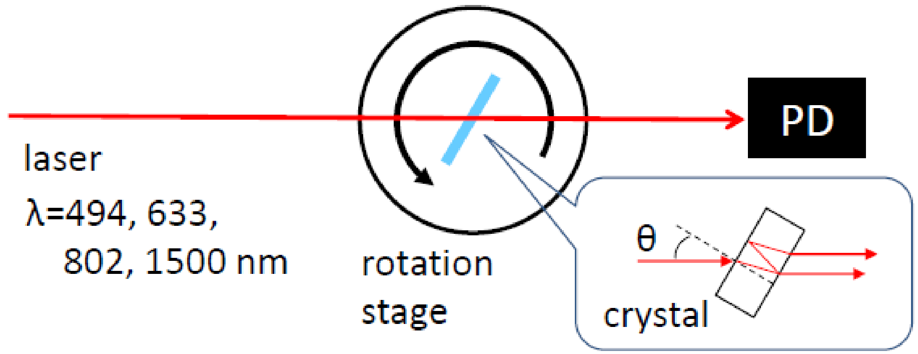
tuning Laser-incident angle θ

$$n_{ex}\omega_{ex} = n_{trig}\omega_{trig} + n_{sig}\omega_{sig}$$

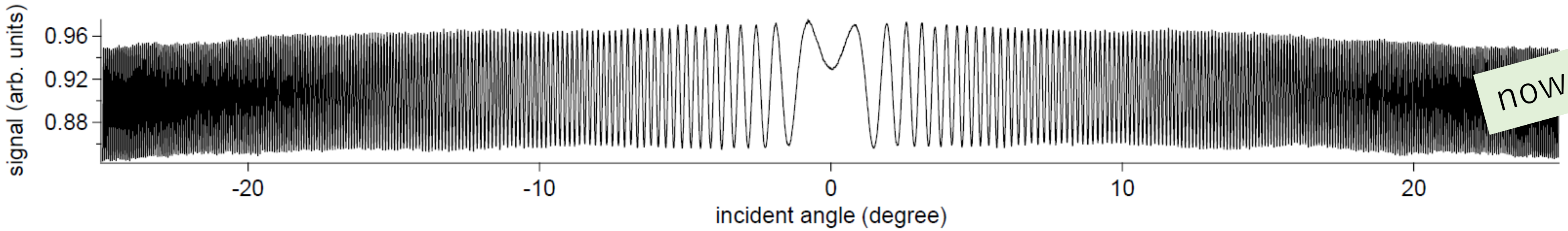
$$\theta = 42.6^\circ$$

Measurement of refractive index

required precision ; 10^{-5}

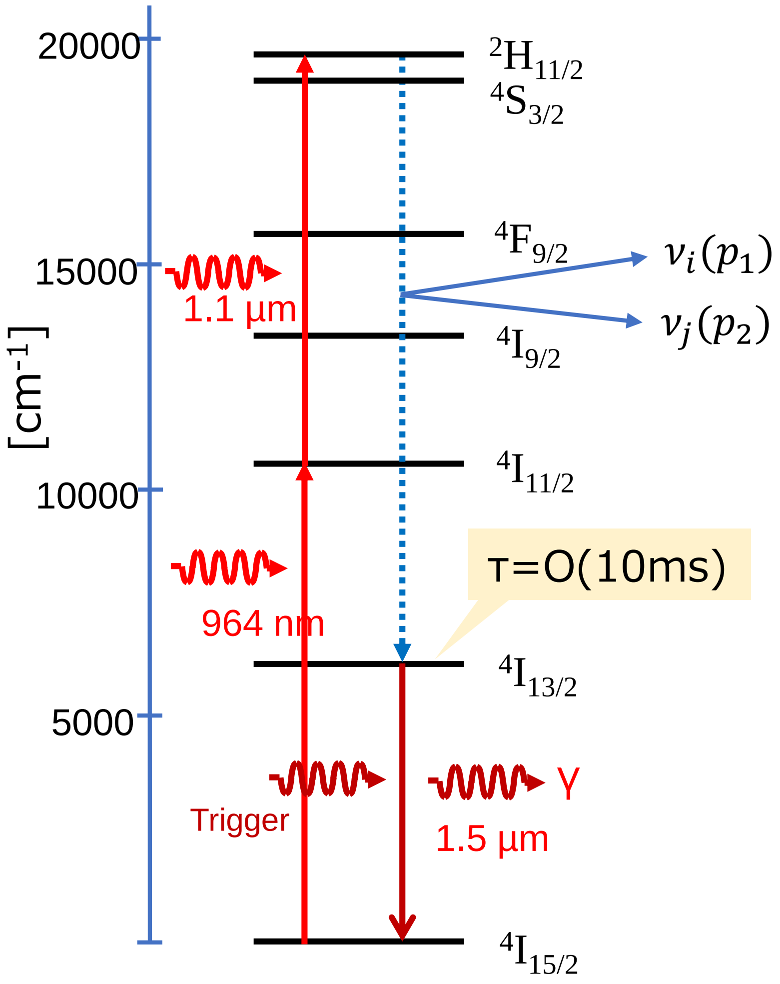


Transmitted intensity for YLF crystal



now in progress

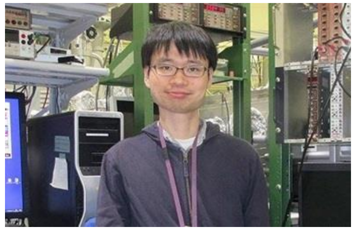
RENP scheme with Er:YLF



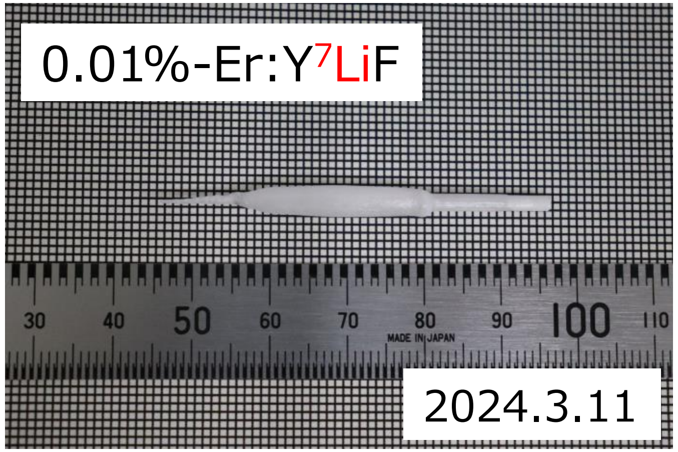
Fabrication of Er:YLF

0.1%, 0.01%-Er:YLF

Micro Pulling down method
@ Tohoku University



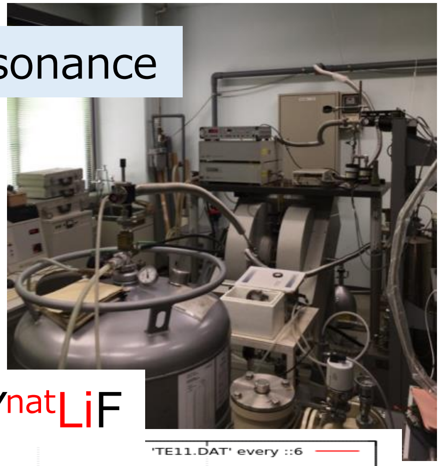
Low-concentration <0.1%
Isotope-enriched ^{7}Li



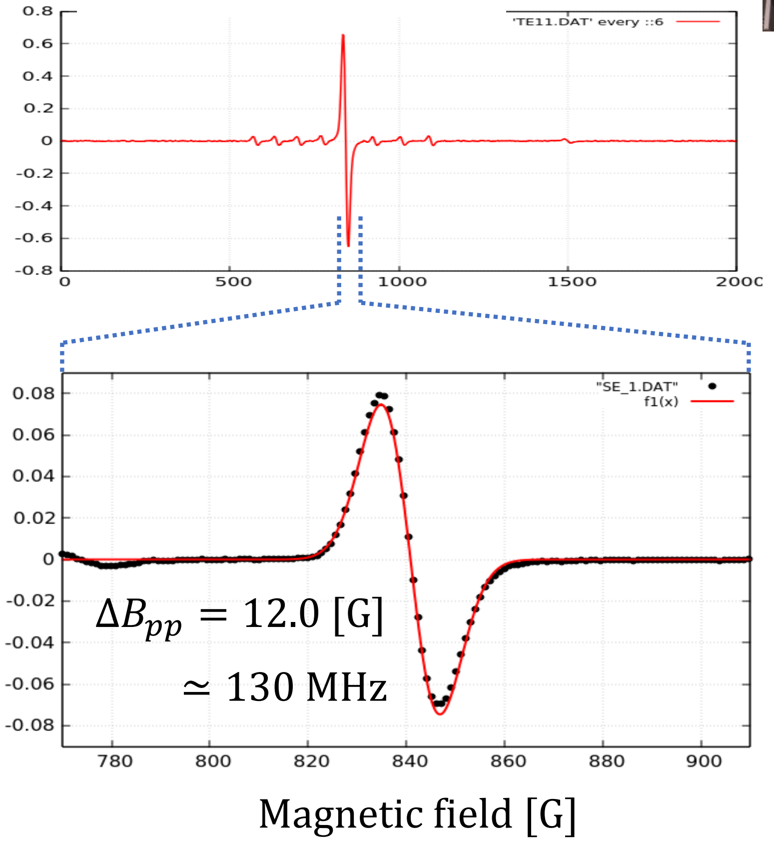
→ go to Narrower-width!

Electron spin resonance

@T = 5.0 K



0.01%-Er:Y^{nat}LiF



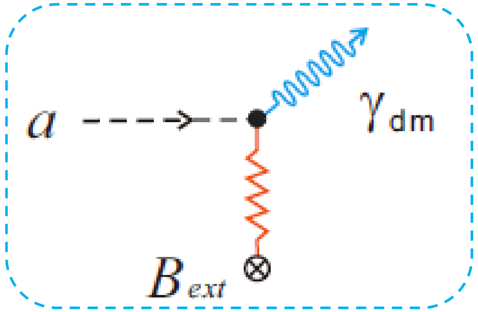
→ $T_1 \sim O(1)\ ms$ @ $5K$

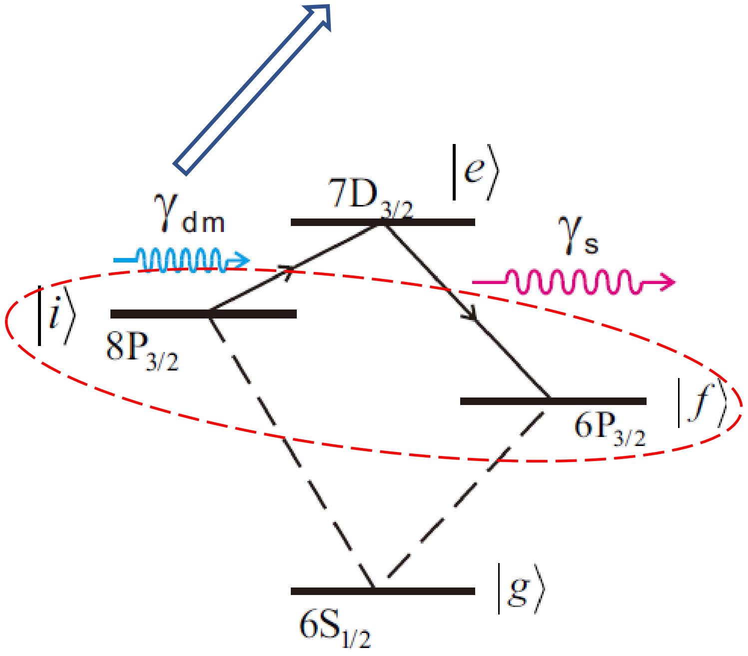
Dark-matter search with cold Cs

Jing Wang,
N. Sasao et al.

- Principle
  - Generate coherence between Cs levels |i> and |f>
  - Transition induced by photons (γ_{dm}) of axion-B_{ext} scattering or dark-photon.
  - Detect signal photons (γ_s) via |e>--|g>
- Signal rate
  - Γ~10 Hz
    - Nρ=10^14, Bext=1 T for axion
    - Nρ=10^10, χ=10^(-12) for dark-photon
- Backgrounds
  - Black body: need to cool down below T<4K
  - Detector dark counts < 1Hz or less

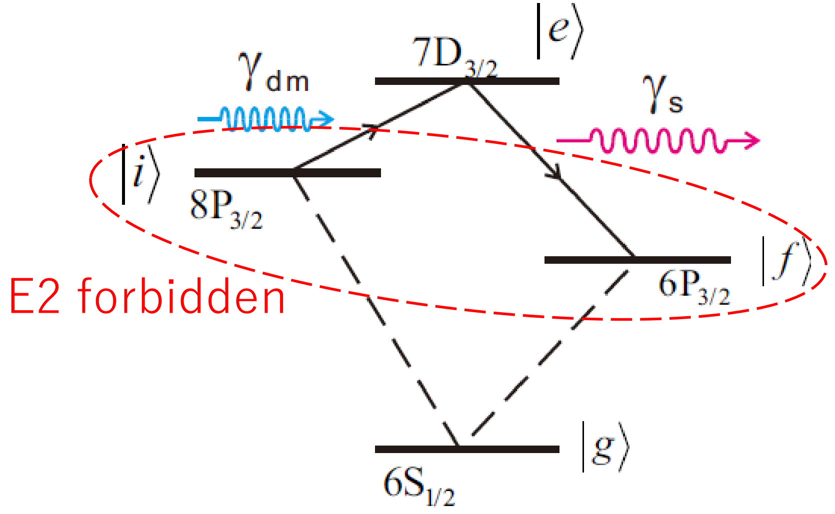
Axion dark-matter

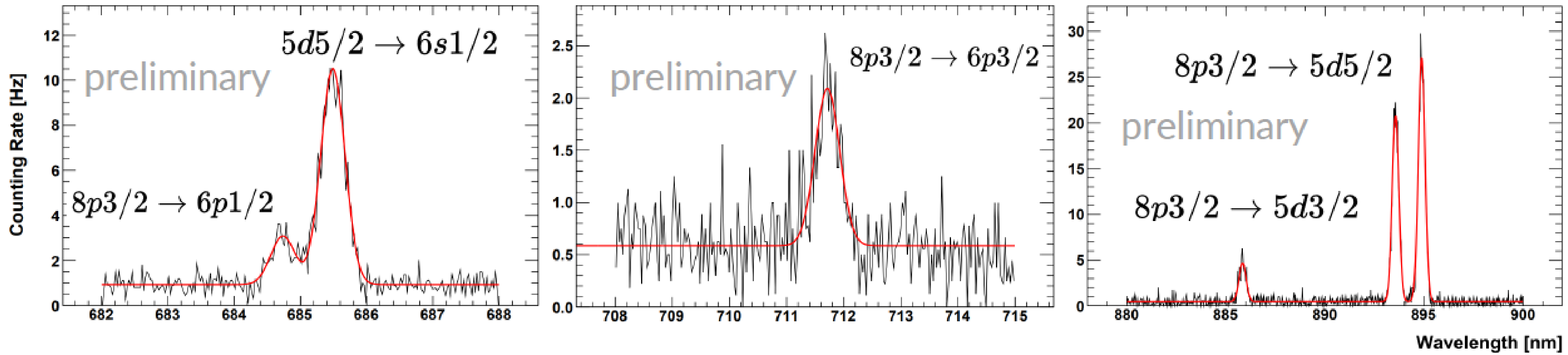




Dark-matter search with cold Cs

- Key feature: coherence
  - How to confirm it experimentally?
  - Measure the forbidden transition rate |i>-|f> and compare with theoretical expectation.
  - Necessary matrix elements are measured.
- Near-future plan
  - Coherence measurement at 4K.
  - Blackbody detection at >4K.
  - Dark photon search/axion search





poster presentation by Jing Wang

Summary

- RENP process is a unique key for neutrino physics
- Macro-coherence amplification is important for neutrino / DM - physics
- Amplification of 2-photon emission with pH_2 ; 10^{18}
- Coherence in Lanthanoid-ion doped in crystals is useful

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  Estimation of PV-magnetization,
  Superradiance experiment in Er:YSO crystals
  Preparation of coherence generation in crystals