Coherently amplified multi-photon emission toward neutrino mass spectroscopy

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Introduction
**SPectroscopy with Atomic Neutrino**

- determine unknown neutrino properties (ex. absolute masses) by using techniques of laser spectroscopy
  - Radiative Emission of Neutrino Pair (RENP)

\[
\begin{align*}
|e\rangle & \quad \gamma \quad |\bar{\nu}\rangle \\
E_{eg} & \quad |\nu\rangle
\end{align*}
\]

- threshold energy

\[
E_{th} = \frac{E_{eg}}{2} \left( \frac{(m_\nu + m_{\bar{\nu}})c^2}{2E_{eg}} \right)^2
\]

(no boost case)

- Emission rate spectra (near endpoint)

\[
\text{Emission rate (a.u.)}
\]

Y. Miyamoto et al.

Prog. Theor. Exp. Phys. 2015 081C01

\[
\begin{align*}
\text{~1 meV (~200 GHz)} & \\
Xe & \\
\text{~}m_0=80 \text{ meV} & \quad \text{~}m_0=50 \text{ meV} & \quad \text{~}m_0=10 \text{ meV}
\end{align*}
\]

\[
\begin{align*}
\text{m}_0: \text{ lightest } & \quad \nu \text{ mass}
\end{align*}
\]

\[
\begin{align*}
\text{photon energy (eV)} & \\
4.1550 & \quad 4.1555 & \quad 4.1560 & \quad 4.1565 & \quad 4.1570 & \quad 4.1575
\end{align*}
\]
Rate Amplification

- De-excitation rate of RENP: extremely small
  ➞ Rate amplification using atomic coherence

If $\Delta k = 0$ holds, the emission rate $\propto N^2$ (rate amplification)
  - momentum conservation among initial and emitted particles

study the mechanism using multi-photon emission processes
Previous experiments

✓ Two-photon emission (TPE) process using vibrational states \((v=0, J=0 \leftrightarrow v=1, J=0)\) of para-hydrogen \((pH_2)\) molecules

- 1-photon \(E_1\): forbidden, 2-photon \(E_1 \times E_1\): allowed

\(pH_2\) Energy diagram

\[ |g\rangle \quad v=0 \]
\[ |e\rangle \quad v=1 \]

trigger laser

signal

Coherence generation by stimulated Raman process

- 532 nm, 684 nm pulse lasers
- stimulate TPE process by a trigger laser
- injection from the same direction

Experimental setup

- 532 nm, 684 nm pulse lasers
- Filters
- 78K detector
- Trigger wavelength: 4423 nm
- Signal wavelength: 5263 nm

Rate amplification factor > \(10^{18}\)

Prog. Theor. Exp. Phys. 2014, 113C01
Current experiment:
Two-photon emission from $\text{pH}_2$ molecules excited by counter-propagating lasers
Coherent amplification condition

✓ Energy-momentum conservation among photons
✓ Process: Two-photon emission (TPE)

no dispersion case

• 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

- one-side excitation

- counter-propagating excitation

- High-quality mid-infrared (4806 nm) laser is required.
**Laser setup (previous experiment)**

- We previously used a mid-infrared laser as the trigger.

- We use this laser as one of the trigger laser again.
- Intensity and linewidth of this laser are not enough for the excitation laser.

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**Diagram**

- **Ti:Sapphire**
  - 871 nm
  - continuous-wave (cw)
- **Nd:YAG**
  - 1064 nm (fundamental)
  - 10 Hz, 10 ns
- **PPLN**
  - 532 nm (SHG)
- **OPG**
- **OPA**
  - 50 mJ
- **LBO**
  - 50 mJ
  - 1367 nm
  - DFG
- **KTA**
  - 4806 nm

- MIR pulse energy: $\sim 15 \mu J/pulse$
- MIR linewidth: $\sim 1 \text{ GHz}$
- Wavelength-tunable

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*Poster: H. Hara*
Laser setup (new)

- 871 nm continuous-wave (cw)
- 532 nm (SHG)
- 1064 nm (fundamental)
- 1367 nm
- 4806 nm

- high-power Nd:YAG laser
- adopt a cavity in the OPG section (effective injection seeder)

MIR pulse energy: ~5 mJ/pulse
MIR linewidth: ~150 MHz
MIR pulse duration: ~5 ns (FWHM)

significant improvement!
Experimental setup (1)

- use circularly polarized beam
  - excitation by the single beam is not allowed
- inject pump and trigger beams simultaneously into the para-H$_2$ target
• Signal light is generated by the trigger laser and advances in the backward direction
  - amplification condition (momentum conservation)

• Wrong-polarization component of the background scattering light is reduced by using a polarized beam splitter.
Construction of the laser system was finished last year.
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 $\delta$

✓ Successfully observed a clear signal peak!

- Signal energy: ~20 nJ/pulse at $\delta=0$
Results: detuning dependence

- vary the detuning $\delta$

Circular polarization of a pump is flipped. ➡ no signal is observed.

- confirmation of the excitation by counter-propagating lasers

![detuning curve](image)

- target pressure: 280 kPa

\[
\begin{align*}
|g\rangle & \quad \delta \\
\omega & \quad \omega \\
|e\rangle & \quad \omega \\
|g\rangle & \quad \omega \\
|\sigma^+\rangle & \quad |e\rangle \\
|\sigma^-\rangle & \quad |m_J=-1\rangle & \quad |m_J=+1\rangle \\
|\sigma^-\rangle & \quad |g\rangle \\
|\sigma^+\rangle & \quad |g\rangle \\
\end{align*}
\]
Results: detuning dependence

- vary the detuning $\delta$

\[ |g\rangle \] $\rightarrow$ $\delta$ $\rightarrow$ $|e\rangle$

- 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: Pressure dependence

- vary the $\text{pH}_2$ target pressure

  detuning curve
  width (FWHM)

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

✓ Consistent tendency is obtained between data and simulation.
trigger frequency dependence

- vary only the frequency of the trigger laser
- amplification condition requires $\Delta=0$

• Setup construction is finished very recently

✓ A signal peak is observed
  - obscure peak due to weaker trigger intensity

✓ Further studies (experiment/simulation) will be conducted.

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<thead>
<tr>
<th>Preliminary</th>
<th>Signal strength (a.u.)</th>
<th>detuning (MHz)</th>
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<tbody>
<tr>
<td>$\delta=0$</td>
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</table>
Next step
Higher QED process

- study of coherent amplification of higher QED process
  - 2-photon E1×M1, 3-photon E1×E1×E1

3-photon emission

\[ \begin{align*}
\gamma &\rightarrow V & \gamma &\rightarrow V & \gamma &\rightarrow V
\end{align*} \]

RENP

\[ \begin{align*}
\bar{\nu} &\rightarrow V & \gamma &\rightarrow V & \gamma &\rightarrow V
\end{align*} \]

same 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

\[ \begin{align*}
|e\rangle &\rightarrow 8.315 \text{ eV} & 5p^{5}\left(2p^{6}\right)_{3/2}6s^{2}\left[3/2\right]^{0}
|g\rangle &\rightarrow 5p^{6}1S_{0}
\end{align*} \]

Poster: K. Okai
Laser setup (Xe)

876 nm continuous-wave (cw)

ECDL  →  TA  →  cw→pulse  →  Amp  →  DFG  →  SHG

Nd:YAG  →  LBO  →  OPG  →  Ti:S  →  LBO

532 nm (SHG)

355 nm (THG)

Nd:YAG

ECDL, LBO (OPG)

Ti:Sapphire (OPA)

POSTER: O. Sato

✓ Experiment will start soon!
Summary

para-H$_2$ experiment
• coherence generation by counter-propagating laser
• observed two-photon emission signal
• further investigation ongoing

Xe experiment
• coherent amplification of higher-order QED processes
• Laser system construction is almost finished and experiment will start soon.
Back up
**Parahydrogen**

Ortho-$\text{H}_2$

- $I$ (nuclear spin) = 1
- $J = 1, 3, 5...$

Para-$\text{H}_2$

- $I = 0$
- $J = 0, 2, 4...$

$\Box$ $J=0$ (ground state) para-$\text{H}_2$: completely spherical wavefunction
  - weak intermolecular interaction
  - longer decoherence time

- generate high-purity (>99.9%) para-$\text{H}_2$ from normal $\text{H}_2$
  - converter: cooled to 13.8 K, FeO(OH) as magnetic catalyst
Laser linewidth measurement

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

- observed absorption spectra

<table>
<thead>
<tr>
<th></th>
<th>width (FWHM)</th>
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<tbody>
<tr>
<td>Observed linewidth</td>
<td>175 (13)</td>
</tr>
<tr>
<td>Doppler width</td>
<td>99</td>
</tr>
<tr>
<td>MIR Laser linewidth</td>
<td>145 (16)</td>
</tr>
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</table>

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

Development of the density matrix

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

\[ \rho: \text{density matrix} \]
\[ \Omega_{gg(ee)}: \text{two-photon Rabi frequency} \]
\[ \Omega_{eg(ge)}: \text{AC Stark shift} \]
\[ \gamma_1, \gamma_2: \text{relaxation rates} \]
\[ \delta: \text{detuning} \]

Development of the electric fields

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

\[ \omega_l: \text{laser frequency} \]
\[ N_t: \text{target density} \]
\[ \alpha: \text{polarizability} \]