The Abdus Salam International Centre for Theoretical Physics

2047-34

Workshop Towards Neutrino Technologies

13 - 17 July 2009

Towards neutrino mass spectroscopy and relic detection using atomic targets; experimental aspects

Noboru SASAO

Okayama University
Center of Quantum Universe
Tsushima-naka
Okayama, JAPAN

Towards neutrino mass spectroscopy and relic detection using atomic targets; experimental aspects

Noboru SASAO
Research Core for Extreme Quantum World
Okayama University, Japan
With SPAN group

(M.Yoshimura/I.Nakano/A.Fukumi/K.Nakajima/H.Nanjyo)

Outline

Yoshiumra's Talk..

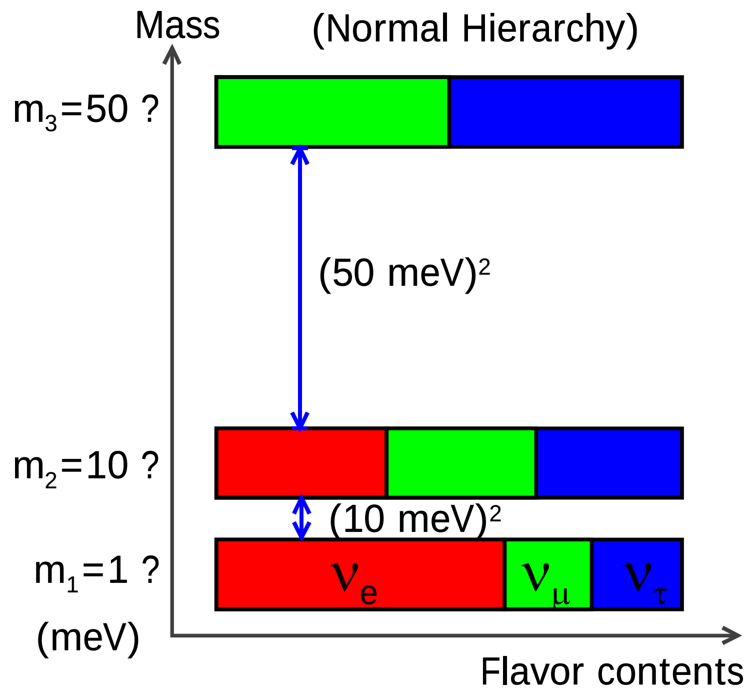
- Physics motivation
- Neutrino spectroscopy with atoms
    - Principle
    - Observable quantities
- Macro coherent amplification
    - Super radiance
    - Macro coherence
- Experimental Status
    - Super radiance from Rb
    - Xe in Ar matrix/ Xe in p-H2 matrix
- Summary

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 experiments
  - T2K/Double choose etc
  - mixing angle θ_{13}
  - CP phase δ
    - Need neutrino factory??



Important questions to be answered

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

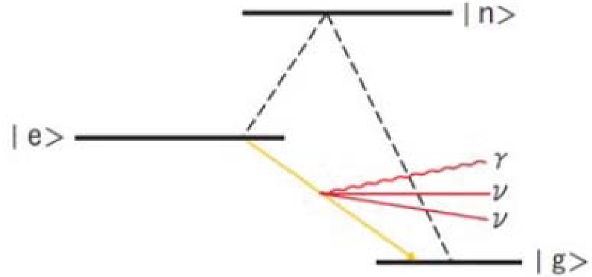
We like to answer these questions by a new way, “spectroscopy by atomic neutrinos”

Neutrino spectroscopy with atoms

--- Observable physics quantities ---

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

Principle of experiment

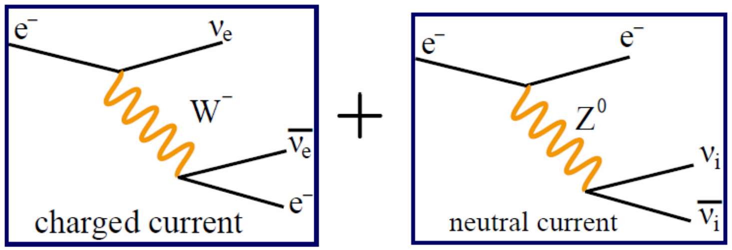


- Prepare excited atoms
- Observe photon spectrum of de-excitation via one photon plus neutrino pair
- Assume for a moment
  - Rate is big enough!
  - Momentum as well as energy conservation among emitted particles
- Photon spectrum and circular polarization contain information on:
  - Mass and mixing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

Will be explained later!!

|e> → |g> + γ + ν ν

|e> → |g> + γ + γ



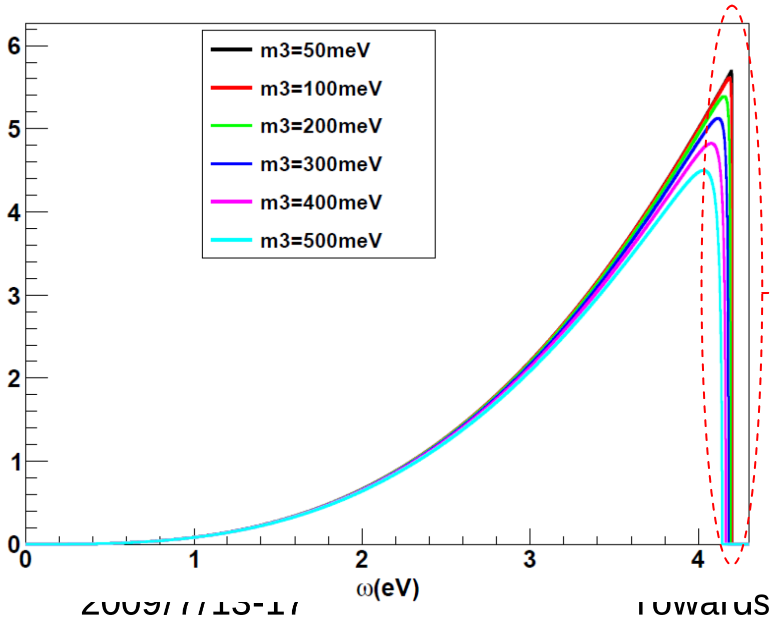
$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}}\bar{\nu}^e\gamma_\alpha(1-\gamma_5)\nu^e\bar{e}\gamma^\alpha(1-\gamma_5)e$$
$$-\frac{G_F}{2\sqrt{2}}\sum_i \bar{\nu}^i\gamma_\alpha(1-\gamma_5)\nu^i\bar{e}(\gamma^\alpha(1-4\sin^2\theta_W-\gamma_5))e$$

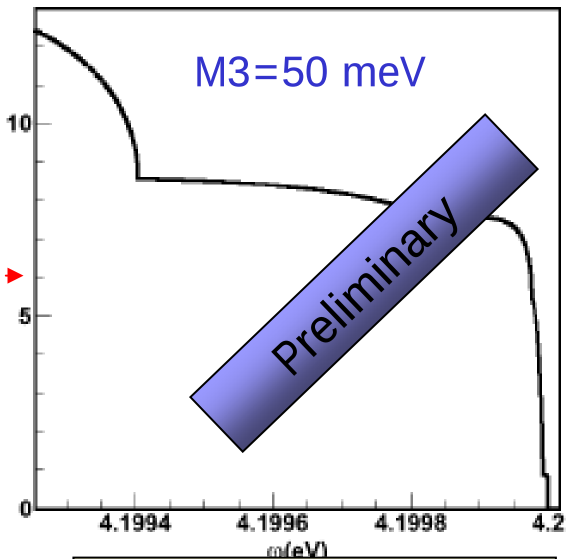
where $\nu_e = \sum_i U_{ei}\nu_i$ $\quad U_{\alpha i} =$ **MNS matrix elements**

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

Absolute mass

- Photon spectrum
  - Similar to μ-> eνν
  - Thresholds (there are 6) are determined by masses.
  - Rough mass scale may be known with 10^3-10^4 events.



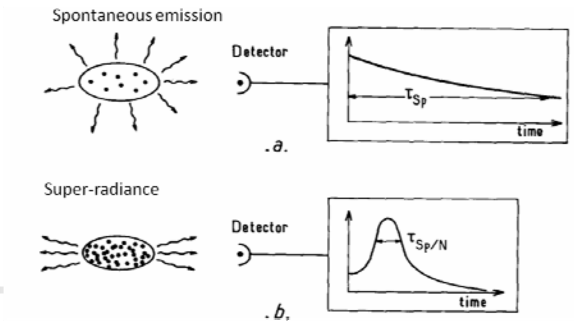


Threshold behavior

Macro-coherent amplification

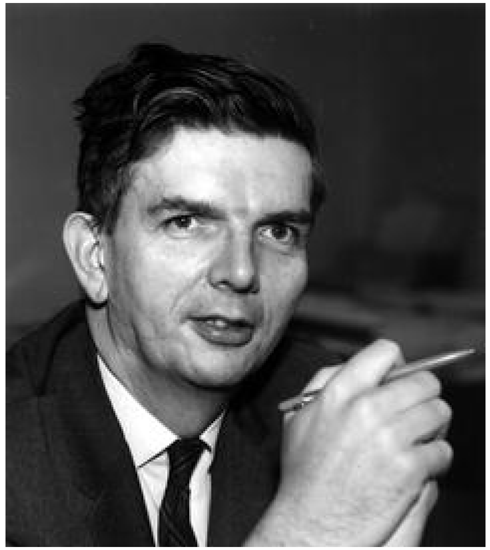
- Super-radiance and its character
- Macro-coherence
- Coherent target

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



Super radiance

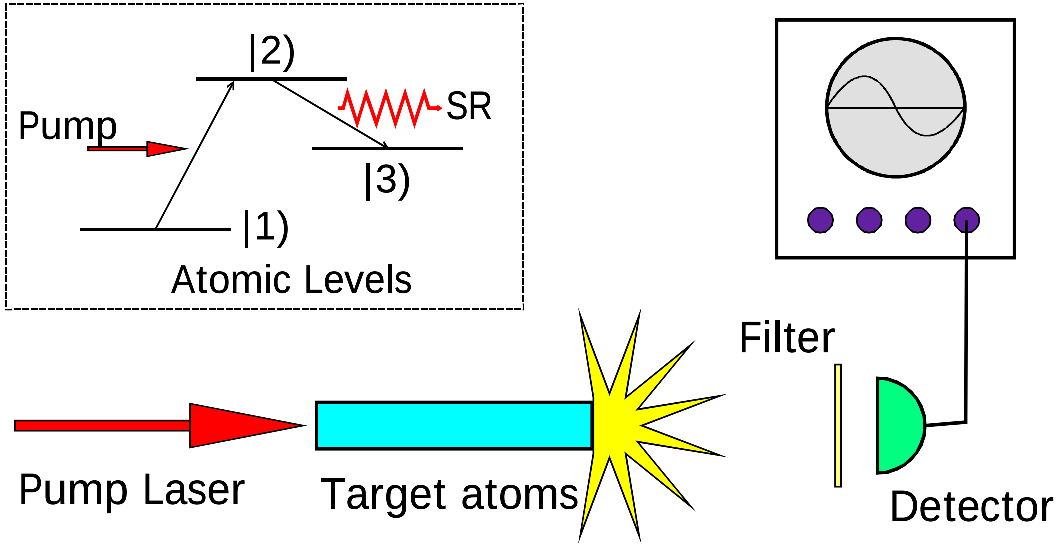
- Theoretical prediction
  - R.H.Dicke (PR93,99(1954))
- Characteristic features
  - Radiation intensity
    - **Proportional to N^2 (N being # of excited atoms)**
    - If spontaneous emission, prop to N.
  - Development of quantum coherent states
  - Non-linear phenomena different from stimulated emission.
- Experimental evidences
  - Skiribanowitz et.al. (PRL30,309(1973))
  - Huge number of papers



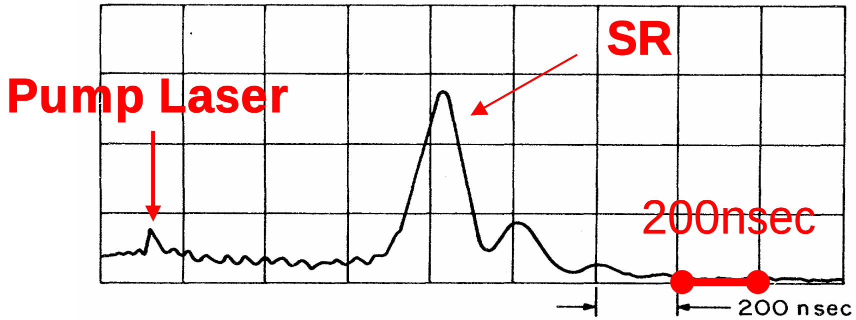
1916 —1997

Super-radiance experimental features —Example of experimental setup—

- Experimental setup
  - Laser excitation
- Intensity
  - Proportional to N^2
    - HF molecule
    - Enhancement up to 10^{10} (natural life=1-10 sec)
    - Existence of ringing (expected theoretically)

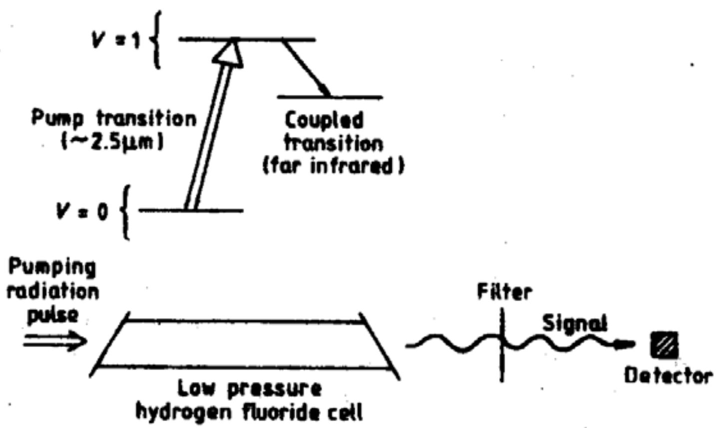


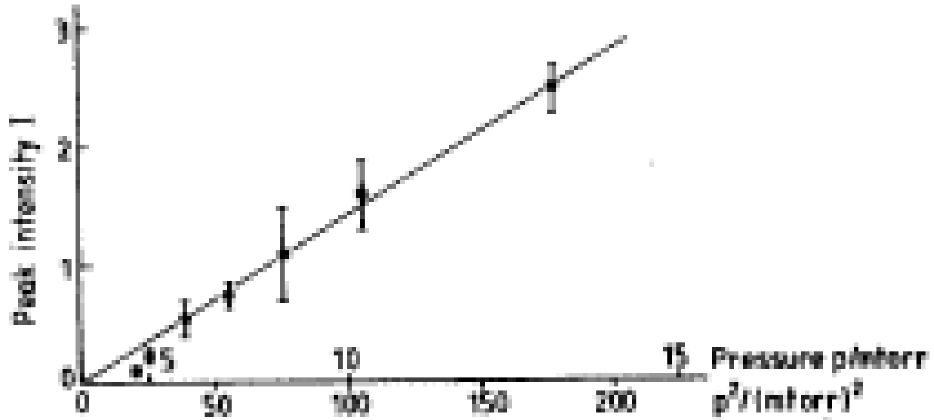
(PRL30(1973)309)



Super radiance experimental features —Intensity—

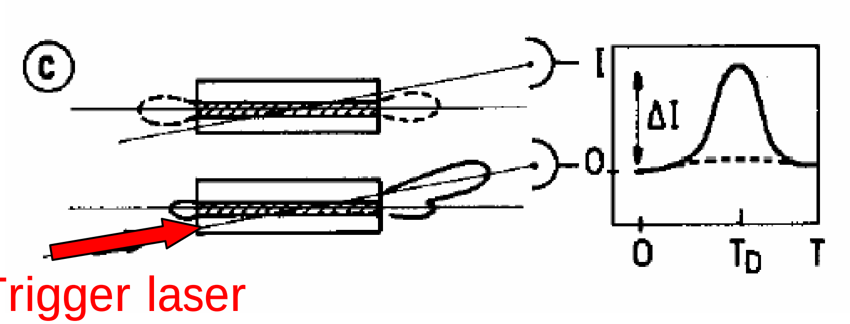
- Proportional to N^2(gas pressure)
  - Exclude stimulated emission (proportional to N)



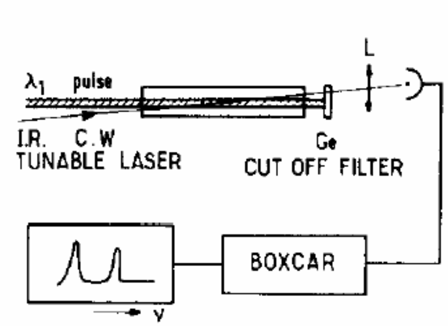


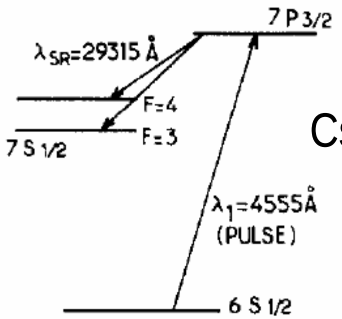
Triggered Super-radiance

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

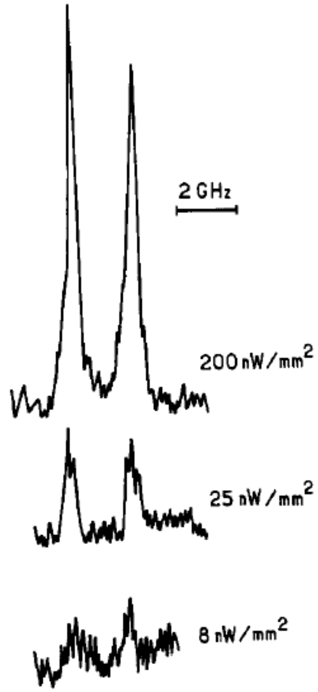


Trigger laser





Cs level



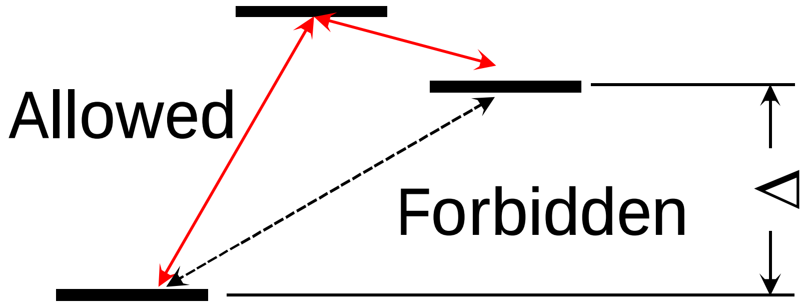
N.W.Carlson et al.
Optics Comm. 32 (1980) 350

Macro-coherence: a way to overcome limitation in super-radiance

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.

Two-photon macro-coherence



- Prepare excited atoms in a coherent state.
  - Two photon rate is expressed by

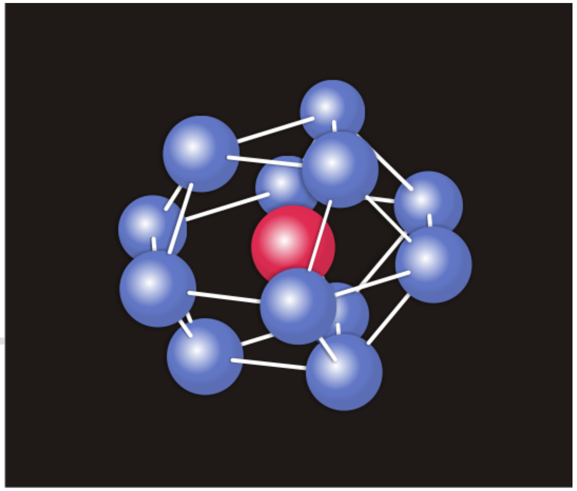
$$\Gamma = \int \left(\Pi_i \frac{d^3k_i}{(2\pi)^3}\right) 2\pi\delta(\Delta - \sum_i \omega_i)\, |n \int_V d^3r e^{i\sum_i \vec{k}_i\cdot(\vec{r}-\vec{r}_0)} \mathcal{M}(\vec{k}_i)|^2$$

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

  - Two photon emission may be enhanced to N^2
- Characteristic features
  - Energy and angle
    - Peak at $\Delta/2$
    - Back-to-back
- Proof of principle experiment
  - No observation in the past !

M. Yoshimura et.al.; arXiv:0805.1970

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
  - Lambda type energy level
- Candidates
  - Rare gas embedded in matrix (p-H2 or rare gas)
  - Atoms embedded in C_{60} fullerene
    - Experiments suggest N/H2/Xe etc inside C_{60} are isolated, weakly interacting with environment.
  - Semiconductor at low temperature
    - Donor hole in the p-n junction depletion layer

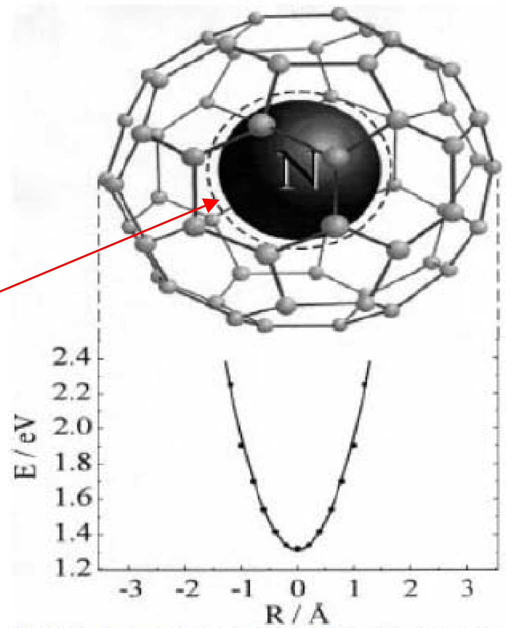
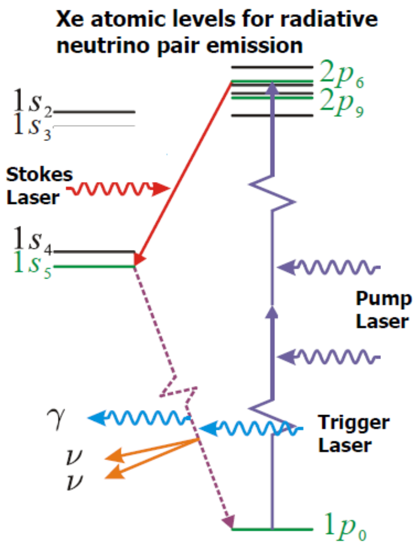


Fig. 6. Schematic view of nitrogen inside C_{60}. The size of the sphere corresponds to the van der Waals radius of nitrogen [12]. The dashed line marks the border of the inner cavity of the C_{60} shell if van der Waals radii are assumed for the carbon atoms [12]. In the lower part of the figure the calculated potential energy of nitrogen in C_{60} is shown as a function of the displacement from the center [4]. In the calculation, no relaxation of the cage atoms is assumed. The energy scale is relative to the energy of nitrogen at infinity



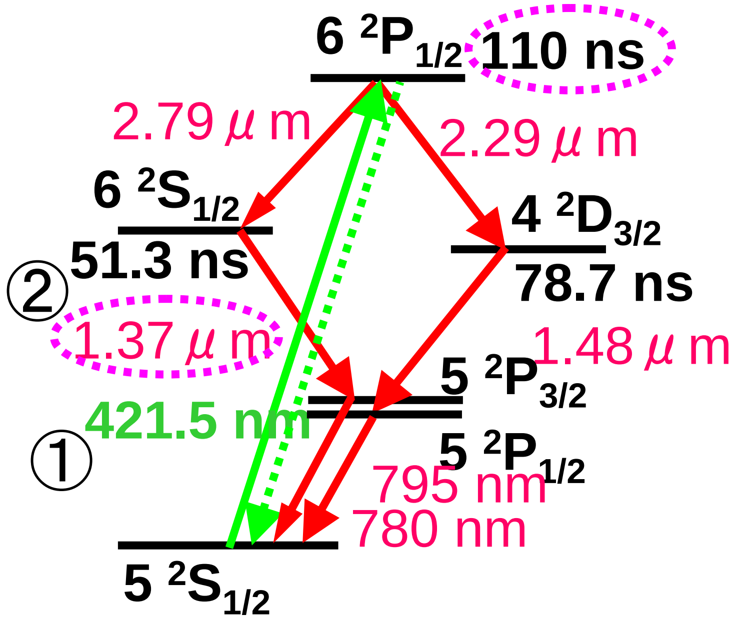
Experimental Status

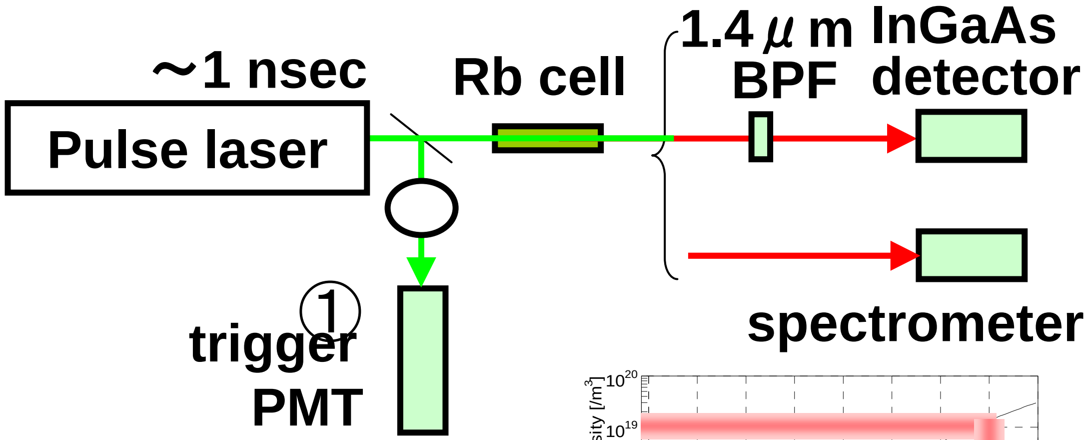
- Cascade super-radiance from Rb
- Xe in p-H2/Ar
  - Note that Xe is one of the candidate atoms for radiative neutrino pair emission

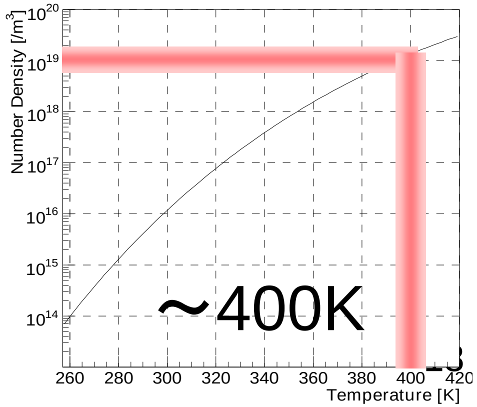
Cascade super radiance from Rb

- To obtain general understandings and techniques related to super-radiance.

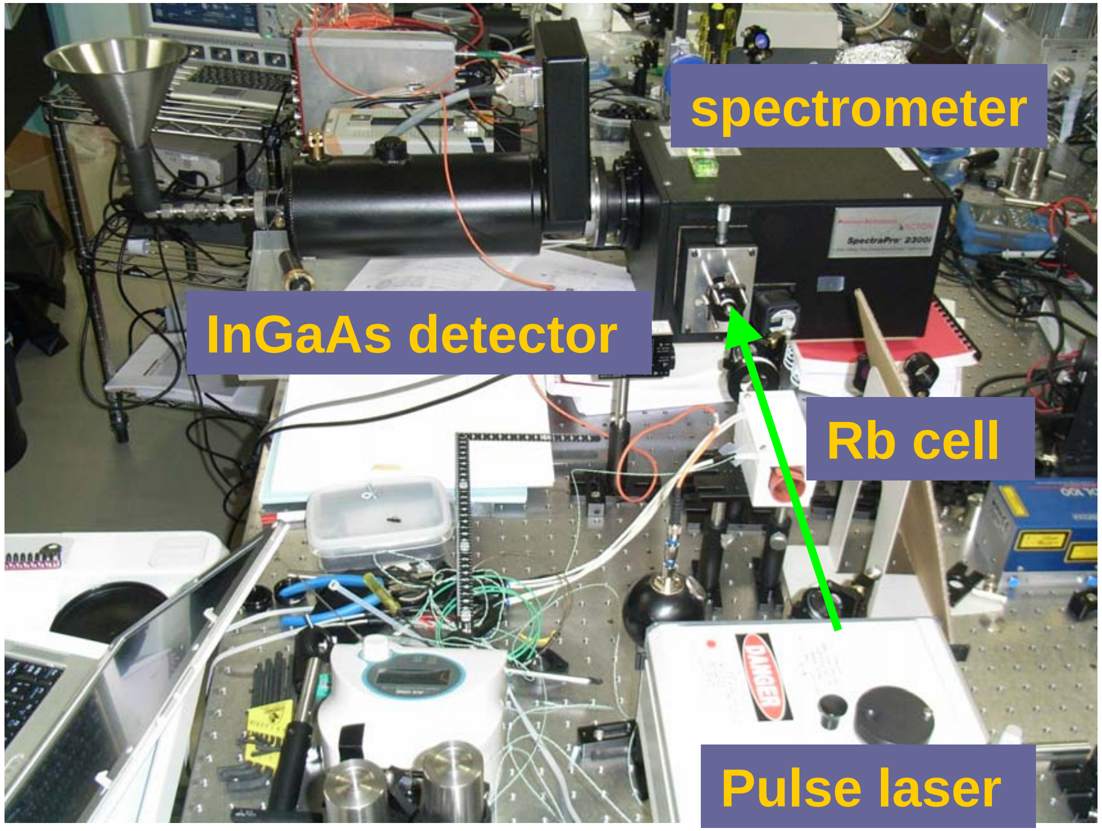
- **Level Diagrams**

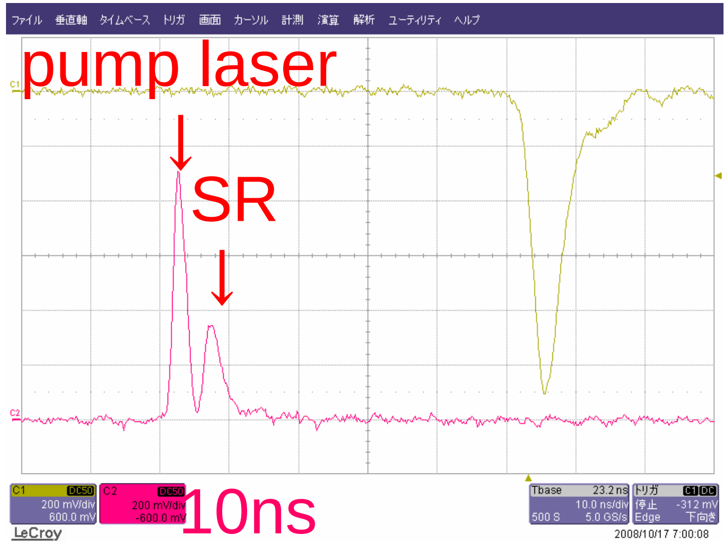






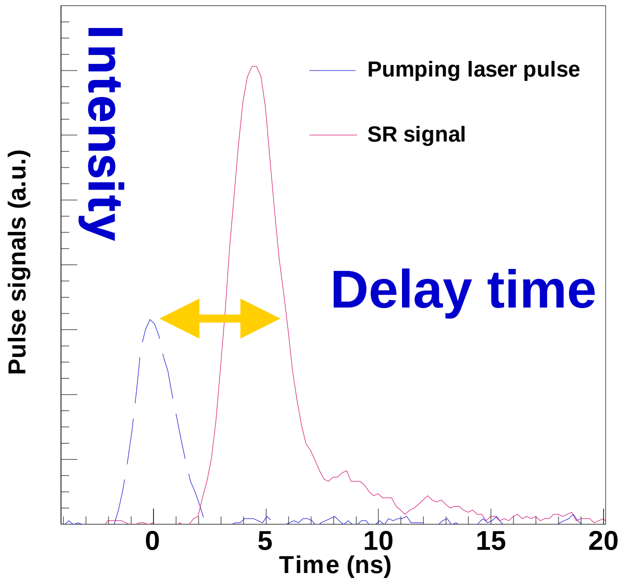
Setup and results

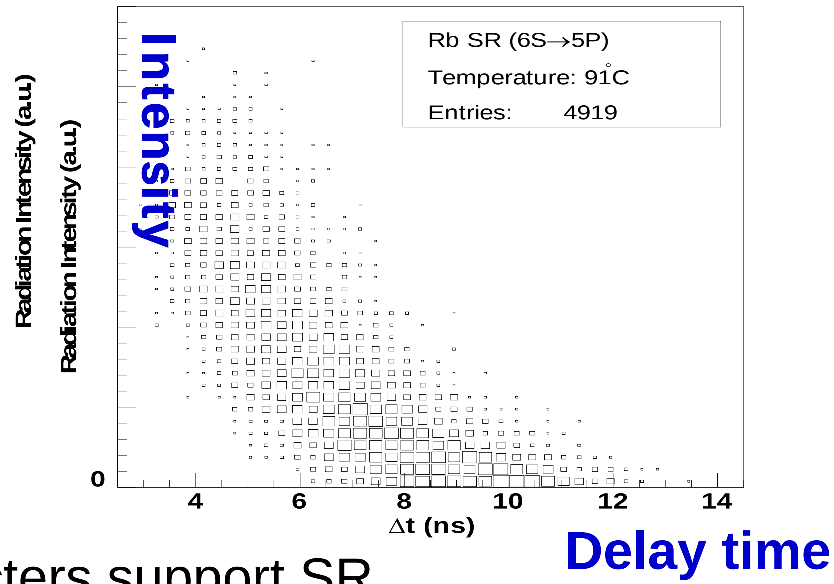




- (top) Pump laser light and SR signal are seen.
（Note; life time is 110+51 nsec）

Correlation between intensity and delay time





- Observed radiation characters support SR

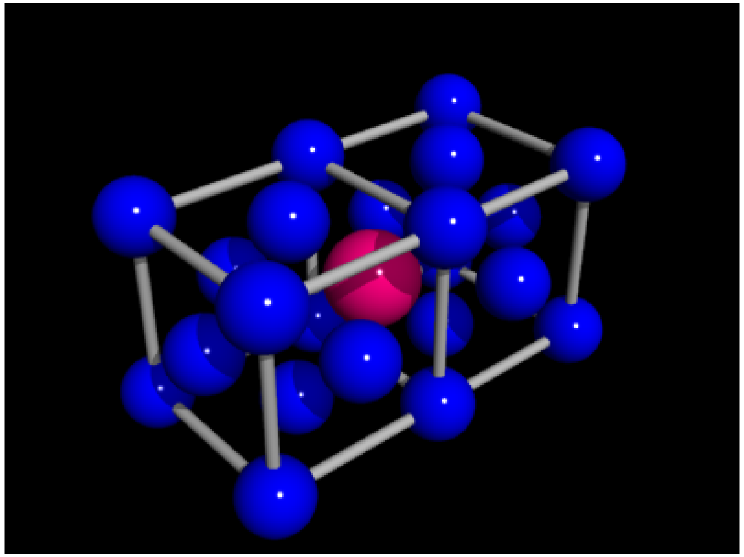
  Delay time (5-10nsec) much shorter than (110+51nsec).
  Intensity inversely proportional to delay time
  Forward/backward angular distribution

Super-radiance experiment: -- summary and prospect--

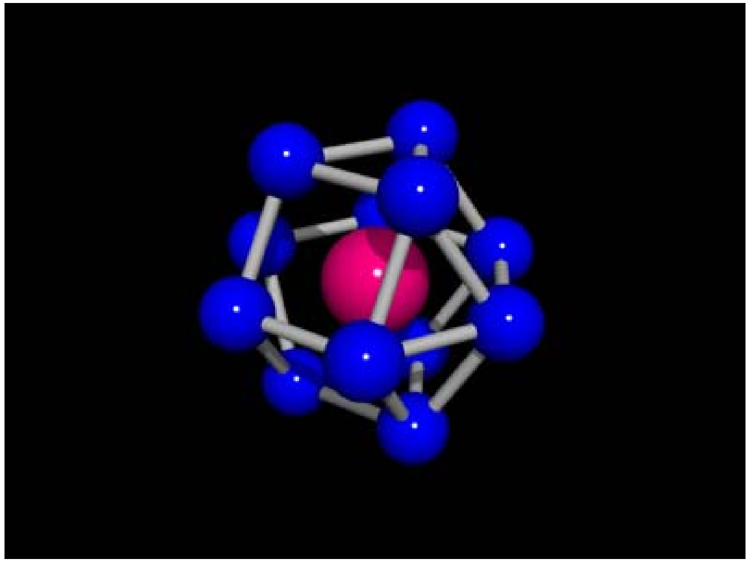
- Observation of SR
  - Delay time(5-10nsec)<<natural life time(110+51nsec)
  - Anti-correlation between delay time and intensity
  - Angular distribution; forward/backward peak
  - SR from $4D_{3/2}$(1.48um) observed.
- Future work
  - Need to observe the 1st stage SR(2.79um,2.29um)
  - Theoretical analysis including pump laser width (2-3nsec) and lateral relaxation time(T2,T2*)
  - Prove N^2 dependence

Matrix preparation

- Xe in Ar
  - With Prof. Wakabayashi (Kinki Univ.)

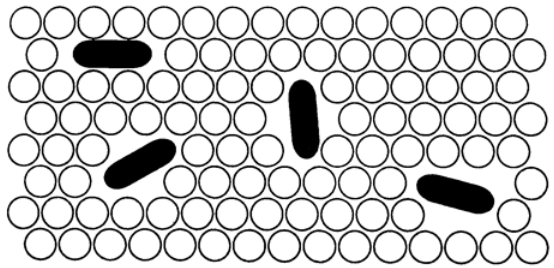


- Xe in para-H_2
  - With Prof. Momose (UBC)



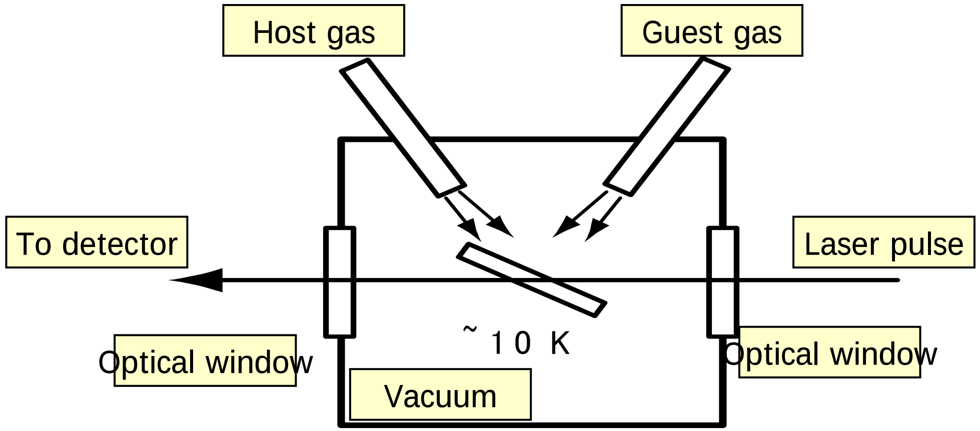
What is matrix？

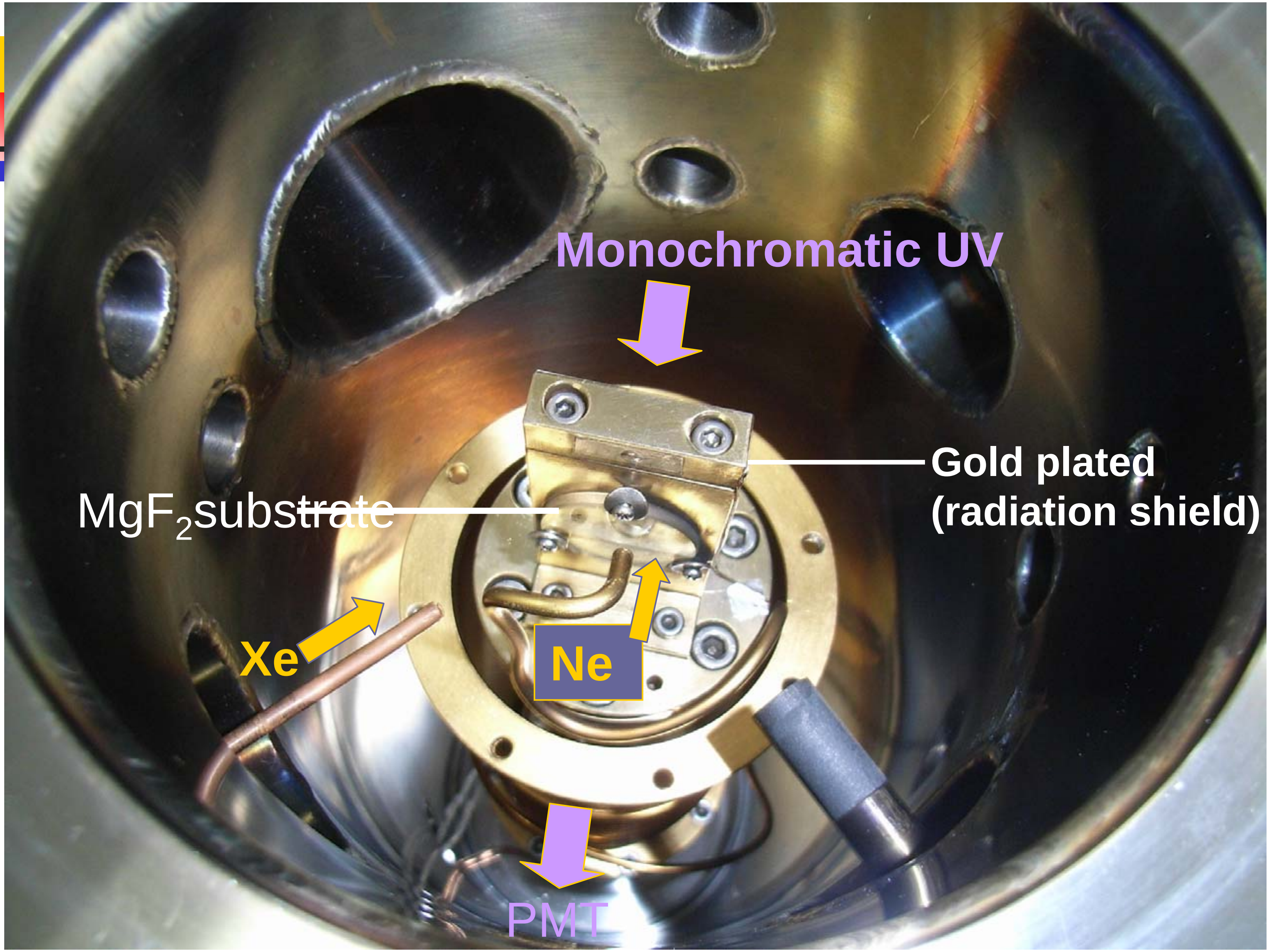
- Matrix is a host material made by molecular crystals of rare gas or p-H2, aiming to confine guest atoms or molecules
  - Interaction with host material is weak.
  - Can suppress rotation.

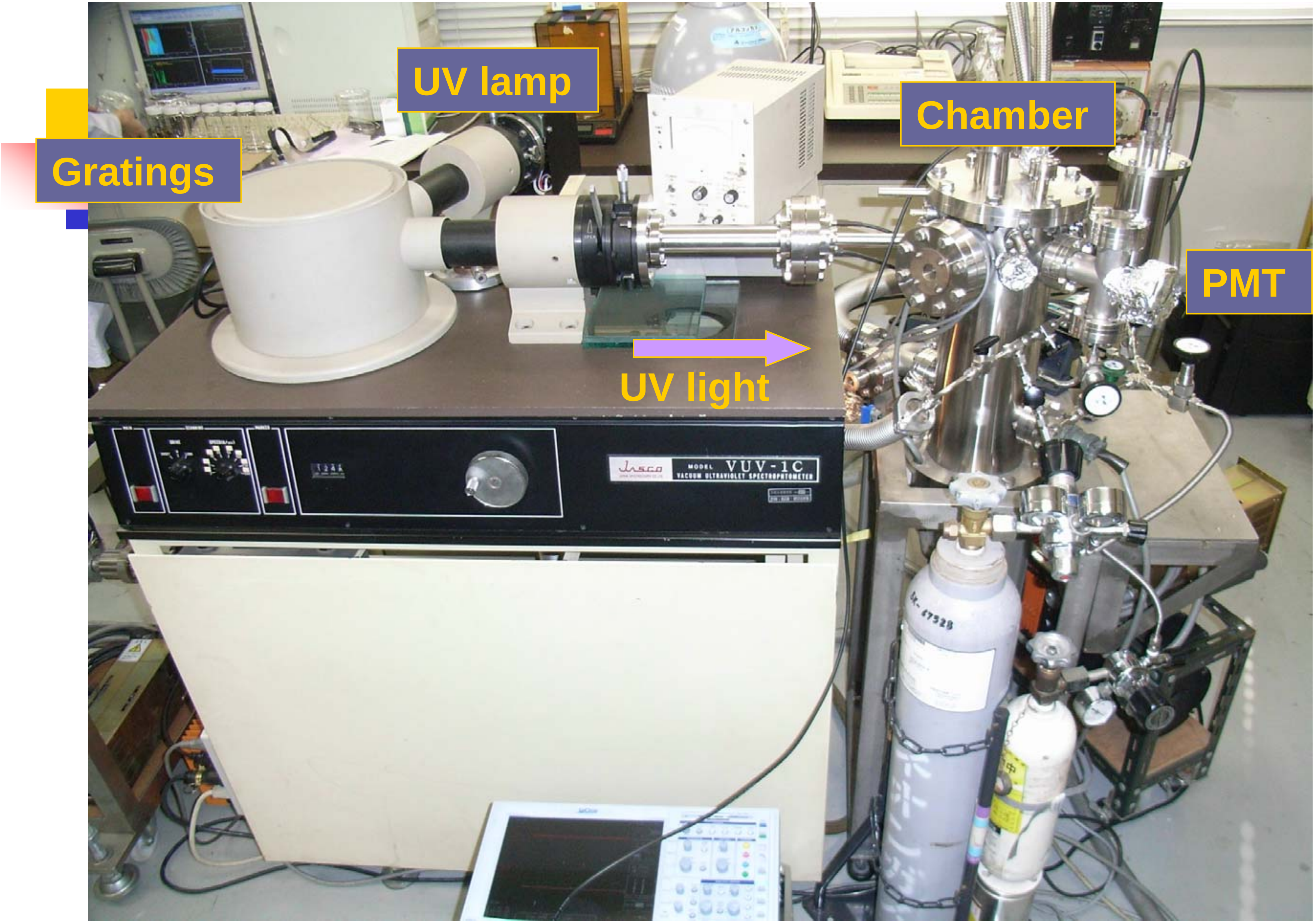


IAN R. DUNKIN
Matrix-Isolation Techniques

High resolution spectroscopy in chemistry.




Monochromatic UV
Gold plated
(radiation shield)
MgF_2 substrate
Xe
Ne
PMT

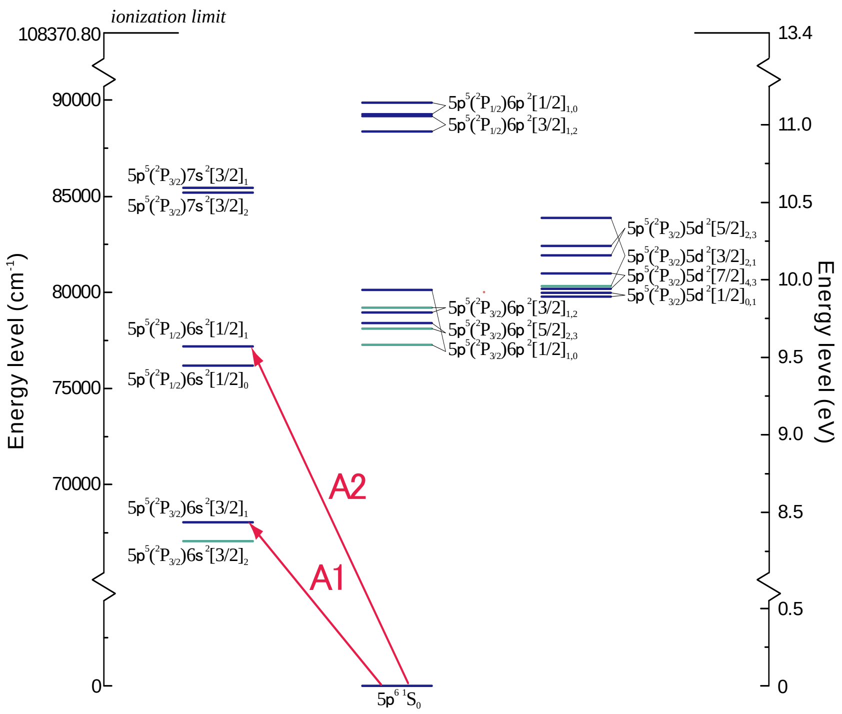


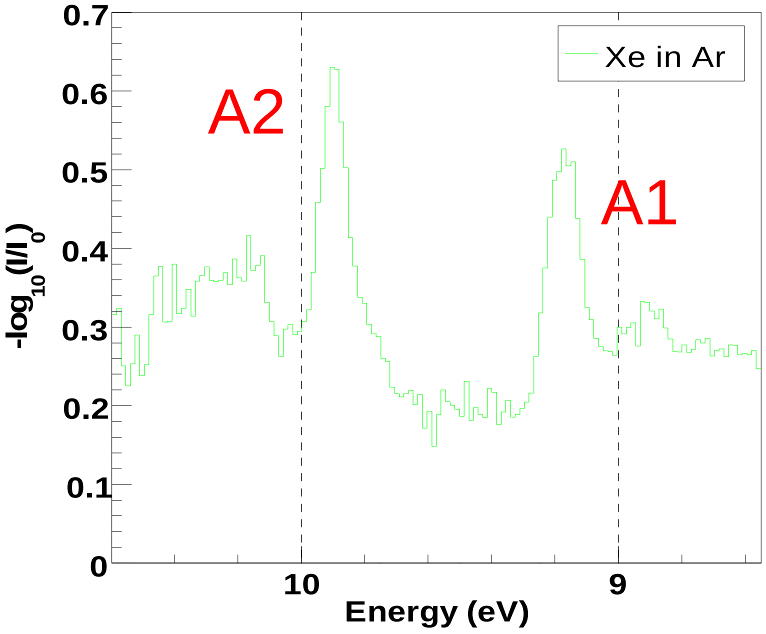
UV lamp
Gratings
Chamber
PMT
UV light
MODEL VUV-1C
VACUUM ULTRAVIOLET SPECTROPHOTOMETER

Xe in Ar Matrix absorption spectrum

- Prepared Xe in Ar matrxi.
- Irradiated monochromatic UV light and observed absorption.

Xe





Xe in p-H_2 matrix

- Why para-H2?
  - Quantum solid
    - Large zero point vibration
    - Large lattice constant
      - Spacing a=3.8 A.
  - Nuclear spin=0
    - Spherical wave functions
    - Less interactive with others.

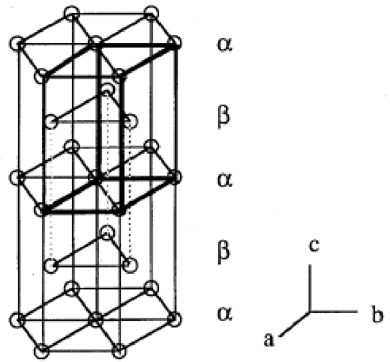
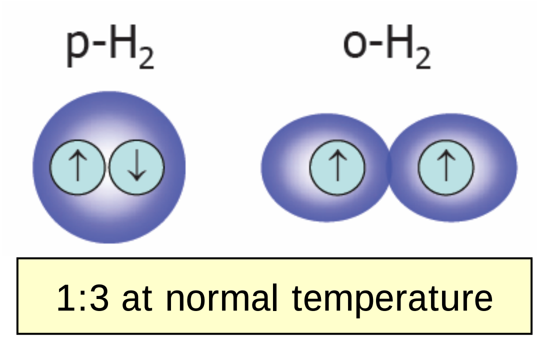
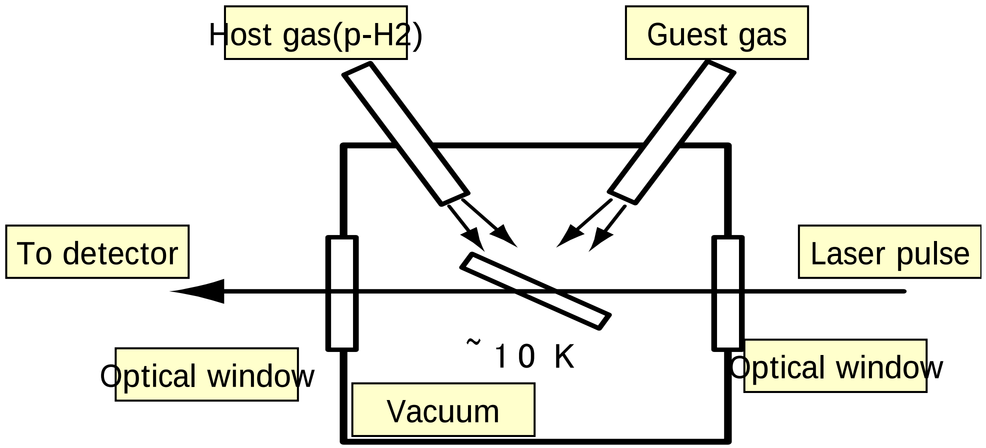
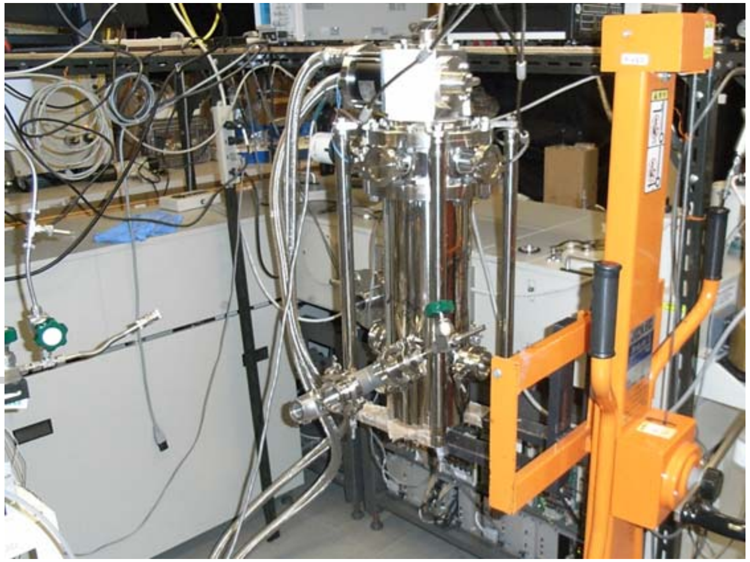


Fig. 1. Hexagonal close packed structure of solid hydrogen.

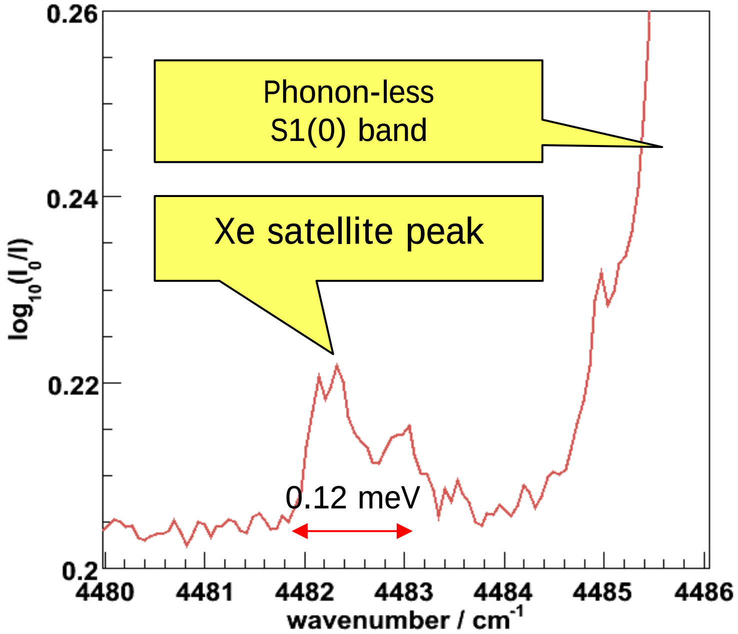


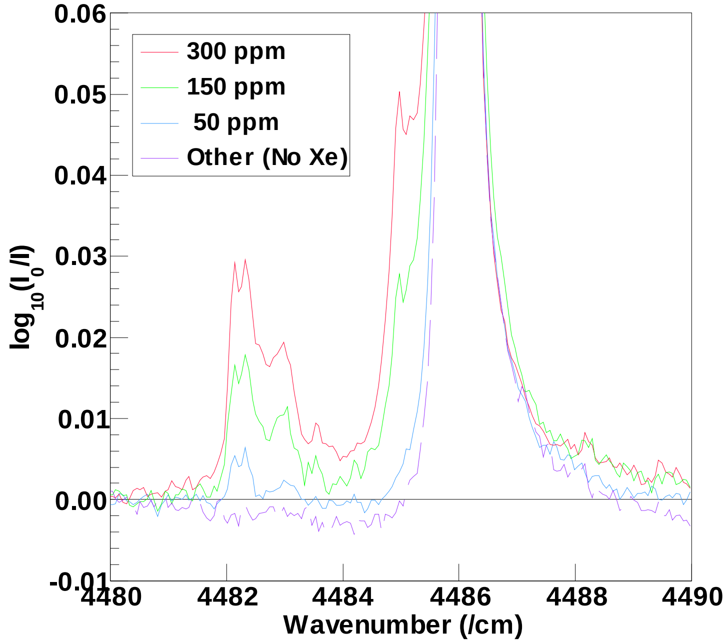


Xe in p-H_2 matrix



From the peak height
Xe density～10^{16}/cm^2





Xe in p-H_2 matrix (previous study)

P. L. Raston and D. T. Anderson, Journal of Molecular Spectroscopy 244, 138 (2007).

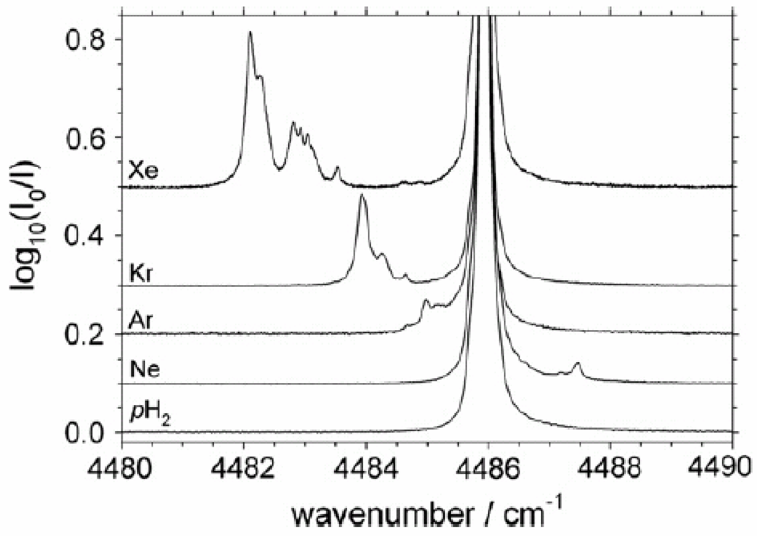


Fig. 2. Infrared absorption spectra in the 4480–4490 cm^{-1} region recorded at 2.0 K for as-deposited samples. Trace (pH$_2$) is for a 2.8(1) mm thick neat pH$_2$ solid containing 100 ppm of oH$_2$. The other spectra are Rg atom doped samples with thicknesses and Rg atom concentrations as follows (Ne) 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.

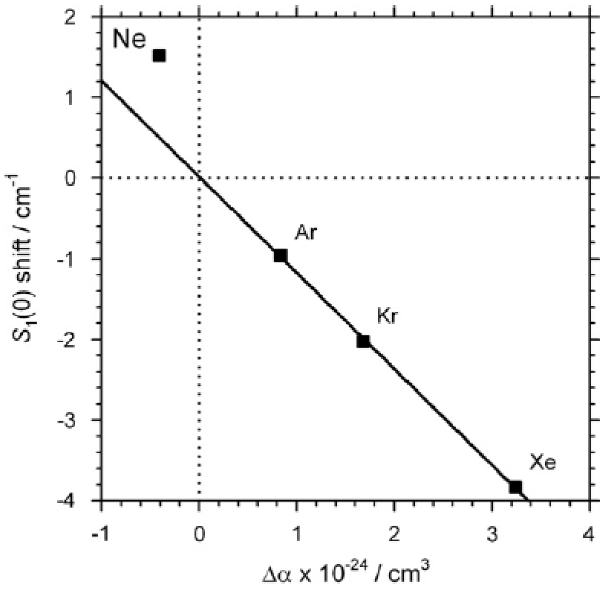
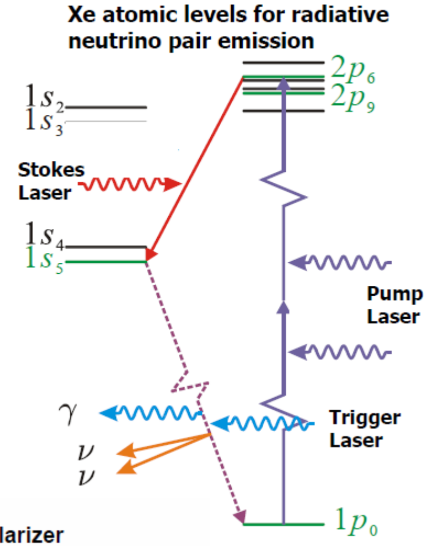
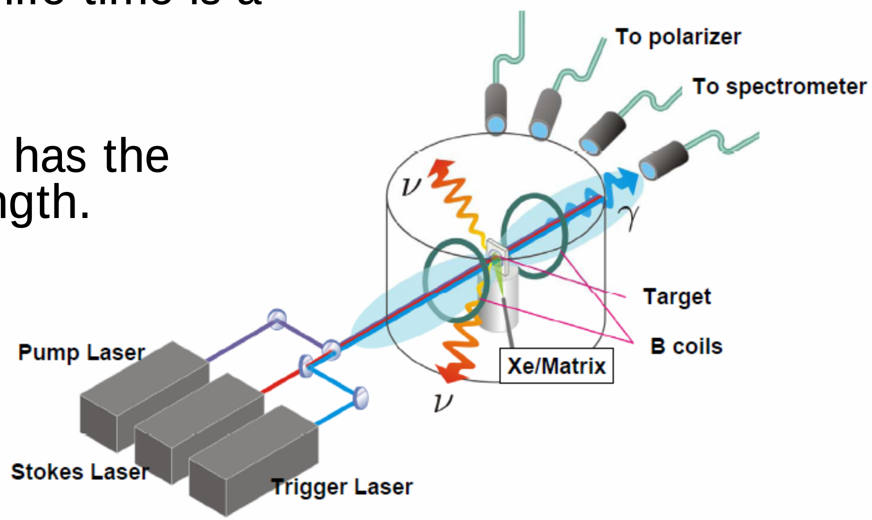


Fig. 3. The wavenumber shift of the Rg $S_1(0)$ satellite line from the unperturbed value as a function of the difference in polarizability between the Rg atom and pH$_2$.

Setup for radiative neutrino pair emission

- Rate
  - 10^{-4}/sec for 100cc p-H2 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
  - Preliminary experiments in progress
    - Super-radiance from Rb cascades
    - Xe in matrix
- Future prospects
  - Observe super-radiance from matrix
  - Observe two-photon super-radiance
    - Proof-of-principle experiment for macro-coherent amplification
  - Observe atomic neutrino
    - Majorana/Dirac mass spectroscopy