OKAYAMA UNIVERSITY

RIIS

SPectroscopy with Atomic Neutrino: its principle and recent progress

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Introduction

known and unknown properties of neutrino

PDG

known properties

- PMNS mixing angle
- squared mass difference
- (Dirac CP phase)
- (Mass ordering)

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$
$\sin^2(\theta_{23}) = 0.421^{+0.033}_{-0.025}$ (S = 1.3) (Inverted order, quad. I)
$\sin^2(\theta_{23}) = 0.592^{+0.023}_{-0.030}$ (S = 1.1) (Inverted order, quad. II)
$\sin^2(\theta_{23}) = 0.417^{+0.025}_{-0.028}$ (S = 1.2) (Normal order, quad. I)
$\sin^2(\theta_{23}) = 0.597^{+0.024}_{-0.030}$ (S = 1.2) (Normal order, quad. II)
$\Delta m^2_{32} = (-2.56 \pm 0.04) \times 10^{-3}\ \mathrm{eV}^2$ (Inverted order)
$\Delta m^2_{32} = (2.51 \pm 0.05) \times 10^{-3}\ \mathrm{eV}^2$ (S = 1.1) (Normal order)
$\sin^2(\theta_{13}) = (2.12 \pm 0.08) \times 10^{-2}$

unknown properties

- absolute mass (only upper limit)
- mass type (Dirac or Majorana)
- (Majorana CP phase)
- etc.

} key parameters for particle physics and cosmology

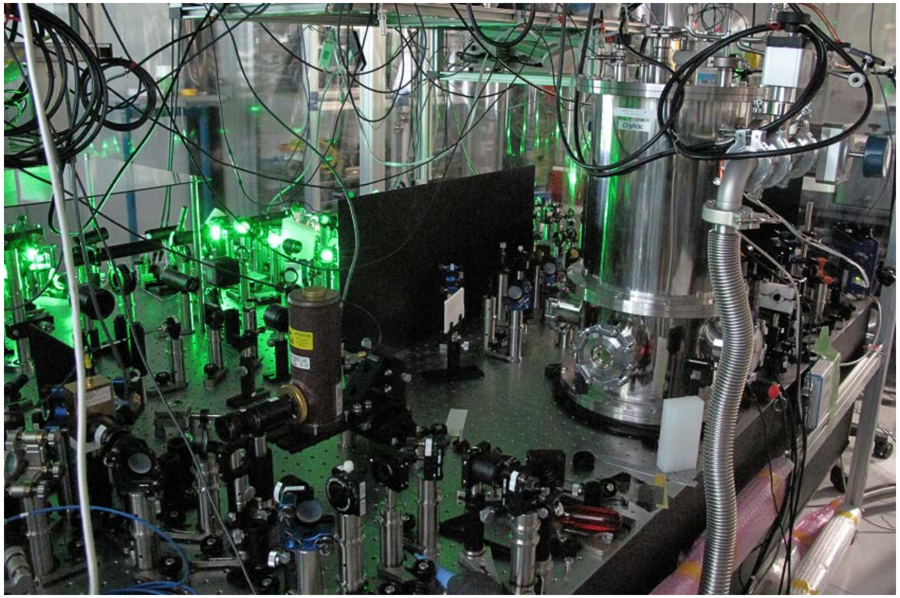
- BSM physics
- leptogenesis

Our approach to neutrino

✓ use atomic or molecular de-excitation process and techniques of laser spectroscopy

table-top experiment

laboratory in Okayama University



interdisciplinary science

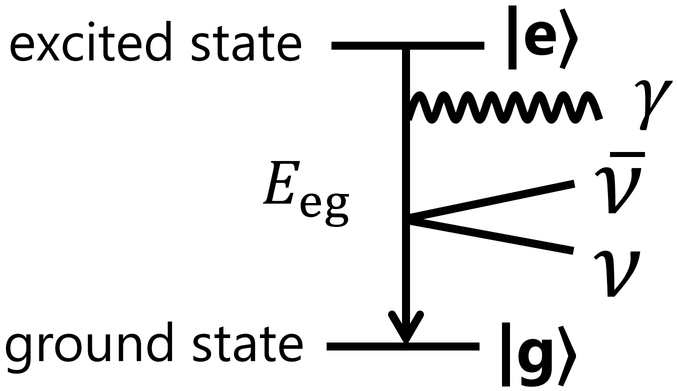
- areas of expertise
  - High energy physics
  - nuclear physics
  - AMO (atomic, molecular and optical) physics
  - chemistry
  - theorists

Experimental principle

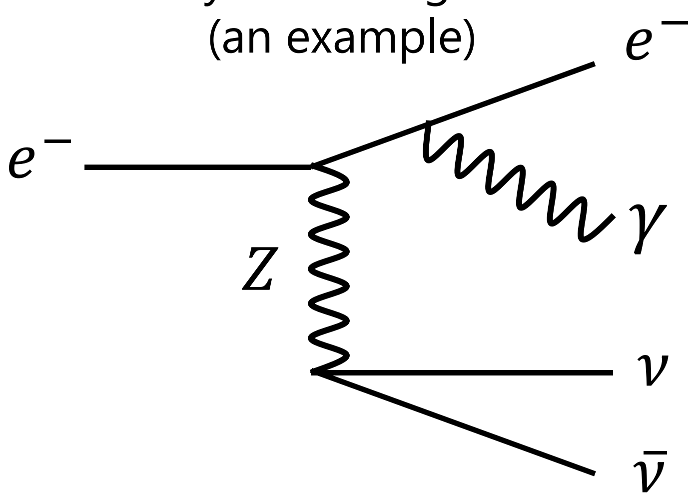
Radiative Emission of Neutrino Pair (RENP)

$$|\mathbf{e}\rangle \rightarrow |\mathbf{g}\rangle + \gamma + \nu + \bar{\nu}$$

transition of atomic or molecular state



Feynman diagram (an example)

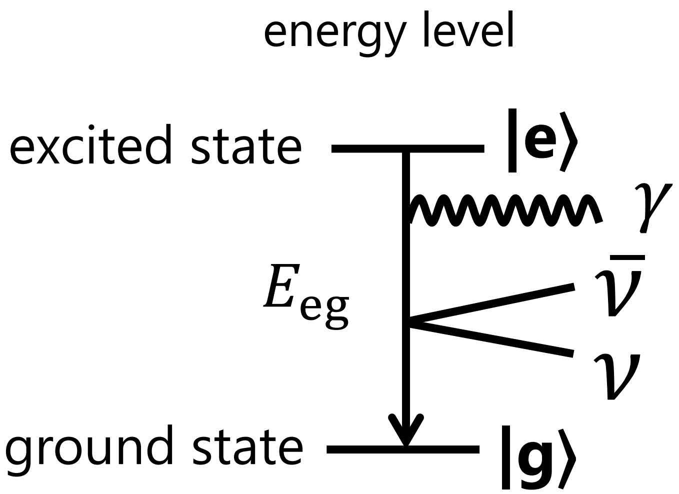


✓ detection of a photon (easy) instead of neutrino (difficult)

Experimental principle

Radiative Emission of Neutrino Pair (RENP)

$$|\mathrm{e}\rangle \rightarrow |\mathrm{g}\rangle + \gamma + \nu + \bar{\nu}$$



- threshold energy of photon

neutrino absolute mass

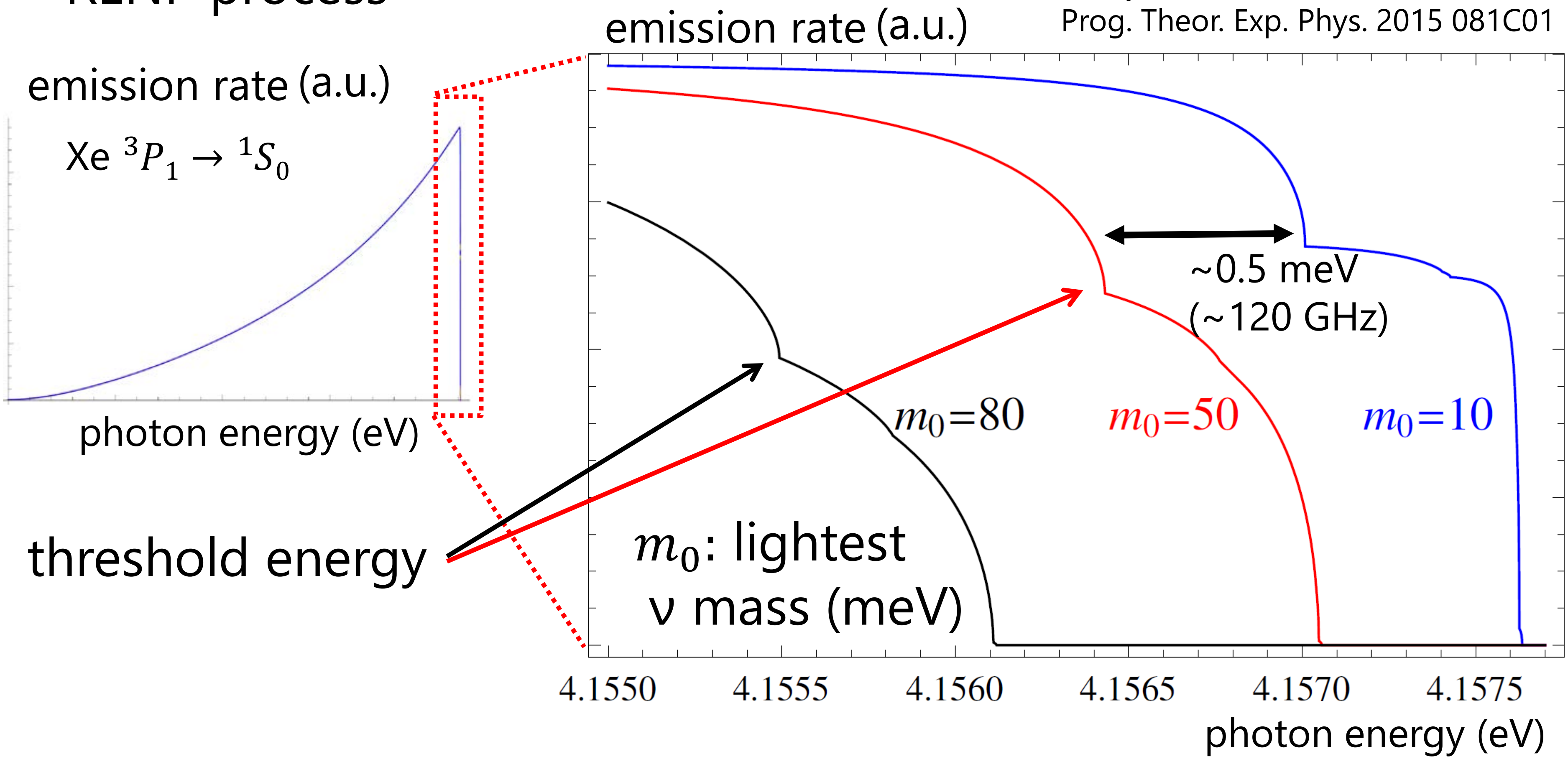
$$E_{th} = \frac{E_{\mathrm{eg}}}{2} - \frac{(m_\nu + m_{\bar{\nu}})^2}{2E_{\mathrm{eg}}}$$

✓ The emitted photon contains information of neutrinos

Energy spectra of emitted photon

- RENP process

Y. Miyamoto et al.
Prog. Theor. Exp. Phys. 2015 081C01



✓ Energy spectra are obtained by scanning the laser frequency

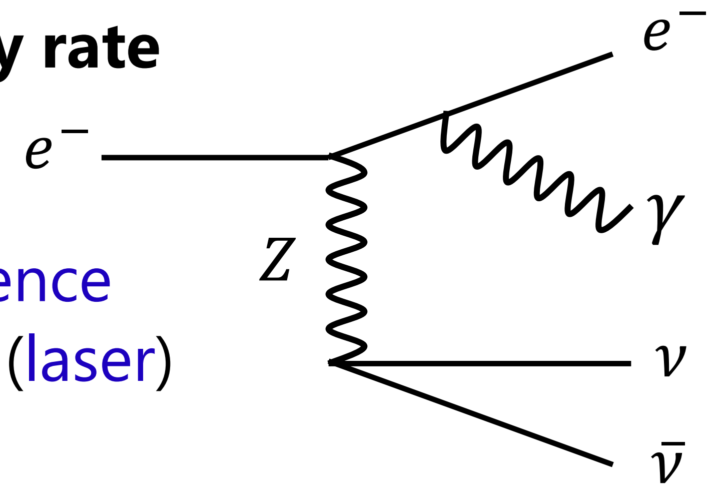
- Frequency resolution is much better than 1 GHz

➡ precise determination of neutrino absolute mass is possible

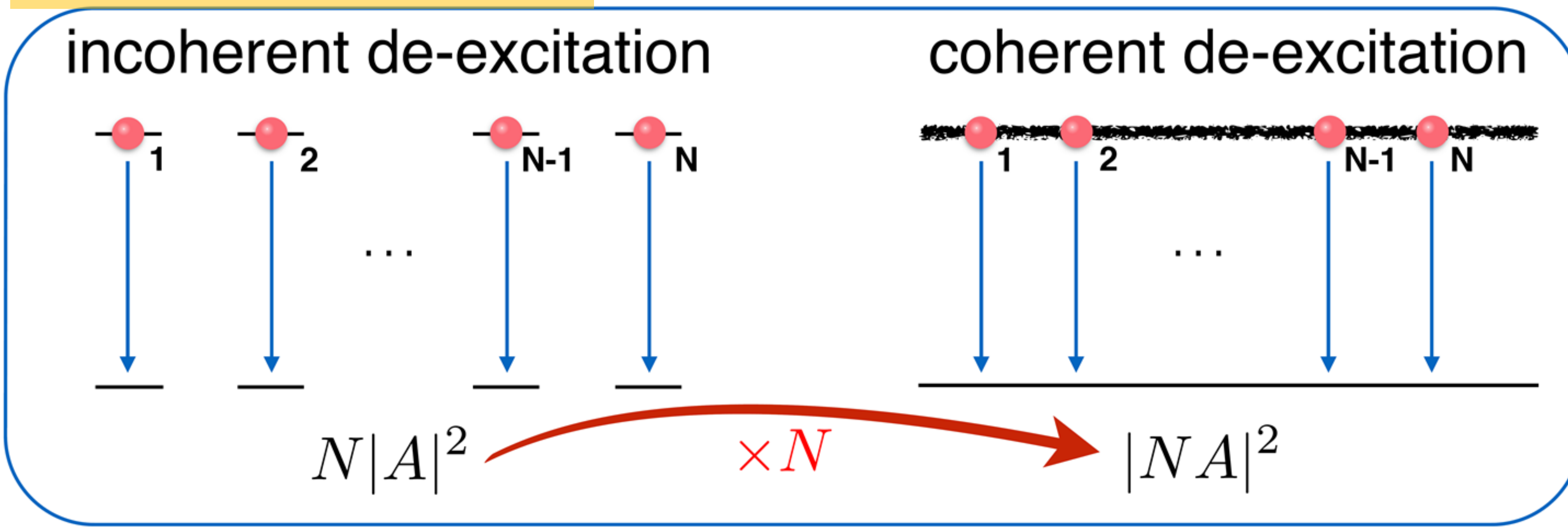
Amplification of emission rate

✓ Critical issue of this method: **very tiny rate**
- typical emission rate ≪ 10^{-30} Hz
- transition includes weak interaction

➡ **rate amplification** by atomic coherence
- obtained by using coherent photons (laser)



Simplified description



Huge enhancement can be achieved!

Rate Amplification

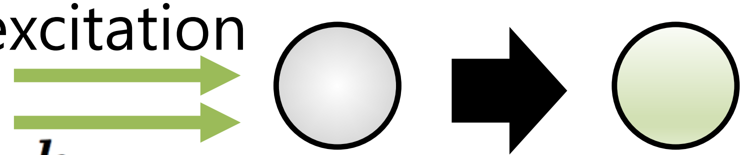
- Condition for rate amplification

proposed by
M. Yoshimura (2007)

coherence generation

lasers for excitation

N atoms



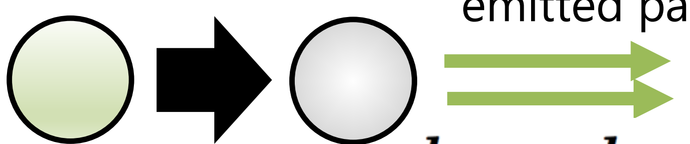
$\boldsymbol{k}_{in1}, \boldsymbol{k}_{in2}, \cdots$

$\boldsymbol{r}_a$

initial spatial phase

$$\sum_a \exp(i\boldsymbol{k}_{in} \cdot \boldsymbol{r}_a)$$

de-excitation process



emitted particles

$\boldsymbol{k}_{out1}, \boldsymbol{k}_{out2}, \cdots$

de-excitation rate ∝

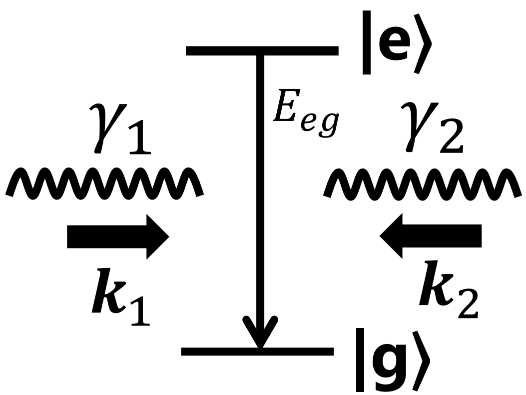
$$\left|\sum_a \exp(i\Delta\boldsymbol{k} \cdot \boldsymbol{r}_a)\mathcal{M}_a\right|^2$$

$$\Delta\boldsymbol{k} = \boldsymbol{k}_{in} - \boldsymbol{k}_{out}$$

- If $\Delta\boldsymbol{k} = \boldsymbol{0}$ holds, the emission rate ∝ ***N*² (rate amplification)**
  - <u>momentum conservation among initial and emitted particles</u>
  - also coherence decay (decoherence) time should be long

✓ **Experimental demonstration of this principle is necessary**

Dirac/Majorana distinction



"boost factor" $b = \frac{|\boldsymbol{k}_{in}|}{E_{eg}}$

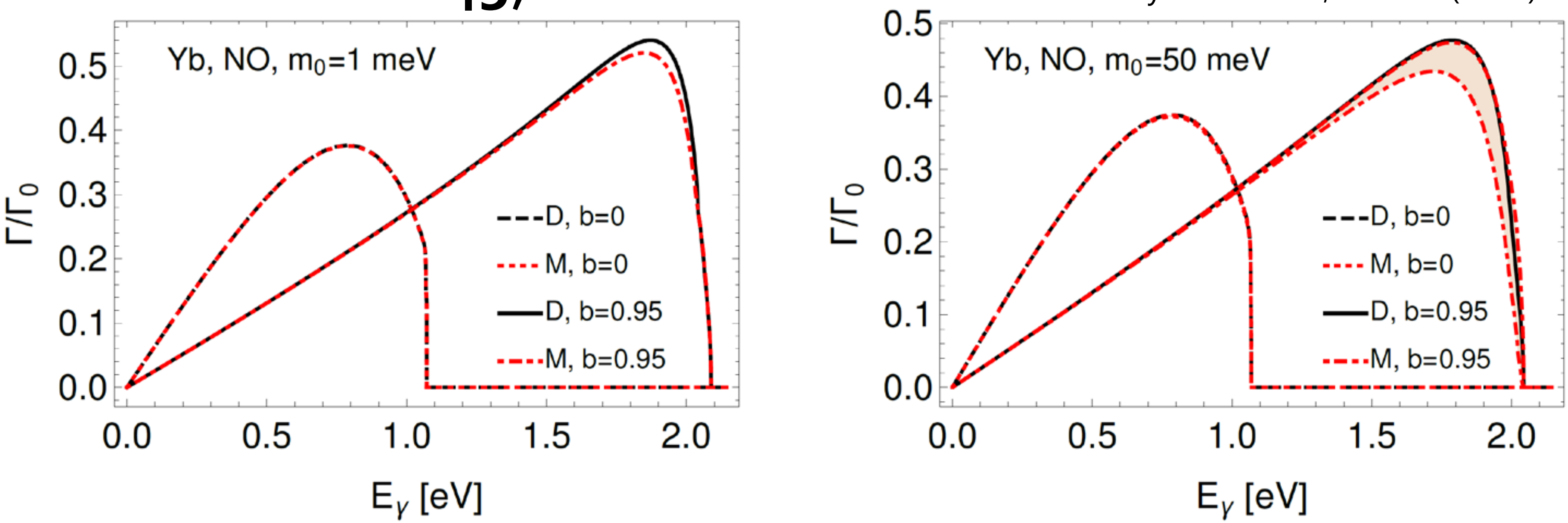
initial spatial phase

$$\sum_a \exp(i\boldsymbol{k}_{in} \cdot \boldsymbol{r}_a)$$

$|\boldsymbol{k}_1| = |\boldsymbol{k}_2| \rightarrow b = 0$

$|\boldsymbol{k}_1| \gg |\boldsymbol{k}_2| \rightarrow b \sim 1$

M. Tanaka, *et al.*
Phys. Rev. D **96**, 113005 (2017)



- Dirac/Majorana distinction : principally possible
  - effect of identical particle emission (Majorana)

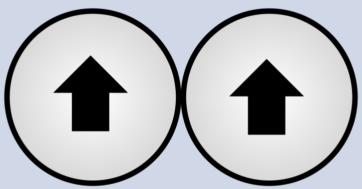
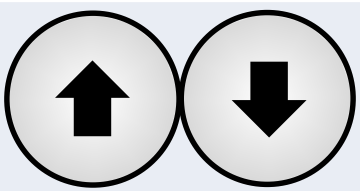
Rate amplification experiment of two-photon emission (TPE) from para-H_2 molecule

para-H_2 experiment

Motivation

- ✓ study rate amplification mechanism using **two-photon emission** processes
  - much easier to observe than neutrino emission process

Properties of para-H_2

	nuclear spin	rotational quantum number
ortho-H_2 	I = 1	→ J=**1**, 3, 5… (odd)
para-H_2 	I = 0	→ J=**0**, 2, 4… (even)

Pauli exclusion principle

dominant @ 78 K

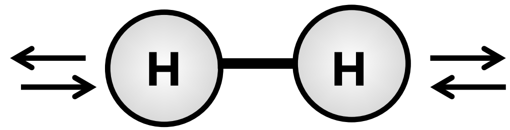
✓ J=0 (ground state) para-H_2: completely spherical wavefunction

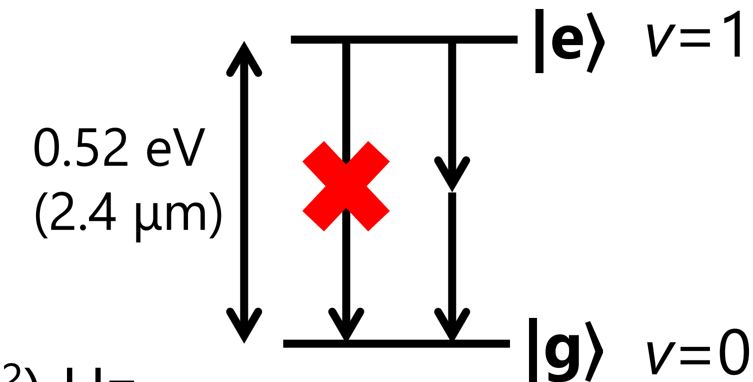
➡ weak intermolecular interaction

➡ **long decoherence time** expected

coherent states of para-H_2

✓ coherence between vibrational states (v=0, J=0 ↔ v=1, J=0) of pH_2 molecules





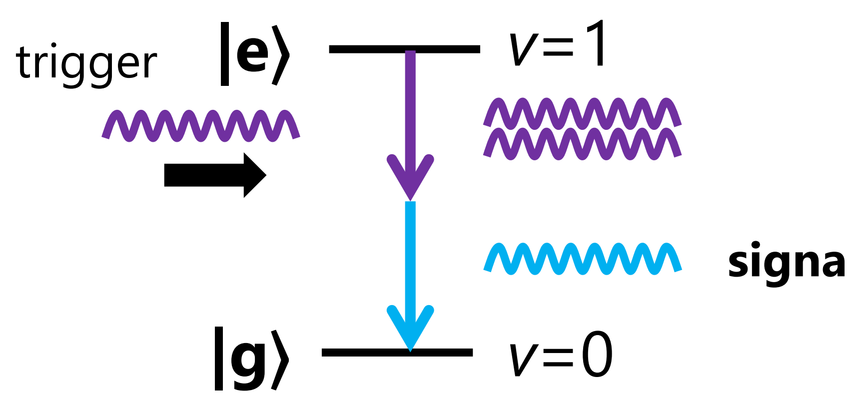
- 1-photon electric dipole transition (E1 transition): **forbidden**
- 2-photon E1×E1 transition: **allowed**

✓ metastable excited state
- spontaneous emission rate: $\mathcal{O}(10^{-12})$ Hz

✓ decoherence time: $\mathcal{O}(1)$ ns (gas)
- mainly due to molecular collision

Induction of two-photon emission

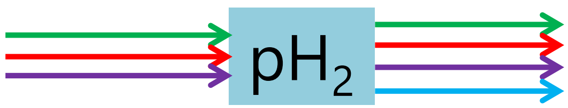
- induce TPE by **trigger laser**
- $\omega_{\mathrm{trigger}} + \omega_{\mathrm{signal}} = E_{eg}$



Coherence generation scheme

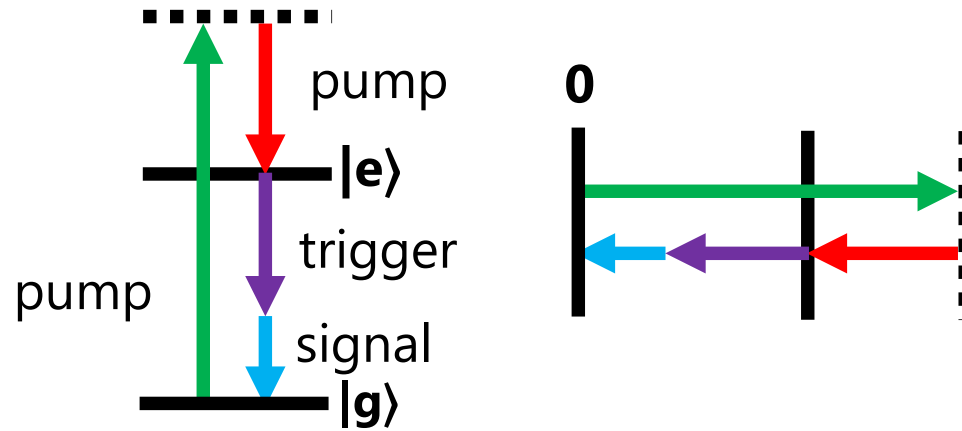
Requirement for rate amplification: 4-momentum conservation

one-side laser excitation

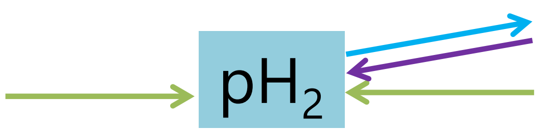


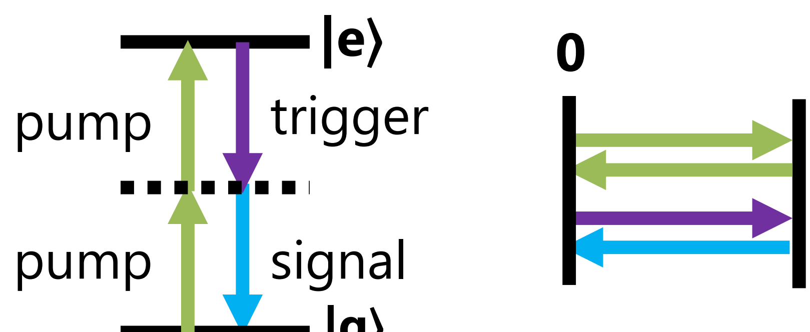
- simpler configuration
- invariant mass by pump photons: 0

Energy | **momentum**



counter-propagating laser excitation

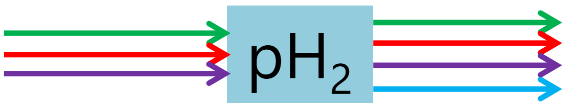




- **non-zero invariant mass**
- necessary for producing massive particle (**neutrino**)

Overview of the para-H_2 TPE experiment

one-side laser excitation



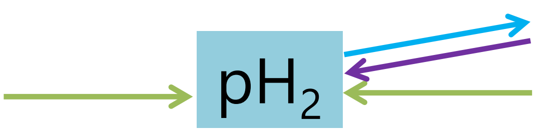
①: para-H_2 gas experiment

②: para-H_2 solid experiment

(difference is explained later)

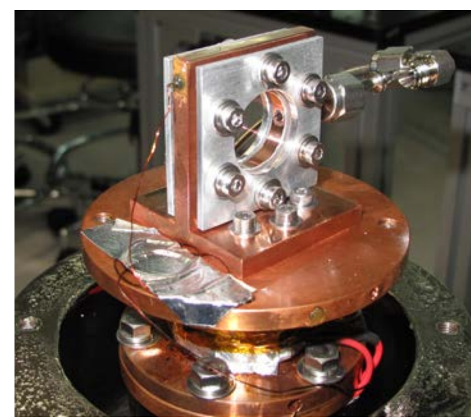
gas para-H_2 cell
cell length: 15 cm
cooled to ~ 78 K

counter-propagating laser excitation



③: para-H_2 gas experiment

solid para-H_2 cell
cell length: 5 mm
cooled to ~ 4 K

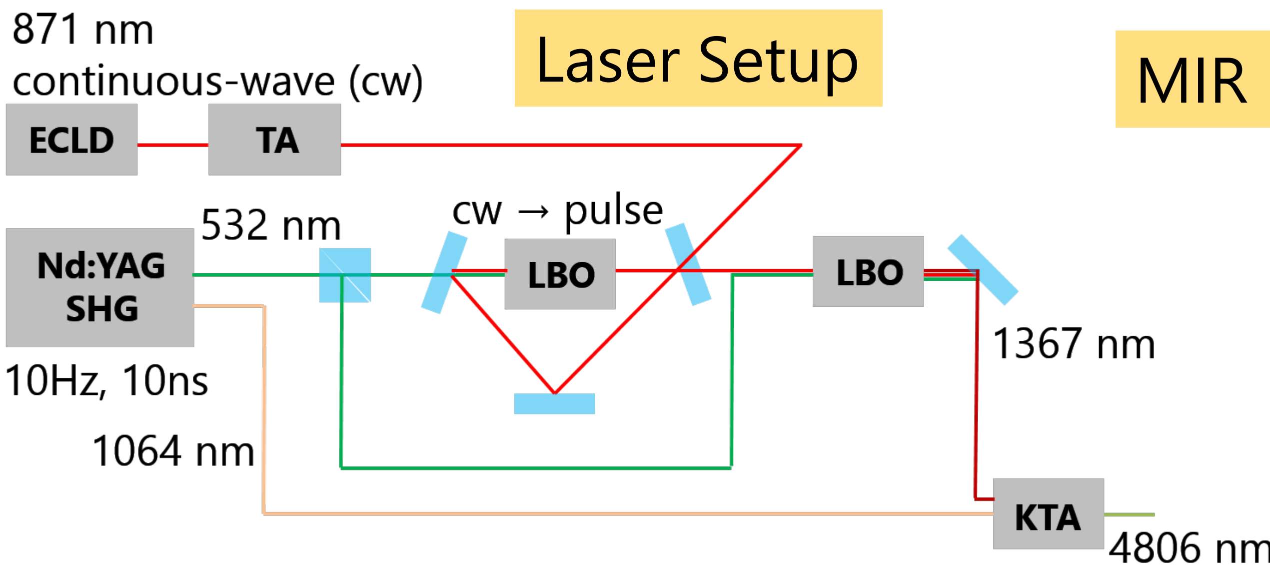


Mid-infrared (MIR) laser generation

✓ developed **high-intensity and narrow-linewidth** MIR laser

- used for **counter-propagating excitation** experiment

Laser Setup



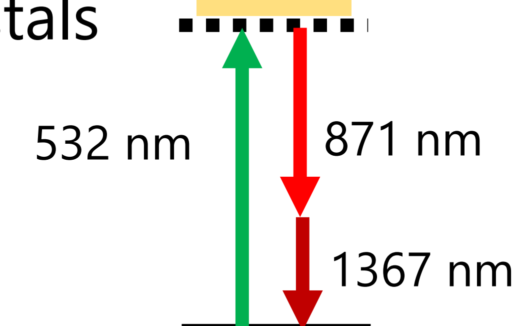
MIR Laser specifications

energy:
~5 mJ/pulse
linewidth:
~150 MHz

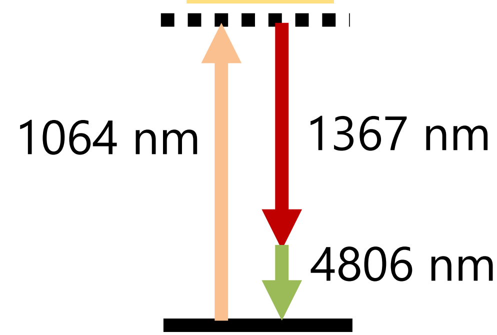
- Frequency conversion by nonlinear-optical crystals

LBO crystals

LBO



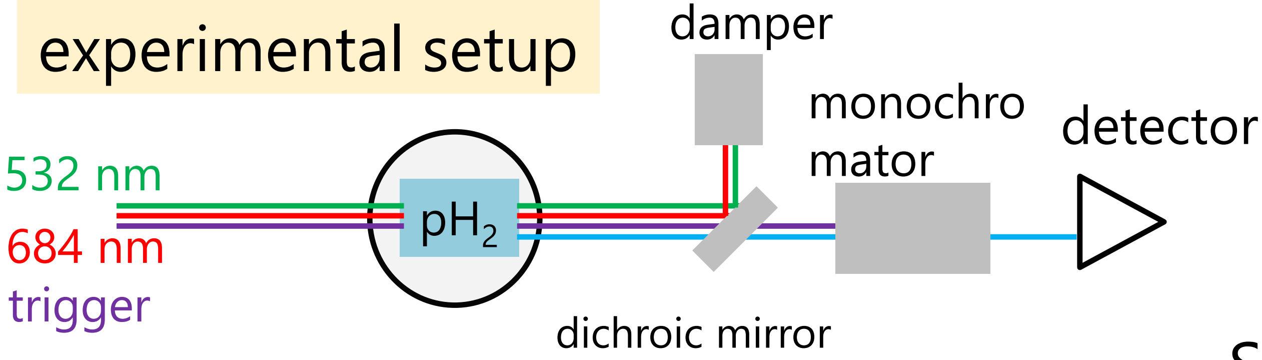
KTA



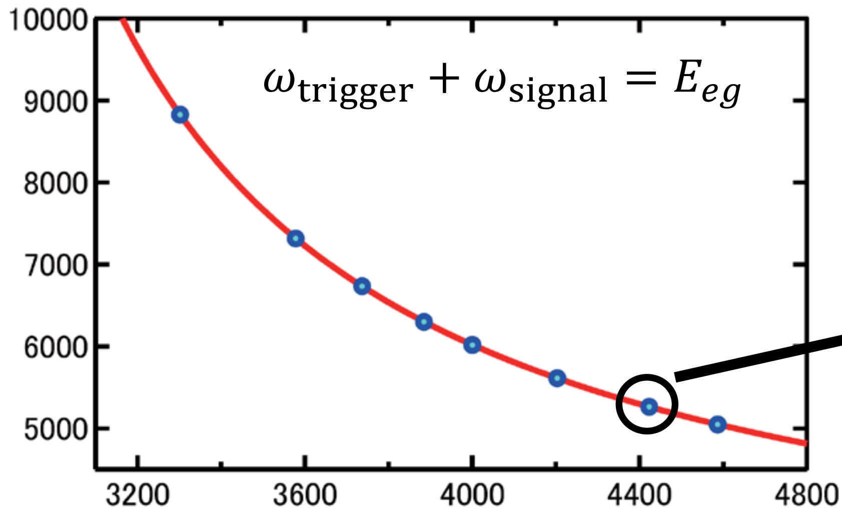
para-H_2 one-side laser excitation experiment

① para-H_2 gas experiment

experimental setup



signal wavelength (nm)

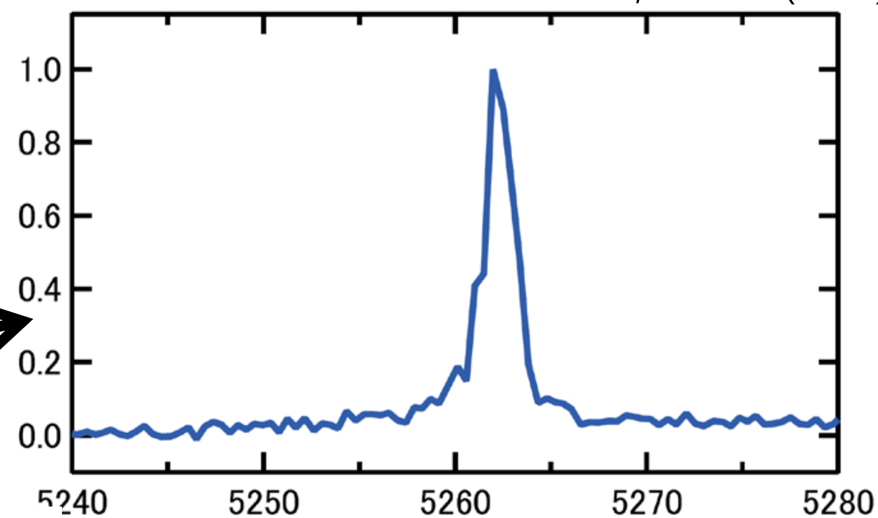


trigger wavelength (nm)

Signal spectrum

signal (a.u.)

H. Hara et al. PRA **96**, 063827 (2017)



wavelength (nm)

Rate amplification factor: (amplified rate)/(spontaneous emission rate) **>10^{18}**

Y. Miyamoto et al. Prog. Theor. Exp. Phys. **2014**, 113C01

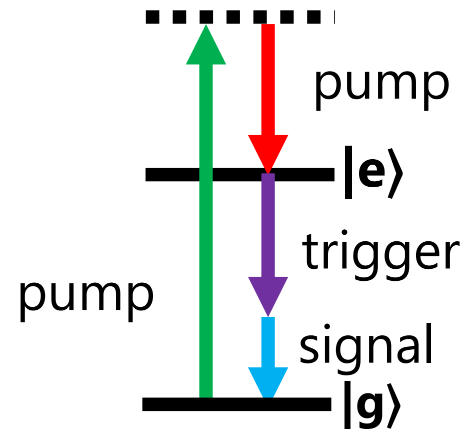
② para-H_2 solid experiment

✓ **solid** para-H_2 : called "Quantum solid"

rotational and vibrational

excited states exist even in solid

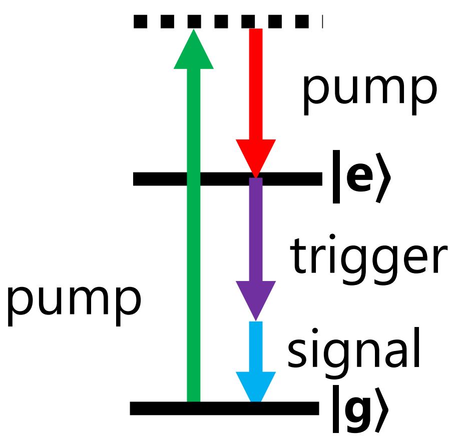
- weak intermolecular interaction:

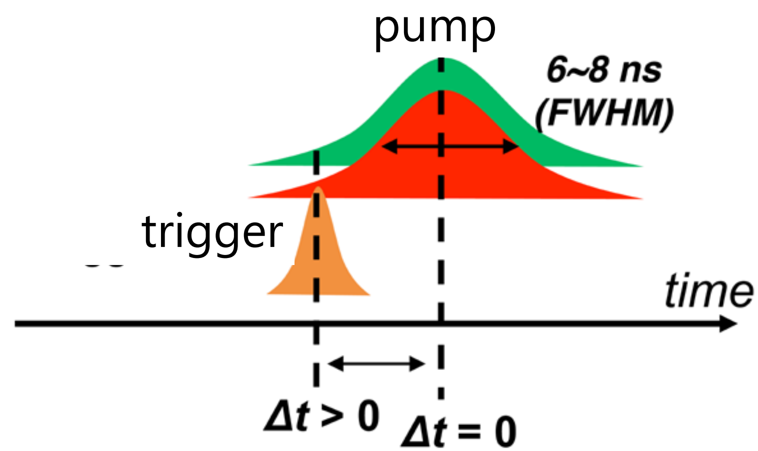


- no collisional broadening (cause of decoherence)

	gas para-H_2	solid para-H_2
density	~ 10^{20} /cm3	$2.6\times\mathbf{10^{22}}$ /cm3
damage threshold	High	low
coherence time	$\mathcal{O}(1)$ ns	$\mathcal{O}(\mathbf{10})$ ns

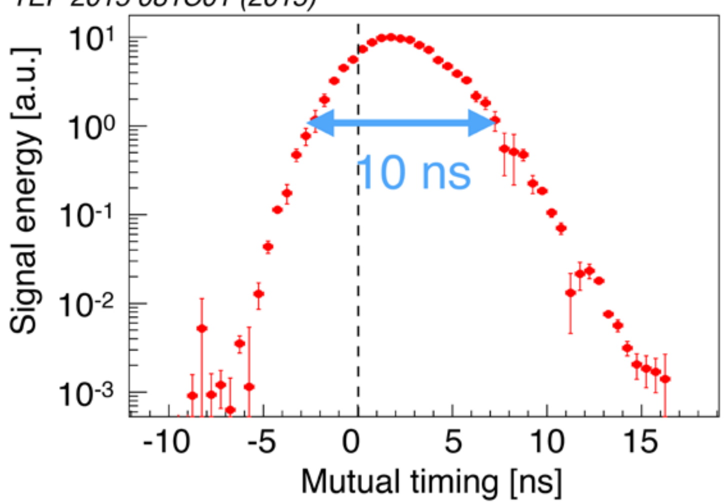
gas V.S. solid timing dependence





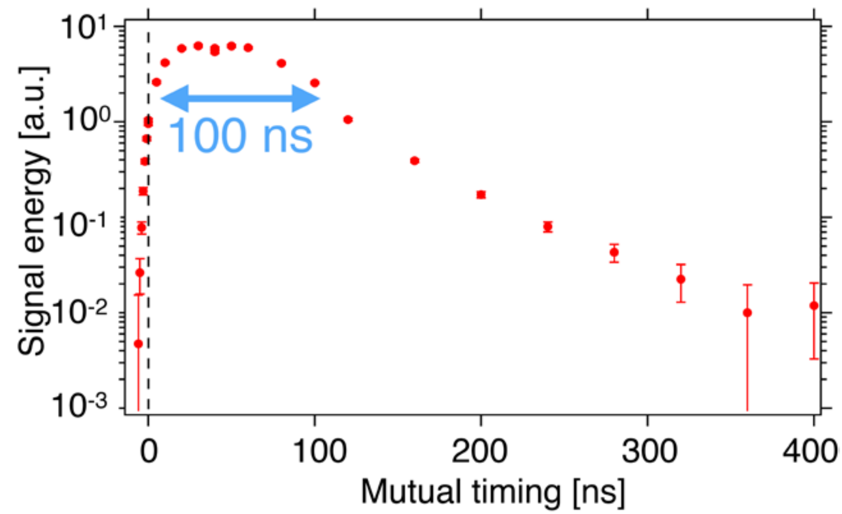
Y. Miyamoto et al., PTEP 2015 081C01 (2015)

gas



Y. Miyamoto et al.
J. Phys. Chem. A **121**, 3943 (2017)

solid

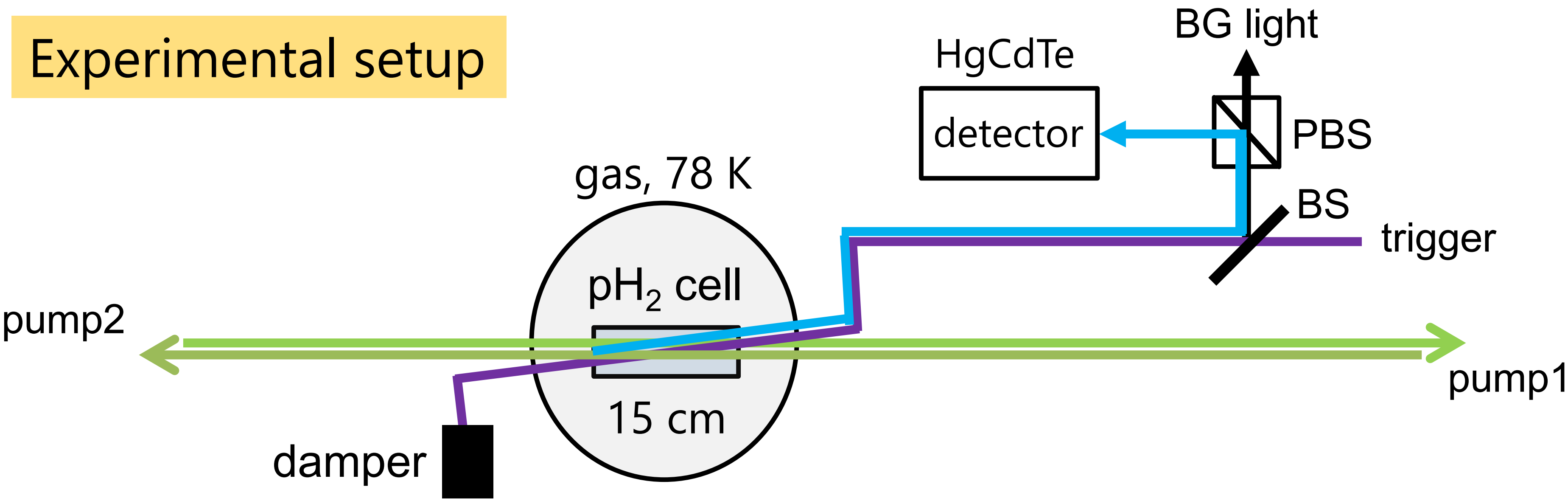


✓ Coherence develops after the pump lasers exist

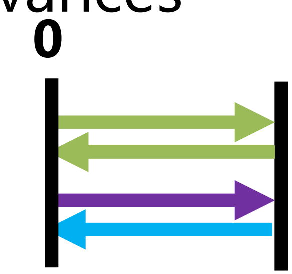
para-H_2 counter-propagating laser excitation experiment

③ Counter-propagating experiment

Experimental setup



- Signal light is generated by the trigger laser and advances in the backward direction
- amplification condition

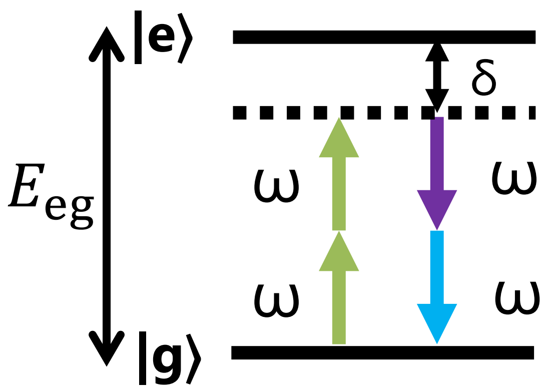


- Wrong-polarization component of the background scattering light is reduced by using a polarized beam splitter.

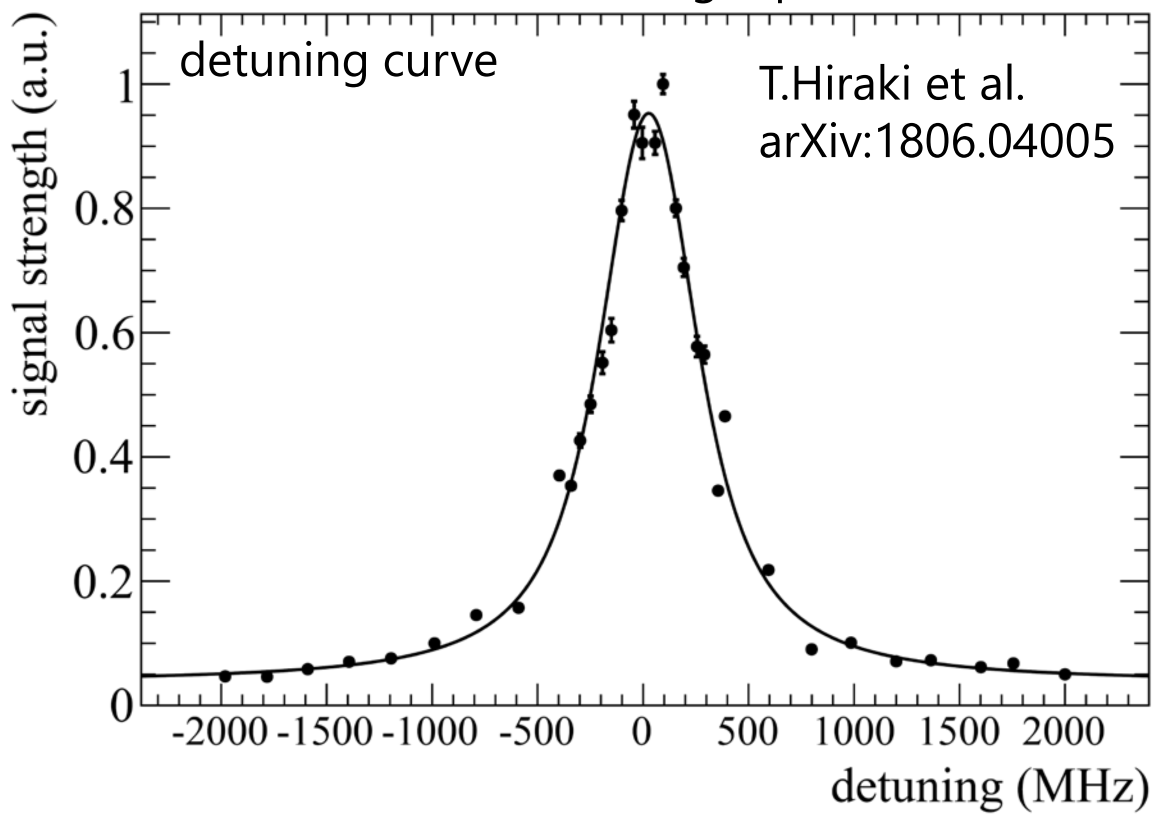
Results: detuning dependence

- use the new mid-infrared laser as both pumps and trigger
  - pump energy: ~1 mJ/pulse, trigger energy: ~ 0.6 mJ/pulse

✓ vary the detuning δ



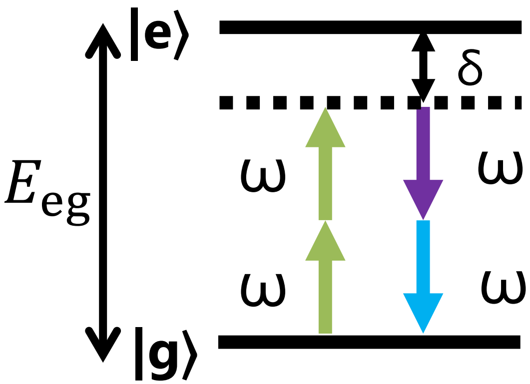
target pressure: 280 kPa



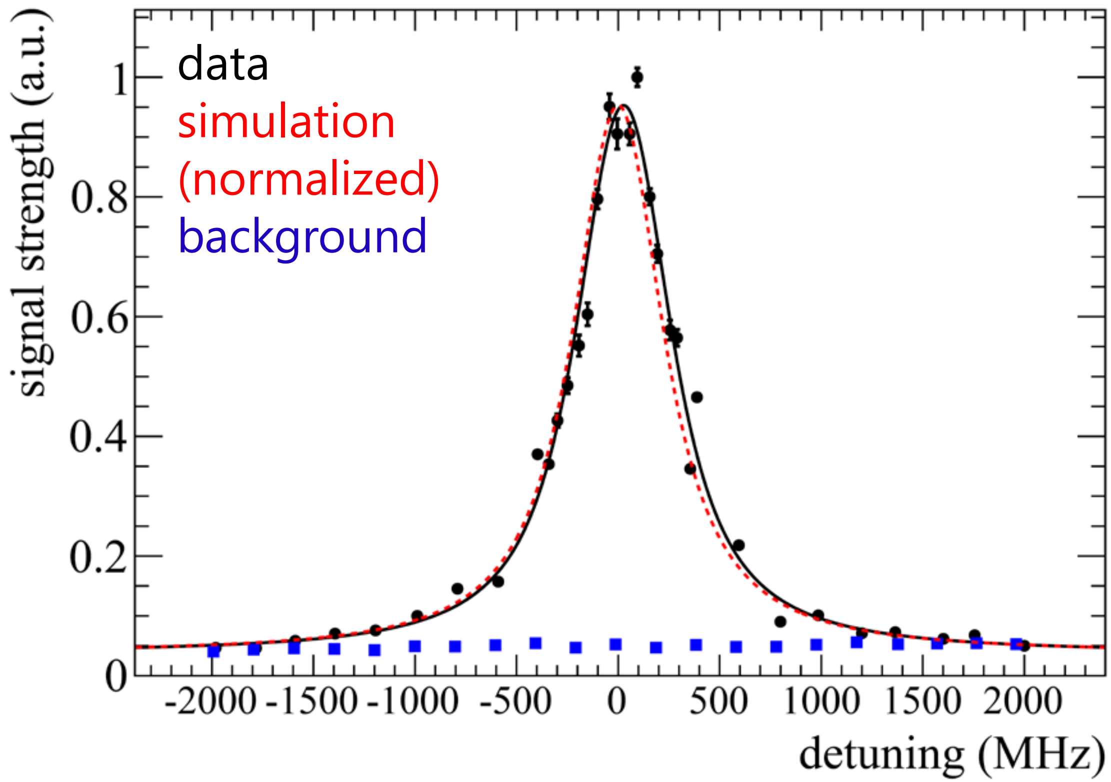
✓ Successfully observed a clear signal peak!

Results: detuning dependence

- vary the detuning δ



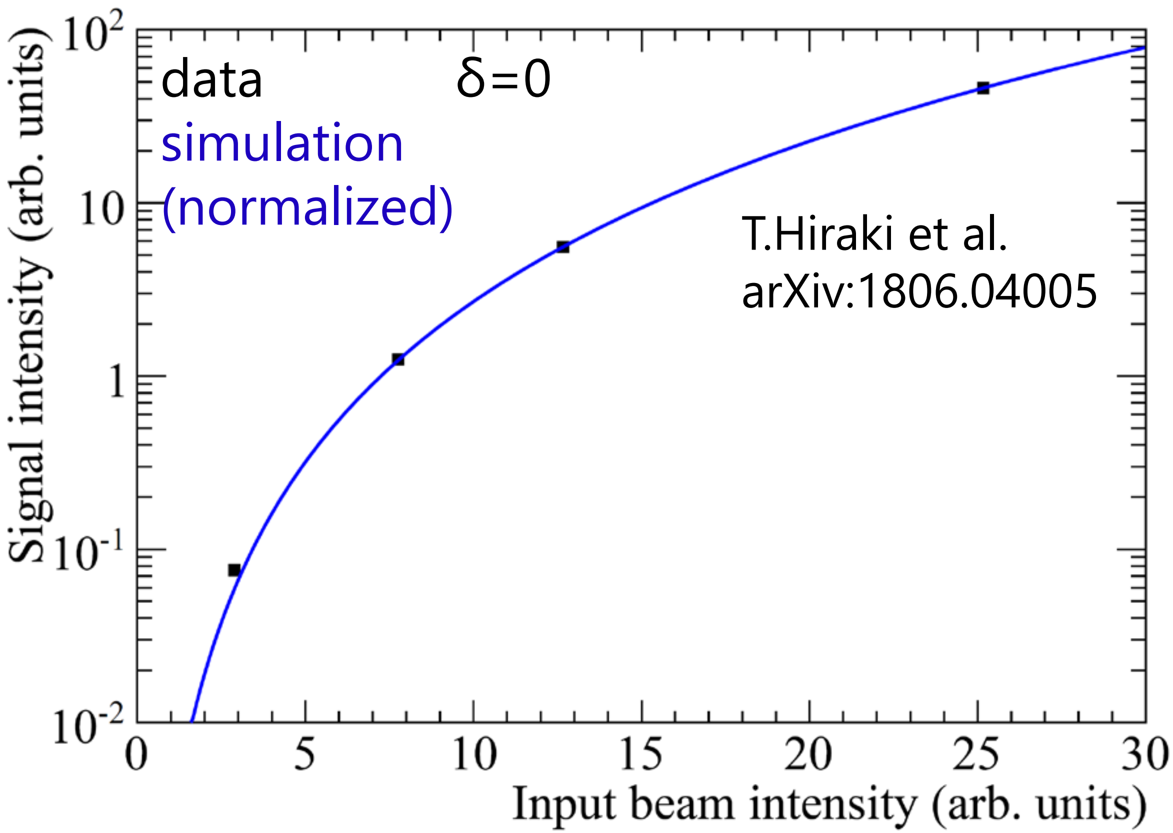
target pressure: 280 kPa



- comparison with simulation based on Maxwell-Bloch equations
- describe development of laser fields and coherence
- Though it is difficult to reproduce absolute signal intensity, curve shape is consistent between data and simulation.

Results: input energy dependence

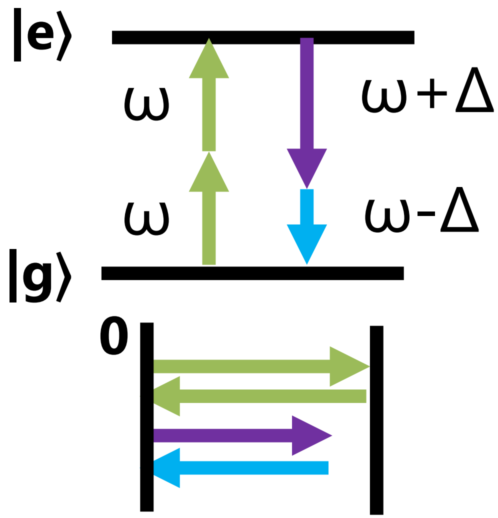
✓ vary the pump and trigger beam energies at the same time



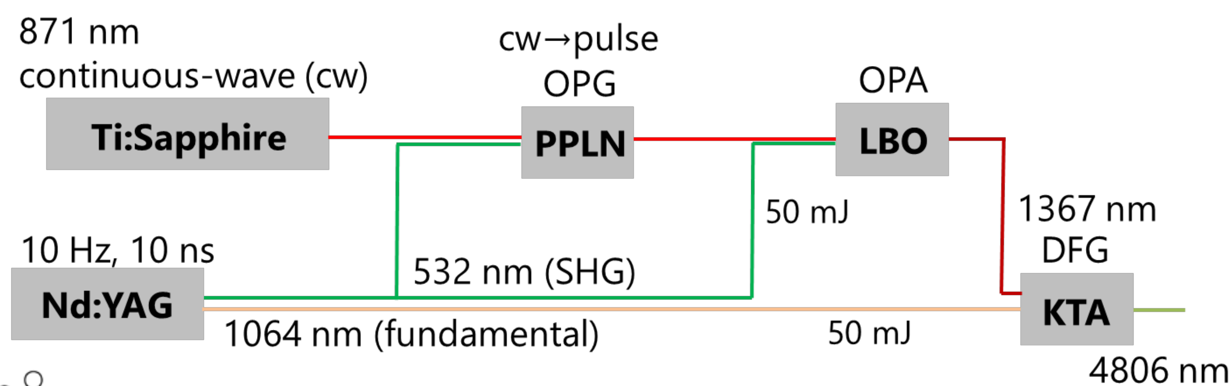
- Signal intensity is proportional to both pump beams and trigger beam

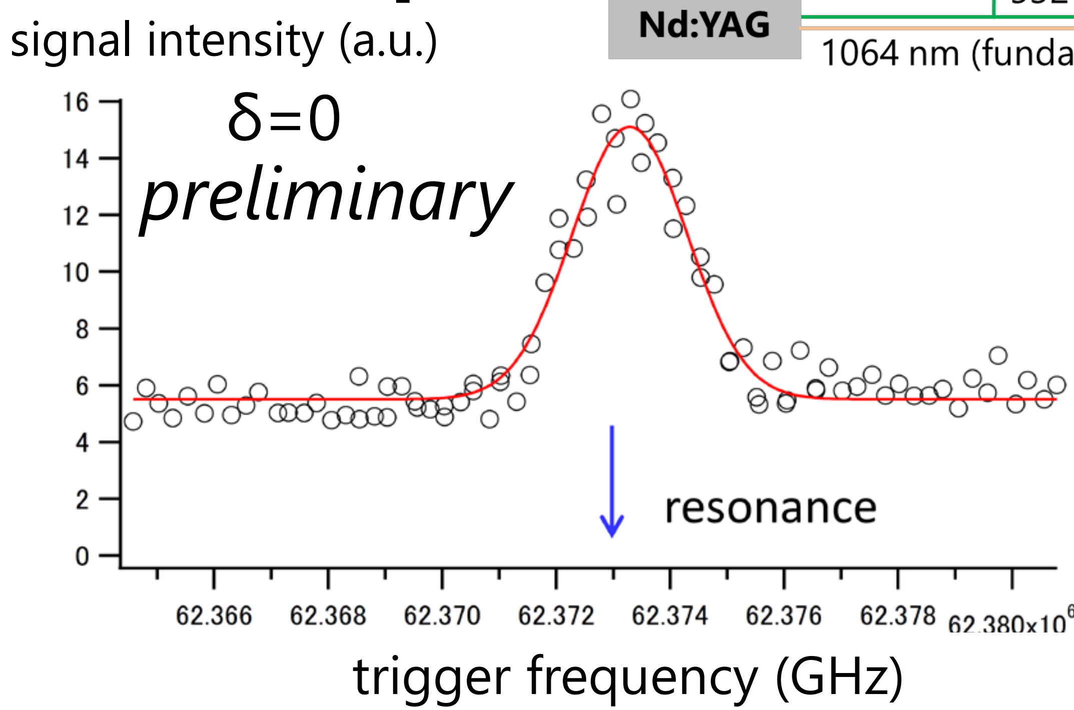
$$I_{\text{signal}} \propto I_{\text{pump1}} I_{\text{pump2}} I_{\text{trigger}} \propto I^3$$

trigger frequency dependence



- vary **only** the frequency of the **trigger** laser
  - amplification condition requires Δ=0
  - another MIR laser is necessary





✓ Signal peak is observed!
- amplification condition is confirmed

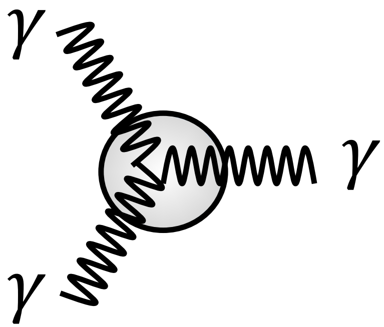
paper in preparation

Next step

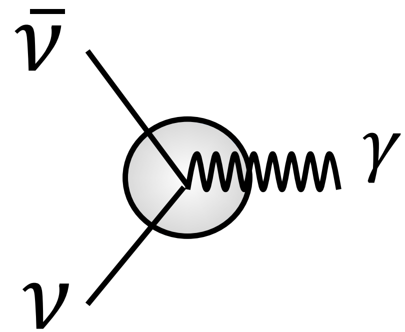
Higher QED process

- study of coherent amplification of **higher QED** process
  - 2-photon E1×M1(magnetic dipole), 3-photon E1×E1×E1

3-photon emission



RENP

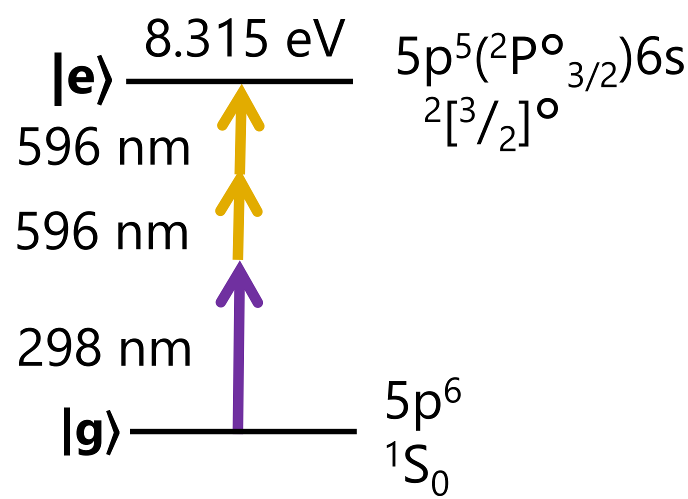


similar kinematics

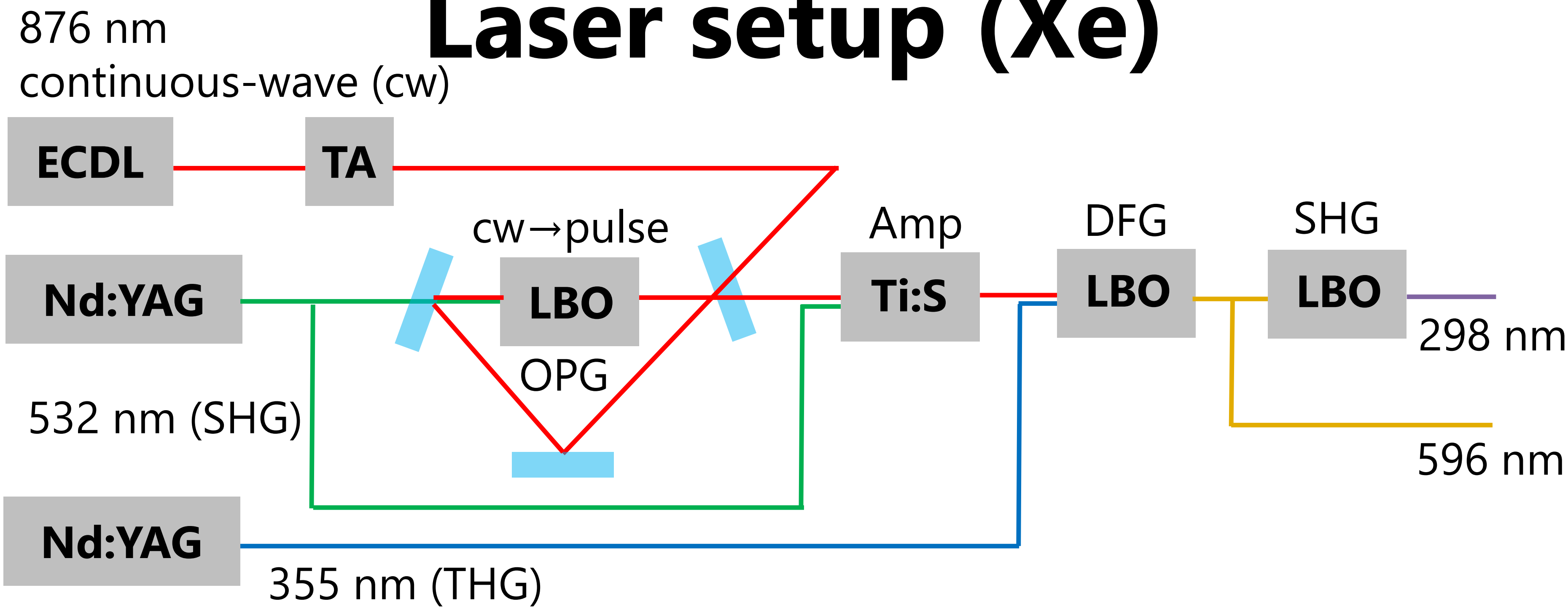
✓ Xe target:
one of the candidates
of the RENP experiment

- use metastable excited state
  - E1, E1×E1: forbidden
  - E1×M1, E1×E1×E1: allowed

3-photon excitation

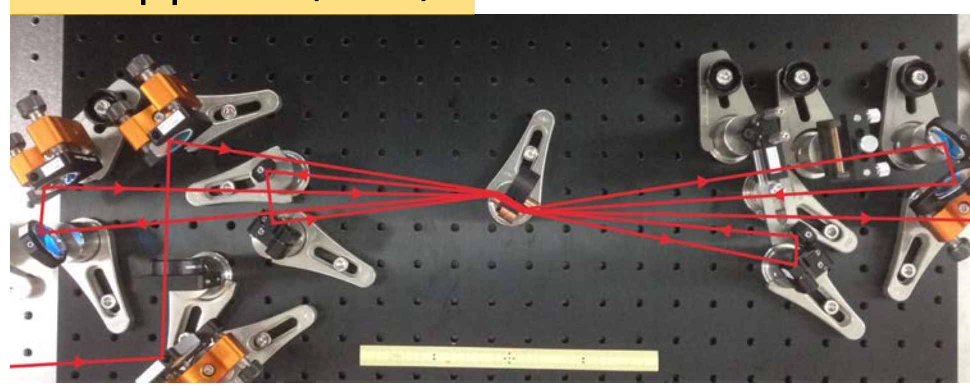


Laser setup (Xe)



ECDL, LBO (OPG)

Ti:Sapphire (OPA)



✓ Experiment will start soon!

Summary

para-H_2 experiment

- Rate amplification of two-photon emission process
- observed TPE signal and verified rate amplification mechanism experimentally
- further study ongoing (counter-propagating solid experiment)

Xe experiment

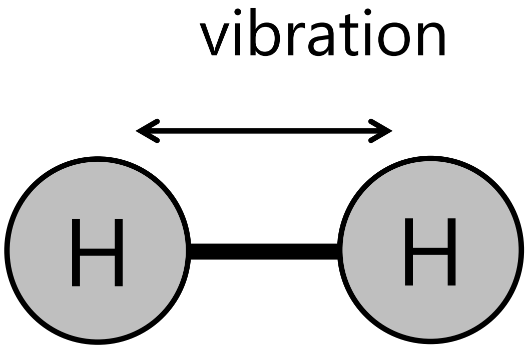
- coherent amplification of higher-order QED processes
- Experiment will start soon

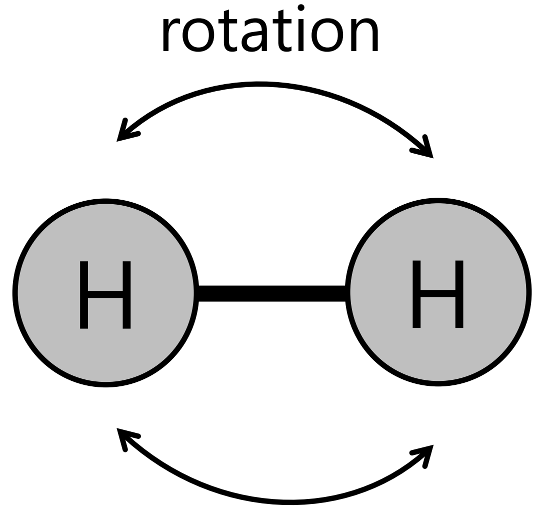
Future prospects

- Background study and reduction (2 or 3 photon emission)
- obtain higher emission rate
- RENP experiment

Back up

H_2





- Vibration or rotation of H_2 molecule are quantized

✓ wavefunction of H_2

$$\psi = \psi_{electron}\psi_{vibration}\psi_{rotation}\psi_{nuclearspin}$$

ψ: antisymmetric under nucleus exchange

$\psi_{electron}$, $\psi_{vibration}$: symmetric @ ground state

	$\psi_{nuclearspin}$	$\psi_{rotation}$
ortho-H_2	symmetric	antisymmetric
para-H_2	antisymmetric	symmetric

Coherent amplification condition

✓ Energy-momentum conservation among photons

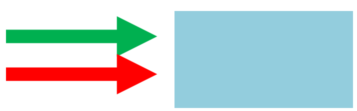
✓ Process: Two-photon emission (TPE)

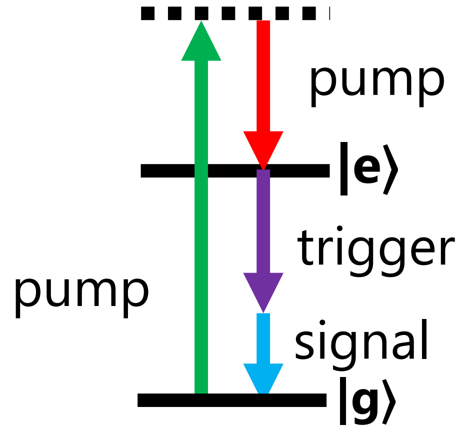
no dispersion case

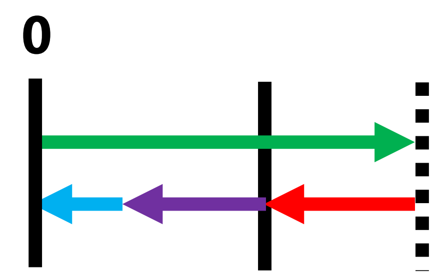
Energy

momentum

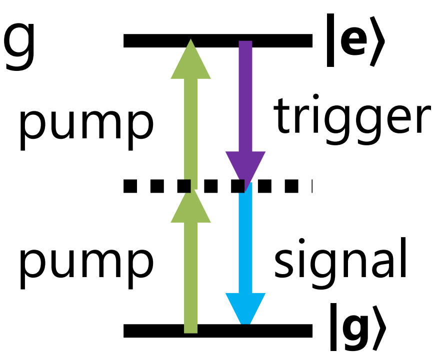
- one-side excitation

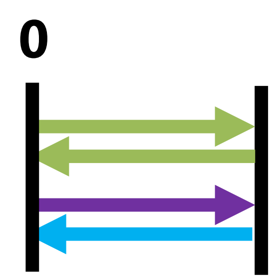






- counter-propagating excitation





The condition is satisfied in both cases

Coherent amplification condition

✓ Energy-momentum conservation among photons+ν

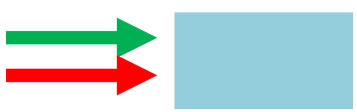
✓ Process: Radiative emission of neutrino pair (RENP)

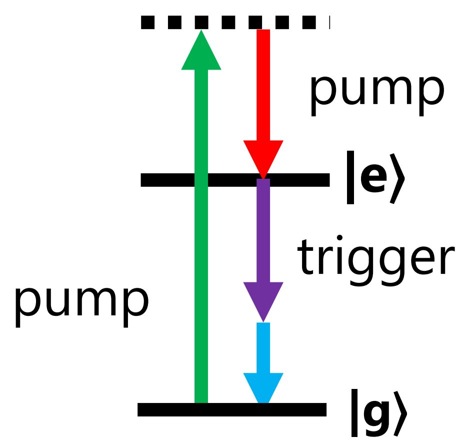
no dispersion case

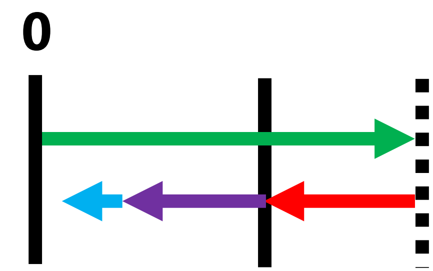
Energy

momentum

- one-side excitation

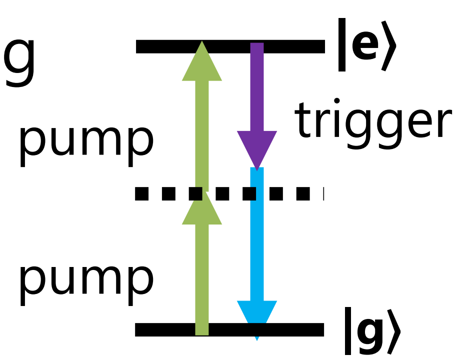


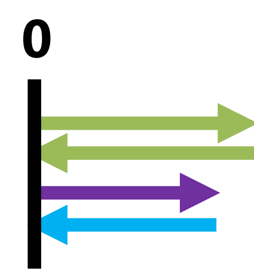




not satisfied

- counter-propagating excitation



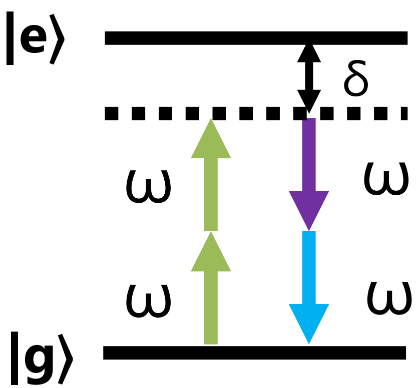


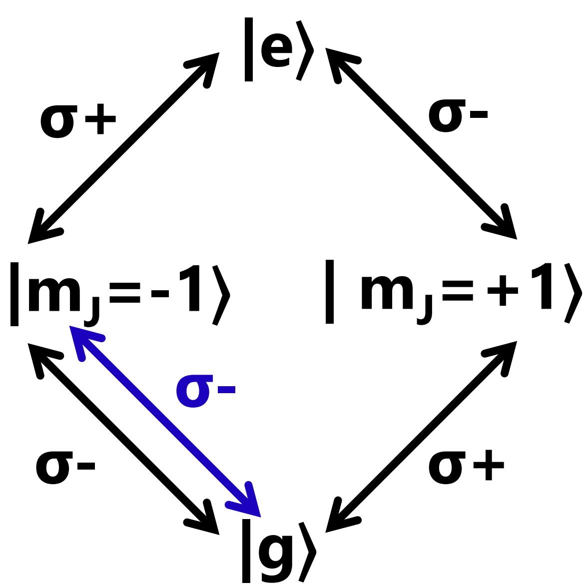
satisfied

✓ High-quality mid-infrared (4806 nm) laser is required.

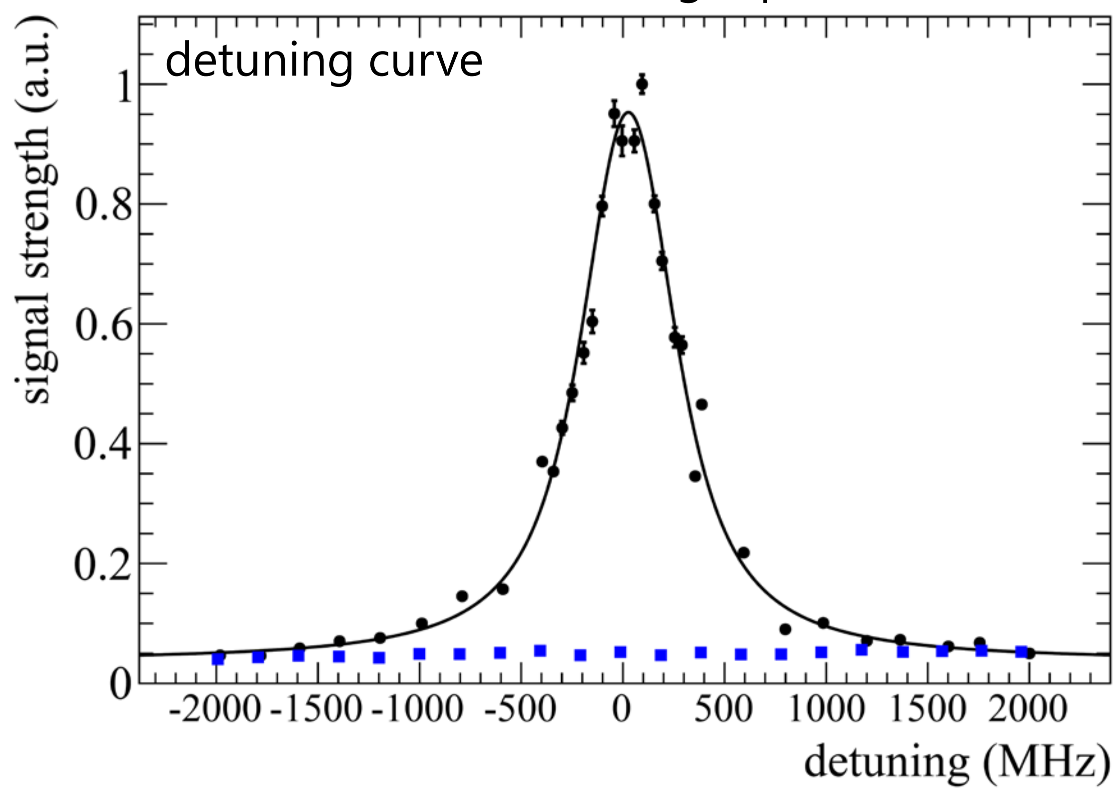
Results: detuning dependence

- vary the detuning δ





target pressure: 280 kPa



- Circular polarization of a pump is flipped.

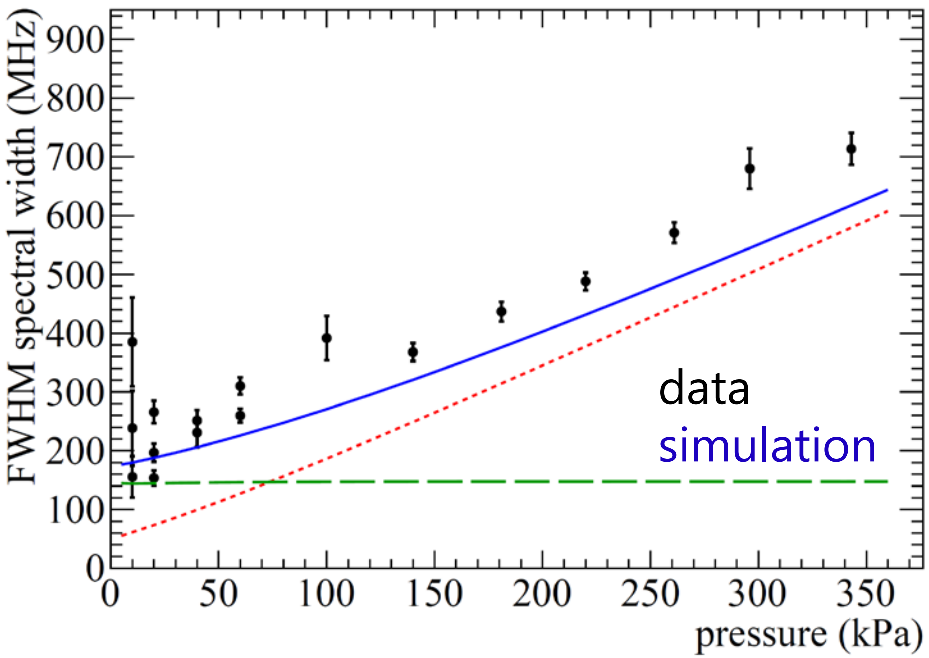
➡ no signal is observed.

- confirmation of the excitation by counter-propagating lasers

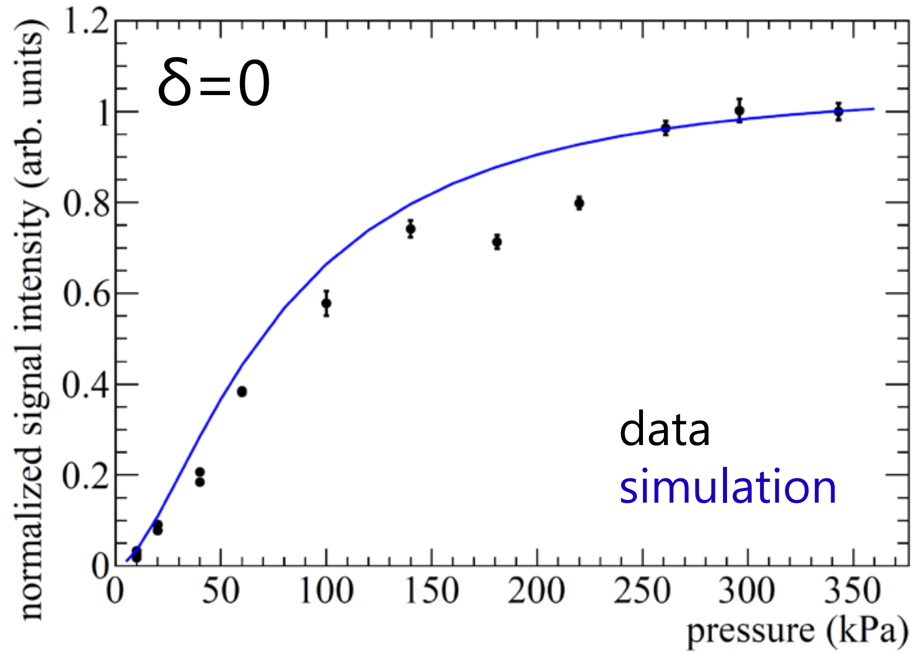
Results: Pressure dependence

- vary the pH_2 target pressure

detuning curve width (FWHM)



normalized intensity

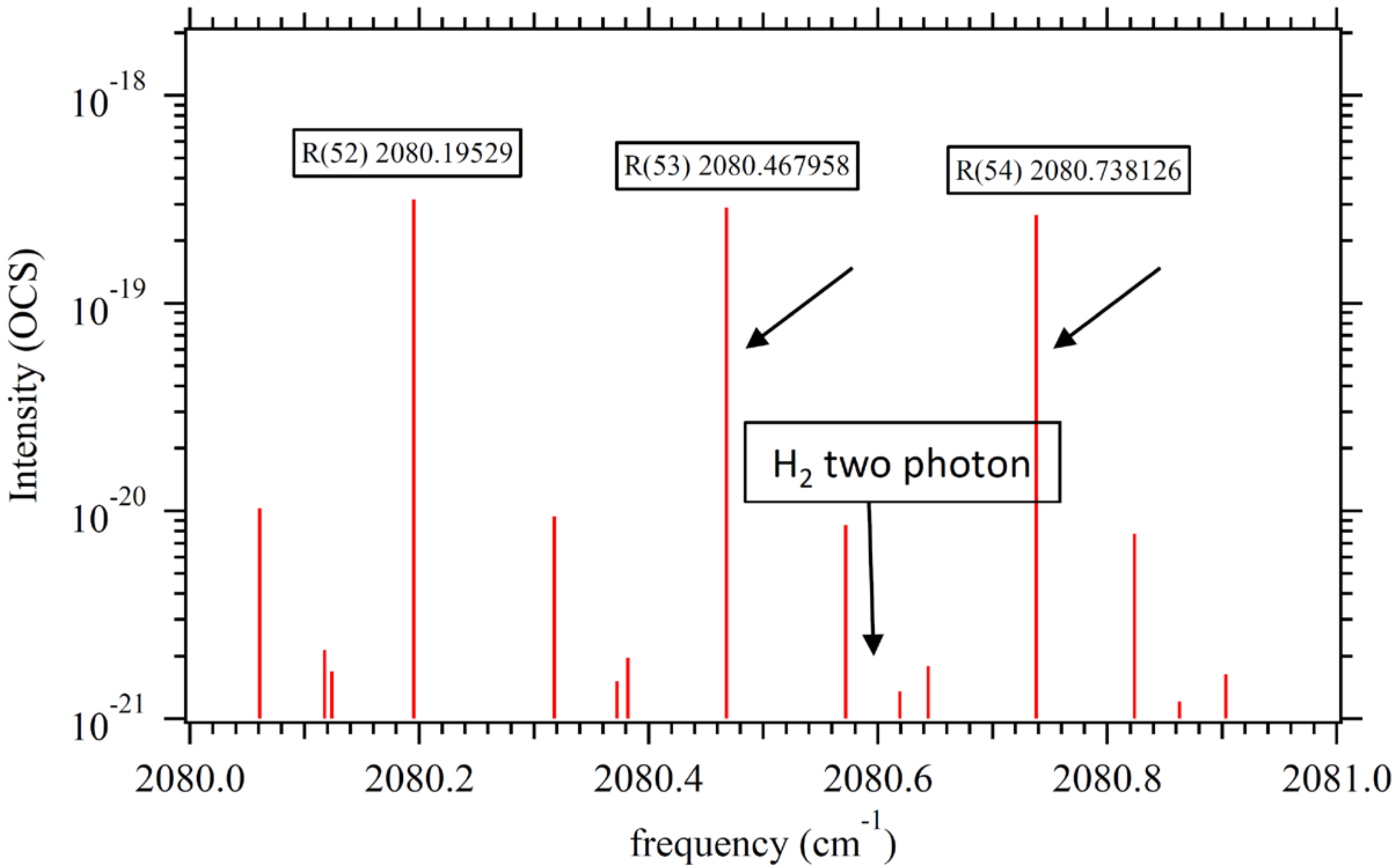


- Laser linewidth and pressure broadening determine the width
- Signal intensity increases as the target density larger.

✓ Consistent tendency is obtained between data and simulation.

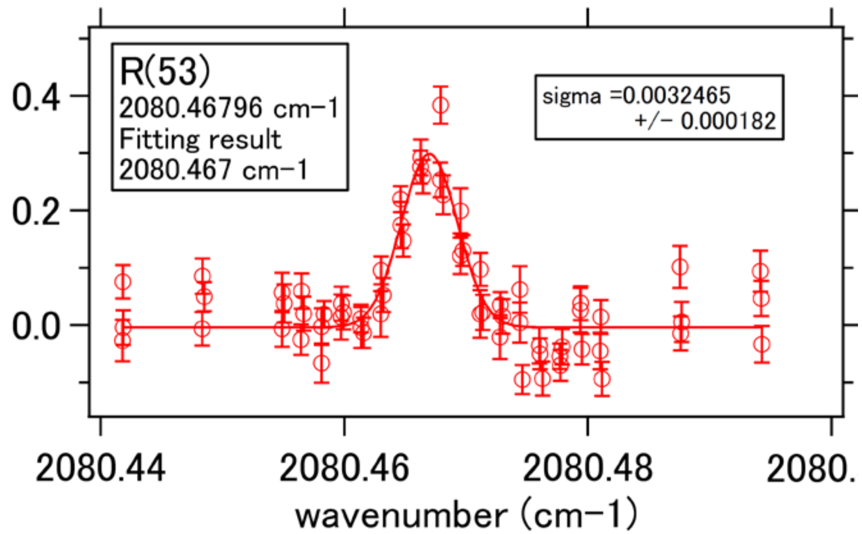
Laser linewidth measurement

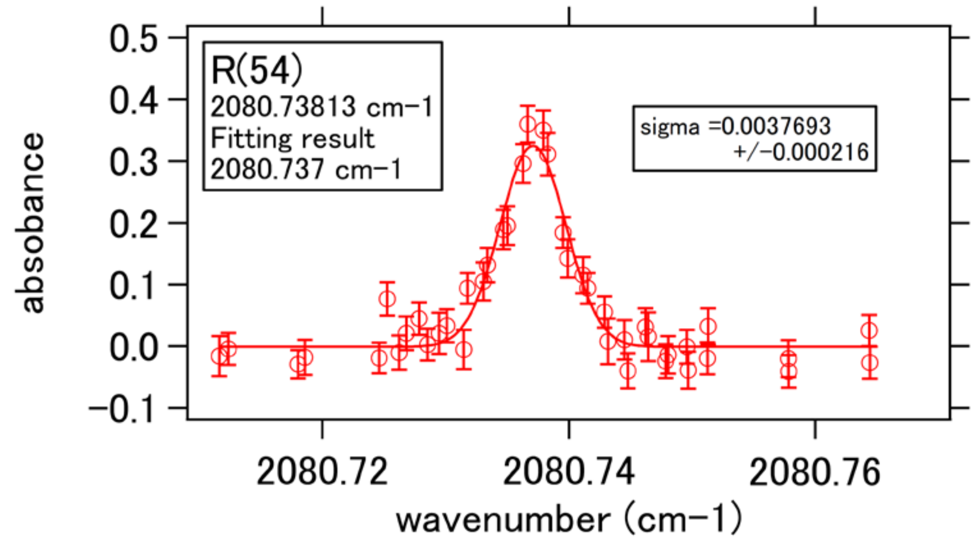
- measurement of the narrow-linewidth MIR laser
- method: absorption spectroscopy of carbonyl sulfide (OCS)



Laser linewidth

- observed absorption spectra





	width (FWHM)
Observed linewidth	175 (13)
Doppler width	99
MIR Laser linewidth	**145 (16)**

✓ narrow laser linewidth (~1.6×FT-limit) is achieved.

Maxwell-Bloch equations

Development of the density matrix

$$\frac{\partial \rho_{gg}}{\partial t} = \mathrm{i}(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}) + \gamma_1 \rho_{ee},$$
$$\frac{\partial \rho_{ee}}{\partial t} = \mathrm{i}(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}) - \gamma_1 \rho_{ee},$$
$$\frac{\partial \rho_{ge}}{\partial t} = \mathrm{i}(\Omega_{gg} - \Omega_{ee} + \delta)\rho_{ge} + \mathrm{i}\Omega_{ge}(\rho_{ee} - \rho_{gg}) - \gamma_2 \rho_{ge}.$$

ρ: density matrix
$\Omega_{gg(ee)}$: two-photon Rabi frequency
$\Omega_{eg(ge)}$: AC Stark shift
γ_1, γ_2 :relaxation rates
δ: detuning

Development of the electric fields

$$\left(\frac{\partial}{\partial t} - c\frac{\partial}{\partial z}\right) E_{\mathrm{p1}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{p1}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{p2}}\right),$$
$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right) E_{\mathrm{p2}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{p2}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{p1}}\right),$$
$$\left(\frac{\partial}{\partial t} - c\frac{\partial}{\partial z}\right) E_{\mathrm{trig}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{trig}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{sig}}\right),$$
$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right) E_{\mathrm{sig}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{sig}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{trig}}\right).$$

ω_l: laser frequency
N_t: target density
α: polarizability

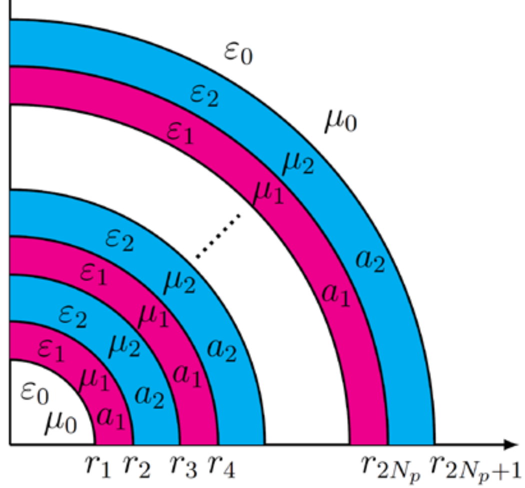
Theoretical studies

- Towards Background-free RENP using a Photonic Crystal Waveguide

M.Tanaka et al. Prog. Theor. Exp. Phys. **2017** 043B03

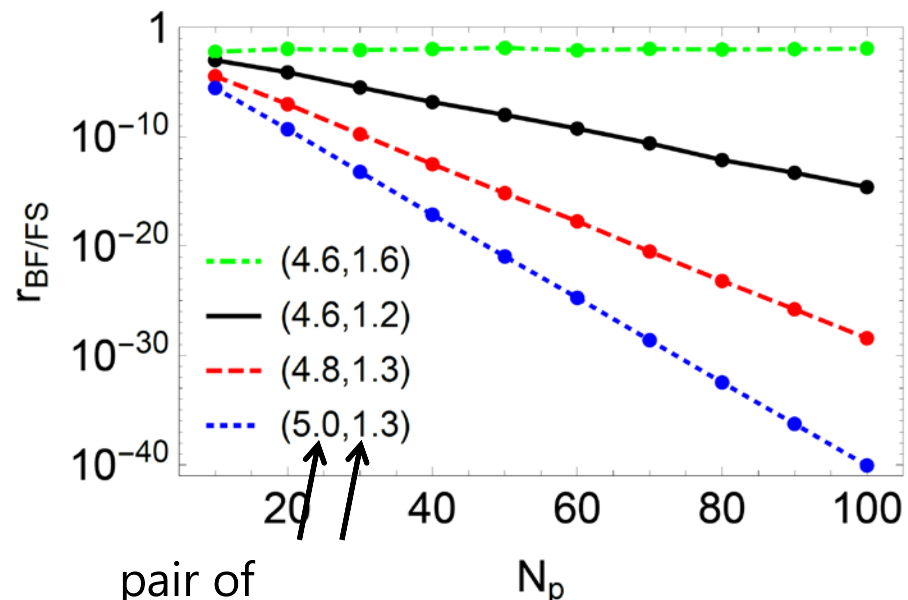
Bragg fiber

periodic dielectric media



lasers

3-photon emission suppression factor



pair of refractive index

number of layer