Towards neutrino mass spectroscopy with Atoms

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On behalf of the A01 group,
“Extreme quantum world opened up by atoms”
Outline

- Physics motivation
- Neutrino mass spectroscopy with atoms
  - Principle of measurement
  - Observable physics quantities
- Macro coherent amplification
  - Super radiance
  - Principle of macro coherent amplification
- Experimental Status
  - Production of meta-stable Ba via super-radiance
  - Xe in p-H2 matrix
- Summary
Physics Motivation

- Summary of neutrino physics
Present status of neutrino physics

- Results of oscillation experiments
  - Finite mass
  - Flavor mixing
  - Only mass-squared difference can be measured.

- Future oscillation experiments
  - T2K/Double choose etc
  - Mixing angle $\theta_{13}$
  - CP phase $\delta$
    - Need neutrino factory??

- Mass (Normal Hierarchy)
  - $m_3 = 50 \text{ meV}$
  - $m_2 = 10 \text{ meV}$
  - $m_1 = 1 \text{ meV}$

- Flavor contents
  - $\nu_e$, $\nu_\mu$, $\nu_\tau$
Prospect of Neutrino Physics

Physics beyond Standard Model

( Understandings of matter-dominated Universe, origin of Mass, GUT )

Present and Future Neutrino Physics

- Majorana (ν=ν̄, phases α, β)
- Mass structure (Absolute: difference)
- Mixing (angles θ, phases δ)

Known/unknowns in neutrino Physics

Measured

Neutrino Spectroscopy with Atoms

Neutrino-less Double beta-decay

Neutrino Oscillation Experiments

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Important questions to be answered

- Majorana vs Dirac?
  - Explain matter dominated universe?
- Absolute mass scale and hierarchy
  - Support see-saw mechanism?
- Mixing angles and phases
  - Give clues for unified theory?
- Cosmic neutrino background
  - Big-bang cosmology true?

We like to answer these questions by a new way, “Neutrino mass spectroscopy with atomics”
Neutrino mass spectroscopy with atoms

--- Observable physics quantities ---

- Principle of the neutrino mass spectroscopy
- Observable physics quantities
  - Absolute mass scale
  - Mixing angle
  - Majorana vs Dirac mass
  - Cosmic neutrino background
Principle of experiment

- Prepare excited atoms
- Observe photon spectrum of de-excitation via one photon plus neutrino pair
- Assume for a moment
  - Rate is big enough!
  - Momentum as well as energy conservation among emitted particles
- Photon spectrum and circular polarization contain information on:
  - Mass and mixing
  - Majorana/Dirac mass type
  - etc

\[ \mathcal{H}_W = \frac{G_F}{\sqrt{2}} \bar{\nu}_e \gamma^\mu (1 - \gamma_5) \nu_e \bar{\nu}_e (1 - \gamma_5) e \]

\[- \frac{G_F}{2\sqrt{2}} \sum_i \bar{\nu}_i \gamma^\mu (1 - \gamma_5) \nu_i (\gamma^\mu (1 - 4\sin^2 \theta_W - \gamma_5)) e\]

where \( \nu_e = \sum_i U_{ei} \bar{\nu}_i \)  \( U_{\alpha i} = \text{MNS matrix elements} \)
Absolute mass

- Photon spectrum
  - Similar to $\mu \rightarrow e \nu \nu$
  - Thresholds (there are 6) are determined by $\nu$ masses.
  - Rough mass scale may be known with $10^3$-$10^4$ events.

\[
\omega_{ij} = \frac{\Delta}{2} - \frac{(m_i + m_j)^2}{2\Delta}
\]
Majorana vs Dirac

Identical particle effects
- Its size is proportional to $m/E$.
- Go to low energy region.

$$
\sum |j_M \cdot j^e|^2 = \sum |j_D \cdot j^e|^2 + \frac{m_i m_j}{2 \hbar_1 \hbar_2} \left( j^e_0 (j^e_0)^\dagger - j^e \cdot (j^e)^\dagger \right)
$$

Graphs showing different materials:
- Xe
- Si-Fe

References:
- 2010/08/08
- FPUA2010
Parity Violation

QED background conserve parity, but in general radiative neutrino pair emission does not.

- Atoms can be polarized by application of magnetic field and circular polarized laser pulse.
- Forward/backward angular asymmetry and/or circular polarization of emitted photon proves that the process involves weak interaction.
Summary of Physics Observables

- Physics observables are very rich!
  - The masses are determined by 6 thresholds in the photon spectrum in $\gamma\nu\nu$.
  - Majorana nature reveals as an identical particle effect.
  - Mixing angle and/or mass hierarchy changes spectrum.
  - Majorana phase may be determined.
  - Observation of relic neutrino may be possible if the mass lightest neutrino is in a few meV region.

- Desperately need an idea to reach rich physics!
Macro-coherent amplification

- Super-radiance and its character
- Macro-coherence
- Coherent target
Super-radiance

- Theoretical prediction
  - R.H. Dicke (PR93, 99(1954))

- Characteristic features
  - Radiation intensity
    - Proportional to $N^2$ (N being # of coherent atoms)
  - Development of quantum coherence
  - Non-linear phenomena different from stimulated emission.

- Experimental evidences
  - Skiribanowitz et al. (PRL30, 309(1973))
  - Huge number of papers

$N_0 \exp\left(-t/\tau\right)$

Size $\sim \lambda$

$T_D / \tau_{sp}/N$
Super-radiance experimental features
—Example of experimental setup—

- **Experimental setup**
  - Laser excitation

- **Intensity**
  - Proportional to $N^2$
    - HF molecule
    - Enhancement up to $N=10^{10}$
      (natural life time=1-10 sec)
    - Existence of ringing
      (expected theoretically)

(PRL30(1973)309)
Super-radiance experimental features

—Intensity—

- Proportional to $N^2$ (gas pressure)
  - Exclude stimulated emission (proportional to $N$)
Triggered super-radiance

- Super-radiance may be triggered by laser injection with appropriate wavelength and power.
- Super-radiance occurs along laser beam

N.W. Carlson et al. Optics Comm. 32 (1980) 350
Summary of Super-radiance

- Cooperative radiation from coherent states
  - Phenomena different from stimulated emission.
  - Coherence can develop during spontaneous emissions.
    - Predicted by Dicke.
  - Coherence development can be accelerated by injection of trigger laser.
- Characteristic features
  - Intensity: proportional to $N^2$, $N =$ atoms in $V_c$.
  - Radiation’s angular dependence: forward and backward peaked.
  - Pulse starts after a certain delay time $T_D$.
  - Ringing may exist.
- Coherence volume $V_C$: $V_C = \lambda^2 L$
Macro-coherence: a way to overcome limitation in (Dicke) super-radiance

\[ V \propto \lambda^2 L \]

Coherence region of super-radiance is limited to a volume characterized by a wavelength. In case of multi-particle emission, an extra condition, namely momentum conservation, will remove this limitation.
Principle of macro-coherent amplification

- Two-photon emission from (coherent) meta-stable states:
  - Two photon rate is expressed by

\[
\Gamma = \int \left( \Pi_i \frac{d^3 k_i}{(2\pi)^3} \right) 2\pi \delta(\Delta - \sum_i \omega_i) \left| n \int_V d^3 r e^{i \sum_i \vec{k}_i \cdot (\vec{r} - \vec{r}_0)} \mathcal{M}(\vec{k}_i) \right|^2
\]

- Warning: explanation above is based on perturbation.
  - May not give correct intensity or rate.

- Characteristic features
  - Energy and angle
    - Peak at \( \Delta/2 \)
    - Back-to-back
  - Paired Super-Radiance (PSR)

\[
\sum_{j=1}^N \exp \left\{ i \left( \vec{k}_1 + \vec{k}_2 \right) \cdot \vec{r}_j \right\}^2 \Rightarrow N^2 \text{ if } \vec{k}_1 + \vec{k}_2 = 0
\]

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Comments on macro-coherent amplification

- Radiative neutrino pair emission:
  - Macro-coherent amplification works much the same way as in the two photon case.

- Proof of principle experiment needed.
  - No observation in the past!
  - The best way: observation of paired super-radiance (PSR).

- Detailed theoretical studies based upon Maxwell-Bloch equation (semi-classical approach: atom described by QM and radiation by classical EM fields) in progress.
  - PSR seems to be triggered by injection of appropriate laser.
  - Also impact on the $\gamma\nu\nu$ process.

M. Yoshimura; in preparation
Our research strategy

Observe paired super-radiance
(proof of principle experiment for macro-coherent amplification)

Our current activity

Detect atomic neutrino

Develop macro-coherent target
(High-density (solid?) target in quantum coherence for $\gamma\nu\nu$ experiment)
Experimental Status

- Production of Barium meta-stable states via super-radiance
  - Ba is one of the best candidate atoms for paired SR.
  - For detail, see poster presentation by C. Ohae.

- Xe in p-H2
  - Xe is one of the candidate atoms for $\gamma\nu\nu$ process.
  - For detail, hear oral presentation by K. Nakajima.
Production of Ba meta-stable states

- Motivation
  - Paired super-radiance as a pop experiment for macro-coherent amplification.
    - QED process is much easier than weak process.
  - Why Barium?
    - Lambda-type energy levels.
    - Meta-stable state: $\tau = 1/8$ sec
    - Easy to access via laser irradiation.

![Diagram showing energy levels and laser transitions](image-url)
Experimental apparatus

- CW laser diode (1500 nm)
- OPO (554 nm)
- CCD
- Thermocouple x6
- Heater
- Heatpipe oven
- Wick
- Ba vapor
- Buffer gas (Ar)
- Photodiode (554 nm)
- Fast photodiode (1500 nm) on xy-stage
- Large area photodiode (1500 nm)

OPO: Optical parametric oscillator
216~2500 nm, 10 mJ, 3 ns, 10 Hz

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Intensity and Delay time vs atom density
Effects of trigger laser

Forward (trigger laser direction)
  w/ trigger (red)
  w/o trigger (blk)

Backward (opposite direction)
  w/ trigger (red)
  w/o trigger (blk)

Example of scope trace (forward)

Example of scope trace (backward)

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Angular distribution sharpened

Without trigger

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With trigger
Paired super-radiance experiment:  
--summary and prospect--

- Production of meta-stable Ba atoms
  - Quick production of Ba via super-radiance
    - within a few nsec
    - $>10^{12}$ Ba produced
  - Some preliminary studies on super-radiance.
    - Delay-time character in good agreement with prediction.
    - Emission peaked in forward-backward direction.
- Triggered super-radiance
  - Enhancement of intensity up to 20
  - Angular distribution sharpened.
  - Important step for a radiative neutrino pair emission

- Future works
  - Study on coherent volume
  - Paired Super-radiance

PSR rate of $\Gamma_{2\gamma} = 4 \times 10^7 /s$ needs $nN = 10^{25} /cm^3$. 
Development of macro-coherent target
Macro-coherent target

**Requirements** (for neutrino pair emission)
- Number of target atoms;
  - Close to Avogadro number
  - Gas target is not enough
- Long coherent time
  - Assemble of isolated dense atoms
- Meta-stable state.

**Candidates**
- Rare gas embedded in matrix (p-H2 or rare gas)
- Atoms embedded in C\textsubscript{60} fullerene
  - Experiments suggest N/H2/Xe etc inside C\textsubscript{60} are isolated, weakly interacting with environment.
- Semiconductor at low temperature
  - Donor-hole in the p-n junction depletion layer
What is matrix?

- Matrix is a host material made by molecular crystals of rare gas or \( \text{p-H}_2 \), aiming to confine guest atoms or molecules
  - Interaction with host material is weak.
  - Can suppress movements (translational/rotational).

High resolution spectroscopy in chemistry.
**Solid para-H₂**

Para hydrogen (H₂) spherical at low temperature weak intermolecular interaction

Solid para hydrogen (*para-H₂*) quantum crystal transparent to infrared-ultraviolet light

used as spectroscopic “matrix” capable of storing a large amount of sample giving homogeneous environment
Xenon in solid para-H₂

Why Xe in Solid p-H₂?
- Xe has meta-stable states
- large amount of Xe can be stored
- long sample stability expected
- small spectral shifts from gas phase?

What should we understand first?
- exact energy structure of Xe in p-H₂
- lifetime of each state
- maximum Xe density
- maximum sample volume
  etc.

PSR rate of $\Gamma_{2\gamma} = 2.33 \times 10^3 /s$ needs $n \, N = 10^{25} /\text{cm}^3$.

$\nu N = n^2 SL = (10^{22} /\text{cm}^3 \times 10^{-6})^2 \times 10^{-4} \text{cm}^2 \times 10^{-2}\text{cm}$

$= 10^{26} /\text{cm}^3$

$10^{-2}\text{cm} = 100 \, \mu\text{m}$
Para-hydrogen matrix apparatus @ Okayama

Cryostat for sample production

FT-IR Spectrometer

Cryostat for para-hydrogen converter
Experiments at UBC (w/ Prof. Momose)

Xe/para-H₂ mixture
with flow rate controlled

T = 3.5 - 5.5 K

1. Deposition
established method
limited thickness

2. Open cell
hard to make good crystals
large volume

MgF₂

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H₂ phase diagram

Dry ice/CH₃OH trap

Cryostat

nozzle
Is xenon isolated?

Data taken at UBC with Prof. Momose.

Rotational-vibrational spectra of solid para-H$_2$ measured by FT-IR spectrometer (Bruker IFS 120HR)

1 cm$^{-1}$ ⇔ 30 GHz ⇔ 0.000124 eV


Xe is probably isolated.
Energy level/lifetime measurements

VUV absorption spectroscopy

Laser-excited fluorescence spectroscopy

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VUV Absorption Spectroscopy
- Preliminary results -

![Graph showing energy levels and transitions]

### Preliminary Results

<table>
<thead>
<tr>
<th>Gas</th>
<th>A1 2P3/2 n=1</th>
<th>B1 2P1/2 n=1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>σ</td>
</tr>
<tr>
<td>Xe/H2[Ref.]</td>
<td>9.061 eV</td>
<td></td>
</tr>
<tr>
<td>10ppm</td>
<td>8.99 eV</td>
<td>0.072 eV</td>
</tr>
<tr>
<td>100ppm</td>
<td>8.99 eV</td>
<td>0.071 eV</td>
</tr>
<tr>
<td>1000ppm</td>
<td>8.99 eV</td>
<td>0.074 eV</td>
</tr>
<tr>
<td>100ppm / H2</td>
<td>8.99 eV</td>
<td>0.071 eV</td>
</tr>
</tbody>
</table>

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Laser-excited Fluorescence Spectroscopy
- Preliminary results -

2010-05-04 run11 Ex232.5nm T_e = 80ns

\[ \chi^2 / \text{ndf} = 386.4 / 292 \]

- \( p_0 = 776.6 \pm 43.2 \)
- \( p_1 = 718 \pm 1.2 \)
- \( p_2 = 19.94 \pm 1.39 \)
- \( p_3 = 1417 \pm 11.2 \)
- \( p_4 = 750.8 \pm 0.5 \)
- \( p_5 = 138.1 \pm 1.4 \)
- \( p_6 = 1.364 \times 10^{-11} \pm 1.451 \times 10^{-01} \)

Background from substrate

\[
\begin{array}{c|cc}
\lambda & \sigma \\
100\text{ppm} & 730.4 \pm 2.4\text{nm} & 24.6 \pm 2.2\text{nm} \\
1000\text{ppm} & 734.5 \pm 0.8\text{nm} & 28.7 \pm 0.7\text{nm} \\
\end{array}
\]

3 \times 10^5 \text{ atoms/pulse for 100ppm}
2 \times 10^6/\text{pulse for 1000ppm}
\( \sim 1\text{mJ/pulse, Gate700ns} \)

8.4 eV

\[ 5p^5(2P_{3/2})6p \]

\[ 5p^5(2P_{3/2})6s \]

\[ 5p^5(2P_{3/2})6s \]

\[ 5p^6^1S_0 \]
Successful production of of Xe in p-H₂ Matrix
- Surface density of Xe : $>10^{16}$/cm²
- Identification of P-states by VUV absorption spectroscopy
  - Width narrow enough to do initial $\gamma\nu\nu$ experiments
- Possible observation of fluorescence via two-photon excitation from $5p^5(2P_{3/2})6p$ to $5p^5(2P_{3/2})6s^2[3/2]$$_2$
  - Need confirmation / detailed studies.

Successful production Xe in Ar Matrix
- Achieved Xe surface density: $10^{15}$/cm²

Successful production of pure N@C₆₀
- $10^{14}$ pure N@C₆₀ produced
- In progress:
  - Study on electronic excitations of N@C₆₀
  - For Detail, see poster presentation by Wakabayashi.
Example of an experimental setup for radiative neutrino pair emission

- **Rate**
  - \(10^{-4}/\text{pulse for 100cc p-H}_2\)
  - with Xe fraction of \(10^{-3}\)

- **Background control**
  - Long life
    - The 1s5 level life time is a few x 10 sec.

- **Trigger**
  - Signal photon has the same wavelength.

- **Parity violation**
Summary and prospects

- Proposed a new method of neutrino spectroscopy
  - Use of atomic levels
  - Use of a new mechanism: Macro-coherent amplification

- Present status
  - Paired super-radiance experiment being prepared.
    - Production of meta-stable Barium states via super-radiance
    - Barium ion traps (Talk with Taniguchi)
  - Preliminary experiments in progress toward coherent target
    - Xe in matrix
    - N at C60

- Future prospects
  - Observe super-radiance from matrix
  - Observe paired super-radiance
  - Observe atomic neutrino

Detailed studies on $2\gamma$ PSR backgrounds are in progress
Thank you for your attention!

- A01 collaborators
  - Yoshimura, Nakano, Taniguchi, Fukumi, Nakajima, Kuma, Kawaguchi, Tang, Kubosono, Sato, Ohae, Yamaguchi, Yuasa (Okayama)
  - Nanjo (Kyoto)
  - Wakabayashi (Kinki)
  - Nakagawa (Okayama Science)
  - Tanigaki (Tohoku)
Backup slides

- Absolute neutrino mass from other constraints
- Cosmic neutrino background
- Elementary explanation of SR
- Omni-directional Super fluorescence
- Radiative neutrino experiments backgrounds
- N at C60
- Delay time vs number density $n_0$
- Xe in p-H$_2$ matrix/ Xe in p-H$_2$ matrix (previous study)
From other constraints

- **Direct detection**
  - 2 eV (Troitsk) $\to$ 0.3 eV (Katrin)

- **Observational cosmology**
  - $\Sigma M_\nu < 0.7$ eV (WMAP)
  - $\Sigma M_\nu < 0.2$ eV (PLANK)

- **$0\nu\beta\beta$**
  - $\Sigma M_\nu < 0.75$ eV

\[
\sum_i m_i U_{ei}^2 \equiv |m_{\beta\beta}| \simeq m_0 \sqrt{1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m}{2} \right)}
\]

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Cosmic neutrino background

- Pauli blocking effect changes spectra near threshold
  - Threshold reduction
    - $1/2 \times 1/2 = 1/4$
  - Temperature measurement may be possible if $m_1 < \text{a few meV}$.

$$m_1 = 0.1, 1, 5 \text{ meV}$$

M. Yoshimura & Takahashi; hep-ph/0703019
Elementary explanation of SR

\[ |e\rangle|e\rangle \quad t=0 \]
\[ (|e\rangle|g\rangle + |g\rangle|e\rangle)/\sqrt{2} = |s\rangle \quad \text{or} \quad |s\rangle \]
\[ |g\rangle|g\rangle \]

Photon Emission from 2 excited atoms

Suppose there are two excited states, and one of them has gone to the ground state by emitting photon. If we can not tell which of the two is de-excited, then the final state is symmetric state: coherent state shown above.

The situation is similar to Young’s experiment; but in this case intensity actually looks like the one shown below.
Omni-directional Super fluorescence

- Excite Rb (5S→5D) by two laser pulses with $k_1$ and $k_2$ ($k_1=k_2$).
- Observe cascade radiations from 5D→6P ($k_3$) and 6P→5S ($k_4$).
- SRs occur only when $k_1+k_2=k_3+k_4$ is satisfied, when coherence among S and D, D and P are developed.

Kinematics of $k_1+k_2=k_3+k_4$
Backgrounds (in case of Xe in p-H2)

- **Spontaneous emission (1)**
  - The excited level would emit 8.4eV photons.
  - Then they might be converted to 4.2eV photons via inelastic scattering with detector materials.
    - Detector’s angular acceptance ($10^{-3}$), and spectrometer band pass ($\Delta\lambda=0.1\text{nm}$)

- **Spontaneous emission (2)**
  - Emission of 4.2eV photons due to Breit-Wigner tail.
    - Detector’s angular acceptance ($10^{-3}$)
    - BG rate would be similar to signal rate for 300cc p-H2 target.

- Two photon paired superradiance
Backgrounds

- Single Photon SR
  - SR corresponding to 4.2eV photons
  - Effective excited atoms corresponding off-resonance region is too small.

- Trigger Laser
  - Trigger Laser wavelength = signal's
  - Timing information

- PMT’s dark counts
  - Lower photo-cathode temperature to reach 10^{-3}/sec level

Observation of parity violation effects distinguishes signals from all backgrounds above except PMT’s dark counts.
N@C60 production and purification

- **What is N@C60.**
  - C60 can contain various kinds of atoms.

- **Why N@C60**
  - Quiet and peaceful environment.
  - Line width of ESR spectrum: only 200k Hz

Electron $S=3/2$
Nuclear $I=1$
Hyperfine levels 1 2
Transitions 9

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How to produce and purify?

UVとESR信号 (Y05)
Xe in p-H₂ matrix

From the peak height
Xe density ~ 10^{16}/cm²

Phonon-less
S₁(0) band

Xe satellite peak

0.12 meV

log₁₀(I/I₀)

Wavenumber (cm⁻¹)

300 ppm
150 ppm
50 ppm
Other (No Xe)

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Xe in p-H$_2$ matrix (previous study)


Fig. 2. Infrared absorption spectra in the 4480-4490 cm$^{-1}$ region recorded at 2.0 K for as-deposited samples. Trace (pH$_2$) is for a 2.8(1) mm thick neat pH$_2$ solid containing 100 ppm of pH$_2$. The other spectra are R$_g$ atom doped samples with thicknesses and R$_g$ atom concentrations as follows (Ne) 2.8(1) mm, 1000 ppm, (Ar) 1.8(1) mm, 1300 ppm, (Kr) 1.6(1) mm, 440 ppm, and (Xe) 2.5(1) mm, 260 ppm.

Fig. 3. The wavenumber shift of the R$_g$ S$_1$($0$) satellite line from the unperturbed value as a function of the difference in polarizability between the R$_g$ atom and pH$_2$. 
Delay time vs number density $n_0$

- Longer than natural lifetime
- Shorter than pump laser pulse

![Graph showing the relationship between delay time ($T_D$) and number density ($n_0$)](image)