原子を利用したニュートリノ質量分光実験

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岡山大学　極限量子研究コア

Outline

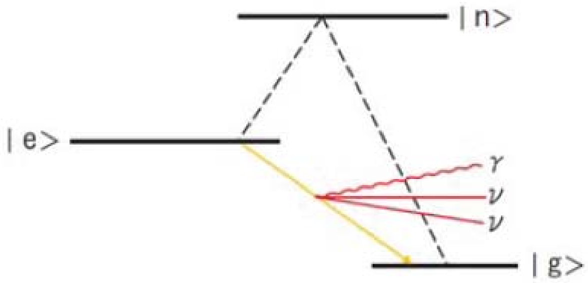
- Neutrino spectroscopy with atoms
  - Principle
  - Observable quantities
- Macro coherent amplification
  - Super radiance
  - Macro coherence
- Prospects
- Summary

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"

Principle of experiment

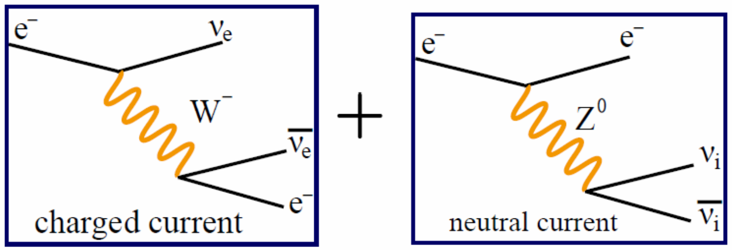


- Prepare excited atoms
- Observe photon spectrum of de-excitation via one photon plus neutrino pair
- Assume for a moment
  - Rate is big enough!
  - Momentum as well as energy conservation among emitted particles
- Photon spectrum and circular polarization contain information on:
  - Mass and mixing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

Will be explained later!!

|e> → |g> + γ + ν ν

|e> → |g> + γ + γ



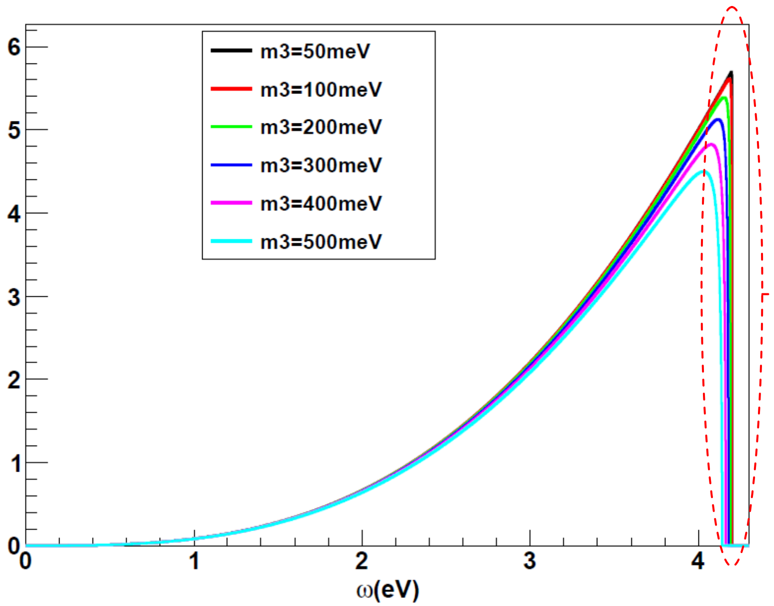
$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}}\bar{\nu}^e\gamma_\alpha(1-\gamma_5)\nu^e\bar{e}\gamma^\alpha(1-\gamma_5)e - \frac{G_F}{2\sqrt{2}}\sum_i \bar{\nu}^i\gamma_\alpha(1-\gamma_5)\nu^i\bar{e}(\gamma^\alpha(1-4\sin^2\theta_W-\gamma_5))e$$

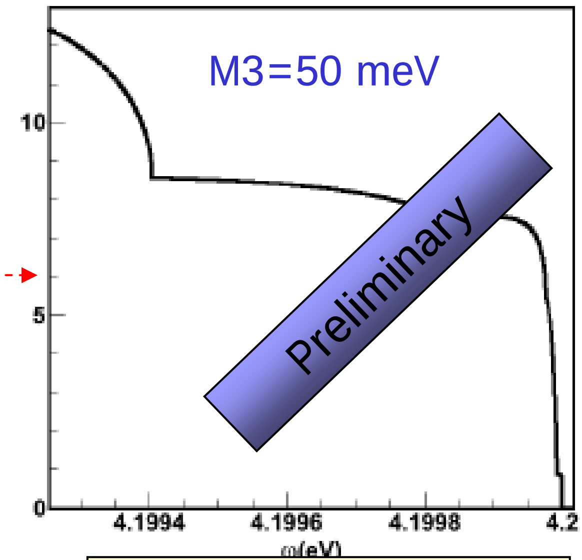
where $\nu_e = \sum_i U_{ei}\nu_i$ $\quad U_{\alpha i} =$ **MNS matrix elements**

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

Absolute mass

- Photon spectrum
  - Similar to μ-> eνν
  - Thresholds (there are 6) are determined by masses.





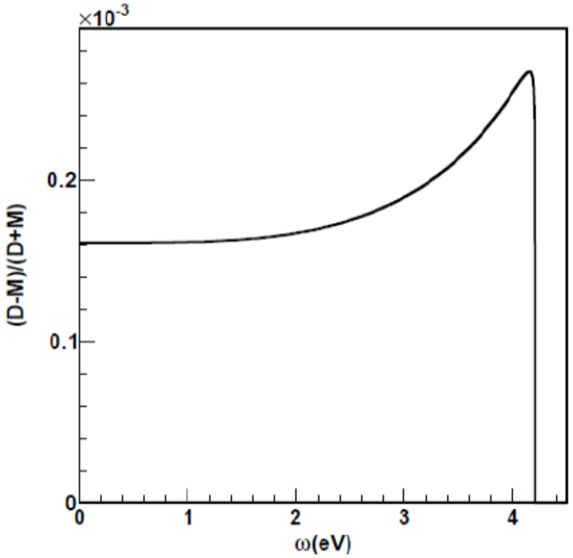
Threshold behavior

Majorana vs Dirac

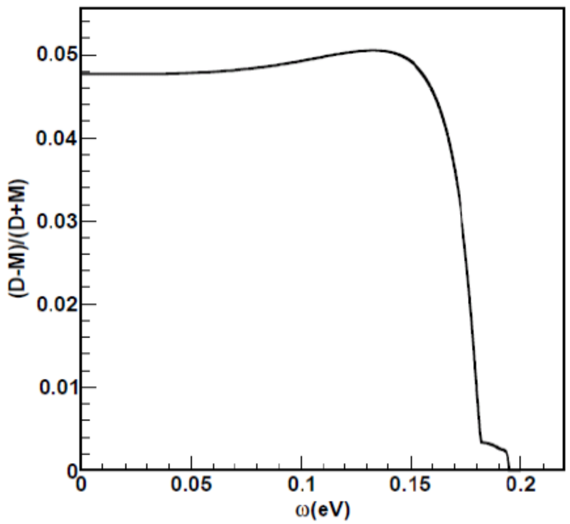
Identical particle effects

- Its size is proportional to m/E.
  - Go to low energy region.

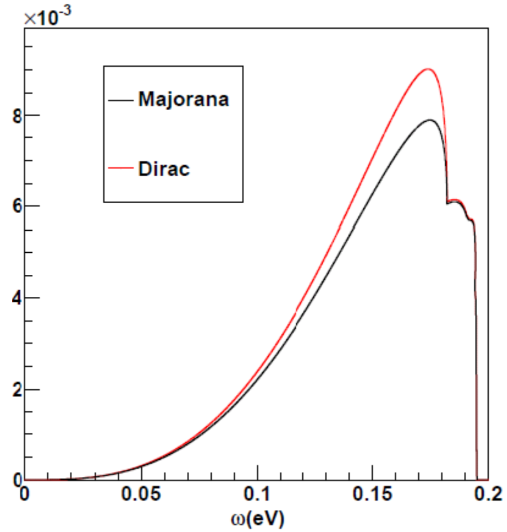
$$\sum_{h_1h_2} |j_M\cdot j^e|^2 = \sum_{h_1h_2}|j_D\cdot j^e|^2 + \delta_{ij}\frac{m_i m_j}{2E_1E_2}\left(j_0^e (j_0^e)^\dagger - \vec{j}^e\cdot(\vec{j}^e)^\dagger\right)$$



Xe

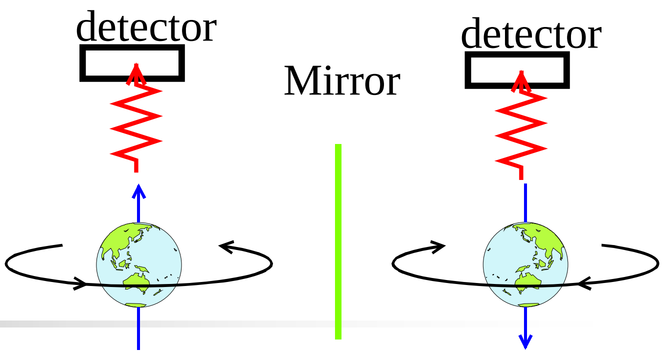


Si-Fe

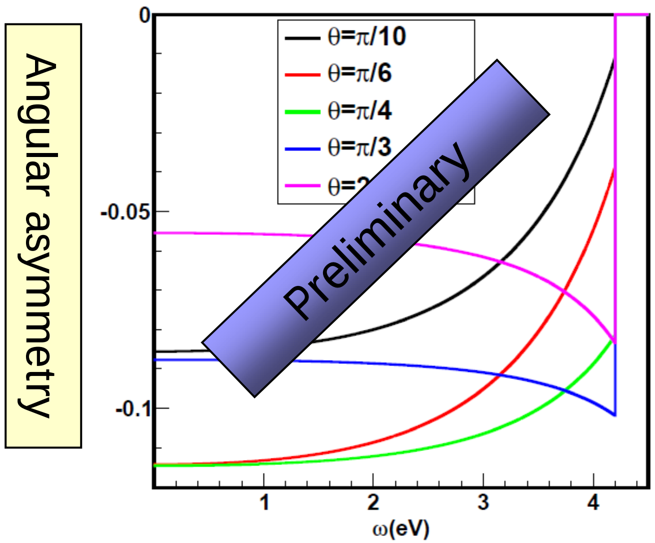


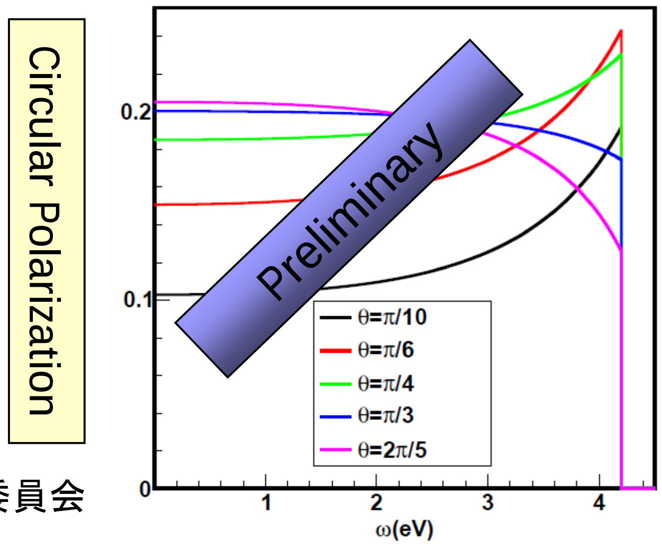
Si-Fe

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





Physics Observables (Summary)

- Physics observables are very rich!
  - The masses are determined by 6 thresholds in the spectrum.
  - 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 lightest neutrinos are in a few meV mass region.
- Desperately need an idea to reach theses rich physics!

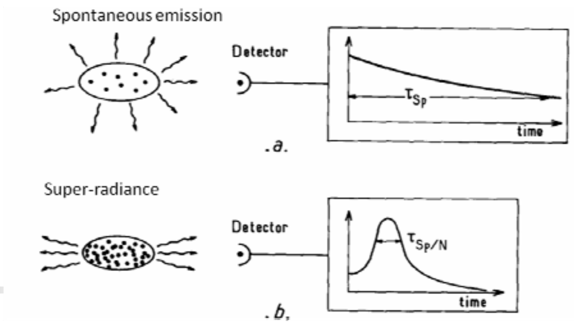
Amplification method

Disadvantage of the atomic method

$$\frac{G_F^2 \Delta^5}{15\pi^3} \approx 3.3\times10^{-34} \left(\frac{\Delta}{\mathrm{eV}}\right)^5 \mathrm{sec}^{-1}$$

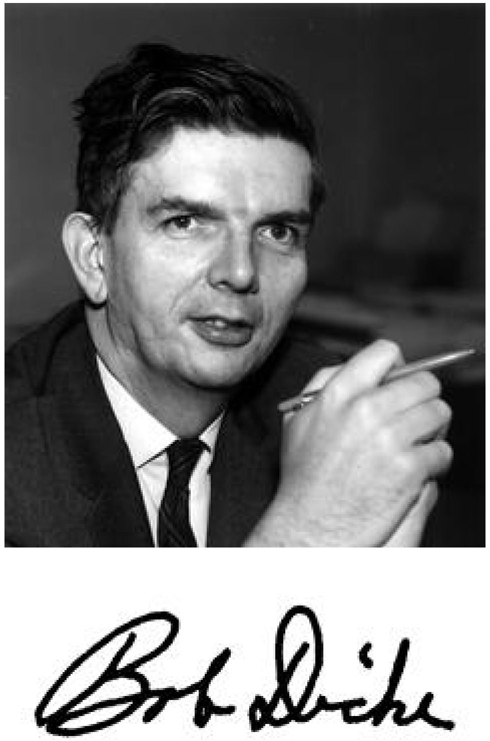
- Weak rate (extremely!)
  - Scale with Q^5
- Need some mechanism to enhance rates!
  - macro-coherent amplification

$N_0 exp(-t/\tau)$



Super radiance

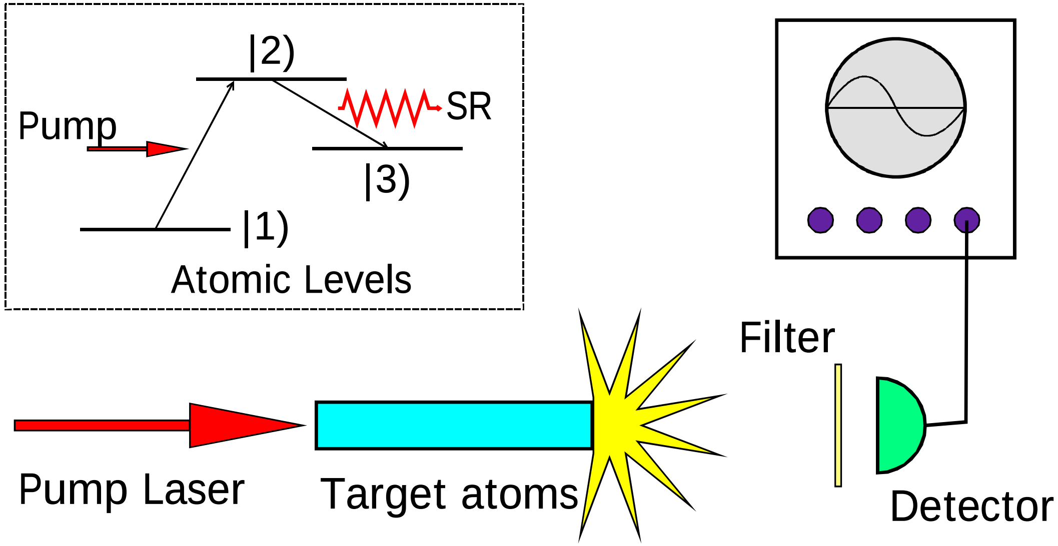
- Theoretical prediction
  - R.H.Dicke (PR93,99(1954))
- Characteristic features
  - Radiation intensity
    - **Proportional to N^2 (N being # of excited atoms)**
    - If spontaneous emission, prop to N.
  - Development of quantum coherent states
  - Non-linear phenomena different from stimulated emission.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



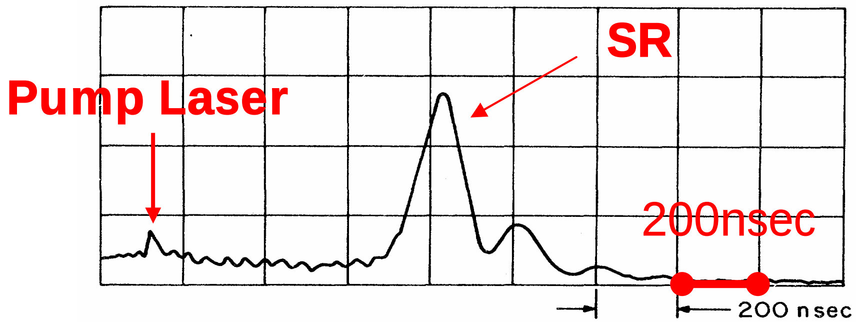
1916 —1997

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）

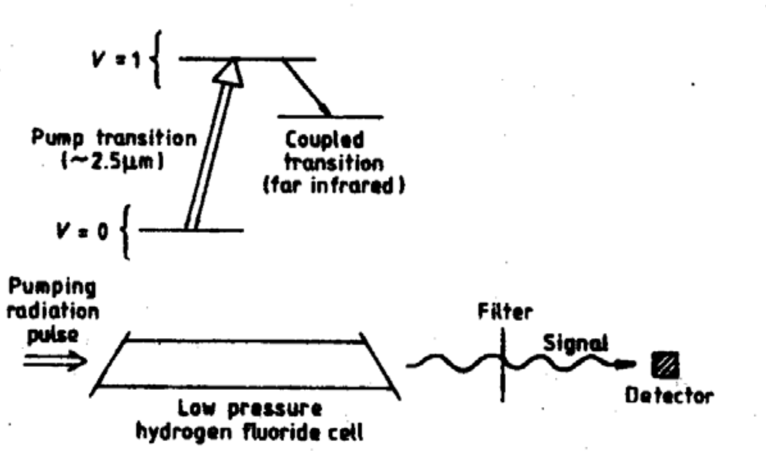


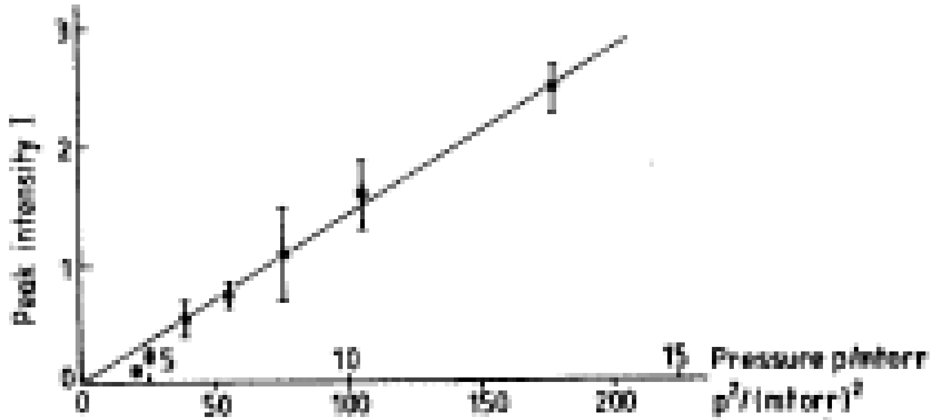
(PRL30(1973)309)



Super radiance experimental features —Intensity—

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





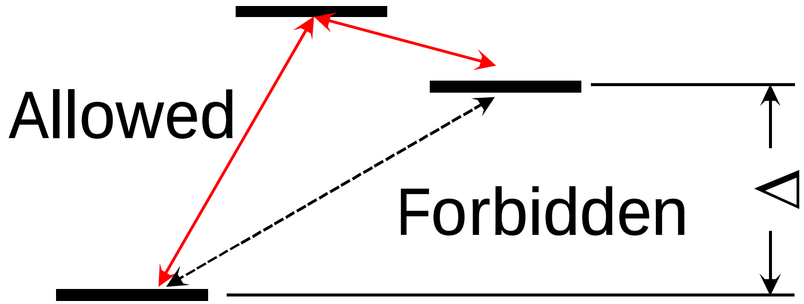
Macro-coherence: a way to overcome limitation in super-radiance

Coherence region of super-radiance is limited to a volume characterized by a wavelength.

$V_c = \lambda^2 L$

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

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

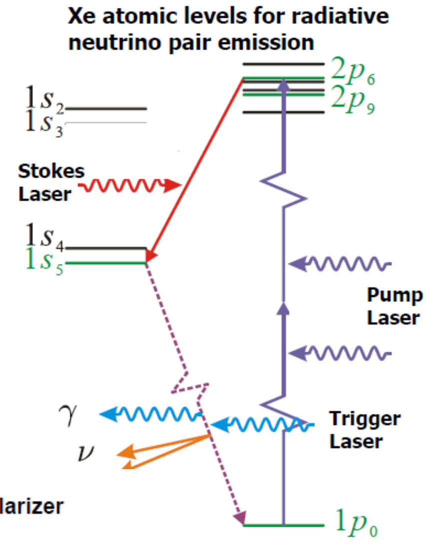
$$\left| \sum_{j=1}^{N} \exp\left\{ i\left(\vec{k}_1 + \vec{k}_2\right) . \vec{r}_j \right\} \right|^2 \Rightarrow N^2 \text{ if } \vec{k}_1 + \vec{k}_2 = 0$$

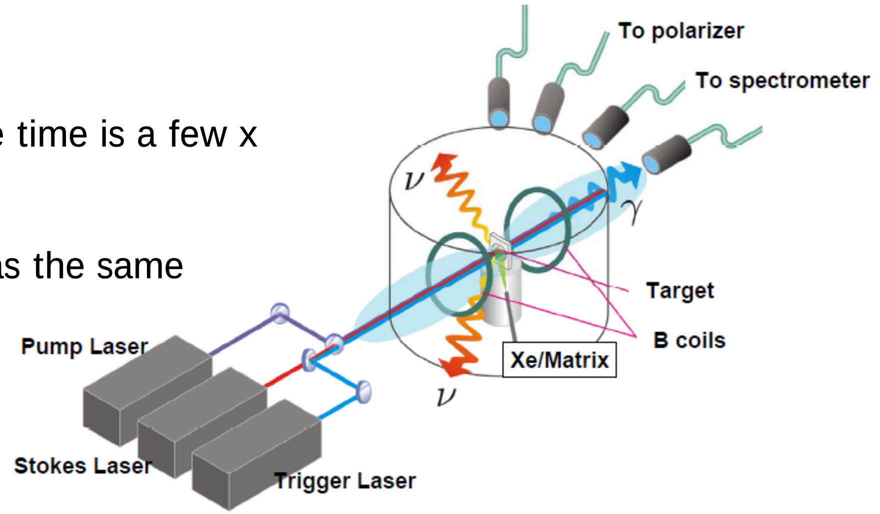
  - Two photon emission may be enhanced to N^2
- Characteristic features
  - Energy and angle
    - Peak at Δ/2
    - Back-to-back
- Proof of principle experiment
  - No observation in the past !

M. Yoshimura et.al.; arXiv:0805.1970

Radiative neutrino pair emission

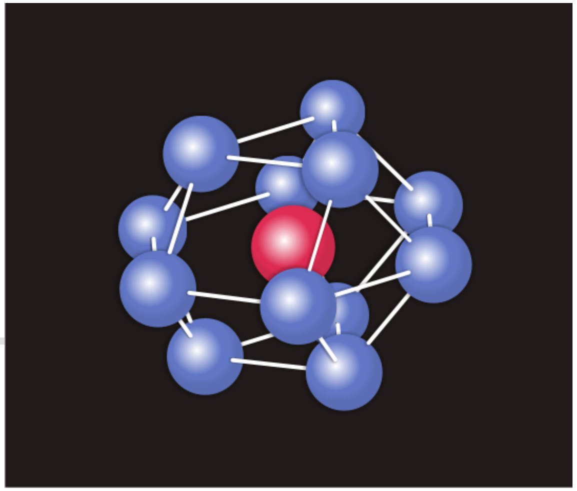
- Macro-coherence requires photon and neutrino pairs to conserve momentum.
- Rate
  - 10^{-4}/sec for 100cc p-H2 with Xe fraction of 10^{-3}
- Background control
  - Long life
    - The 1s5 level life time is a few x 10 sec.
  - Trigger
    - Signal photon has the same wavelength.
  - Parity violation





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



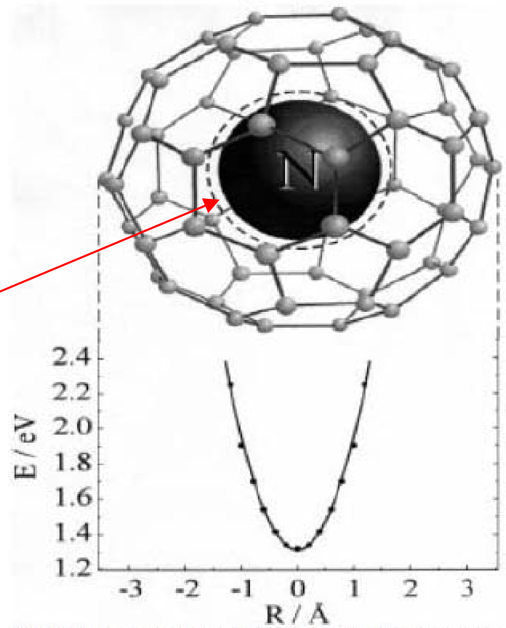


Fig. 6. Schematic view of nitrogen inside C_{60}. The size of the sphere corresponds to the van der Waals radius of nitrogen [12]. The dashed line marks the border of the inner cavity of the C_{60} shell if van der Waals radii are assumed for the carbon atoms [12]. In the lower part of the figure the 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

Prospects and Summary

- Strategy-Present and Future-
- Research group structure
- Summary

Strategy

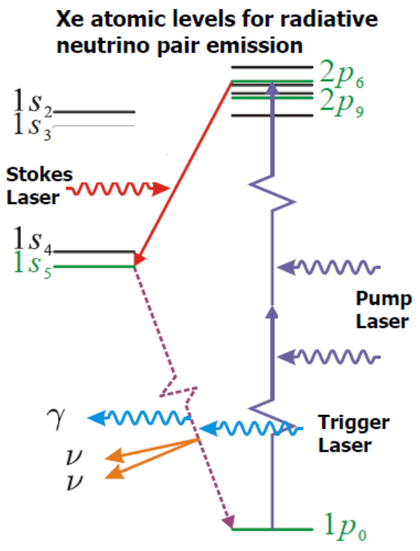
- Observe SR → OK
- Make matrix/Xe in matrix → OK
- Make coherent matrix
- Observe SR from matrix
- Observe two-photon Macro-coherence in gas target
- Observe two-photon Macro-coherence in solid target
- Observe neutrino emission in solid target
- Neutrino mass spectroscopy

Word's first observation

Proof of new principle

2009-2011

2011-2013



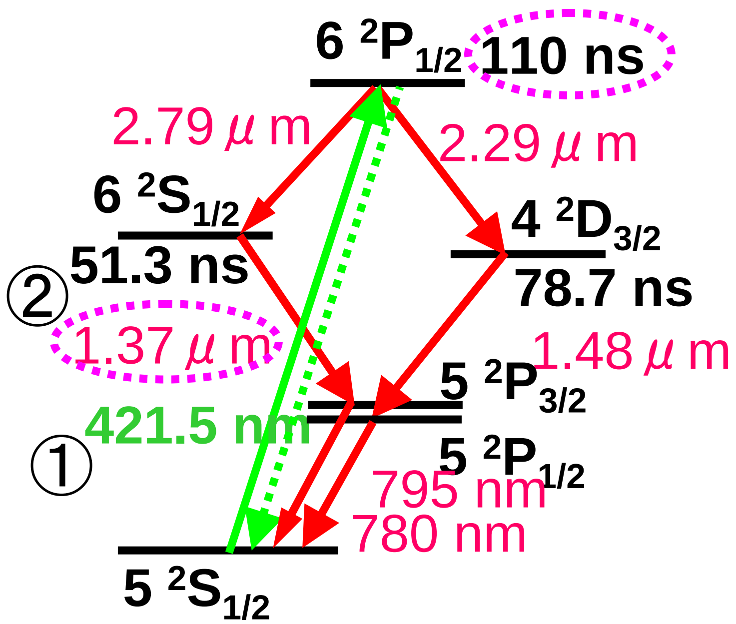
Experimental Status

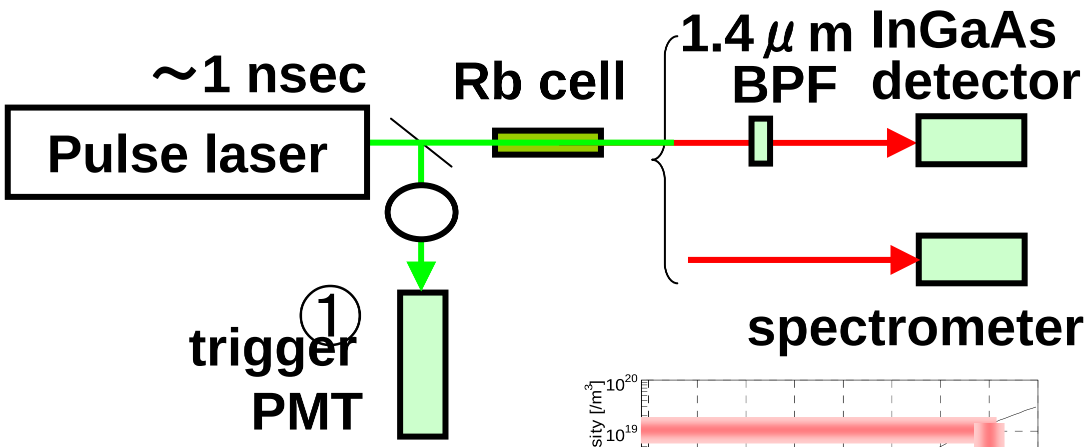
- Cascade super-radiance from Rb
- Xe in p-H2/Ar
  - Note that Xe is one of the candidate atoms for radiative neutrino pair emission

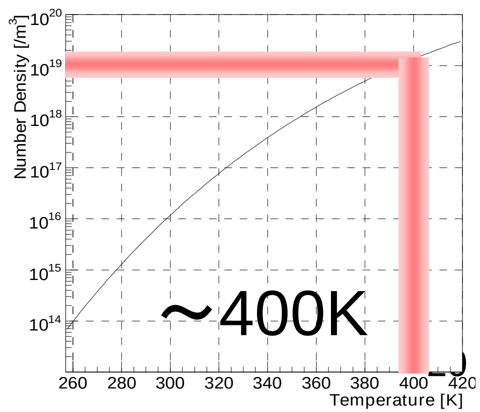
Cascade super radiance from Rb

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

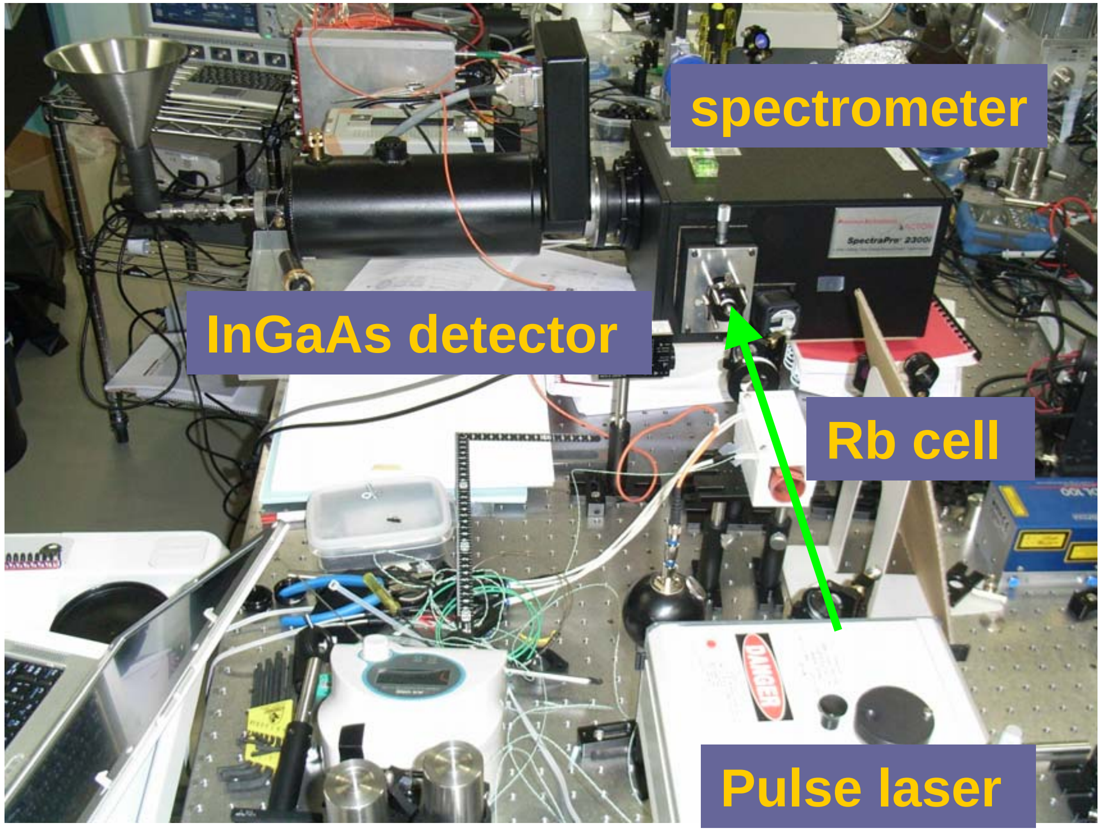
- **Level Diagrams**

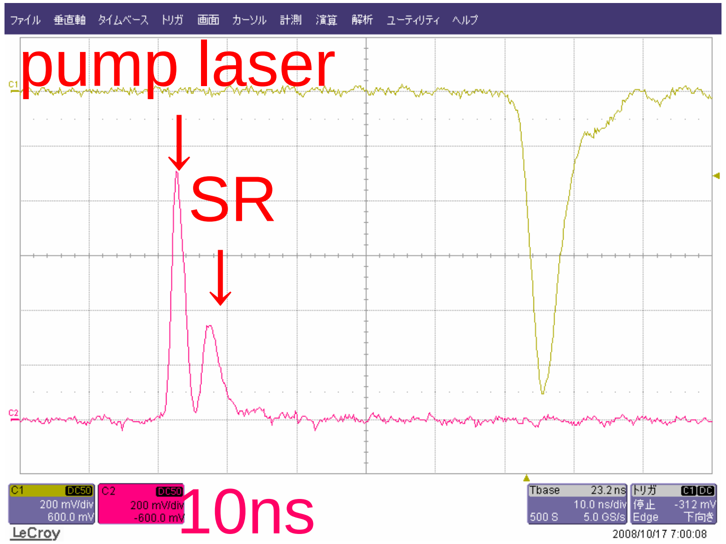






Setup and results

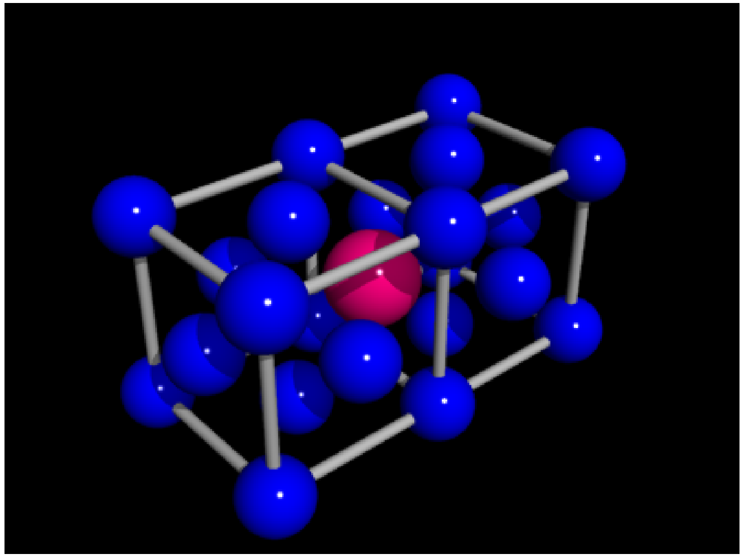


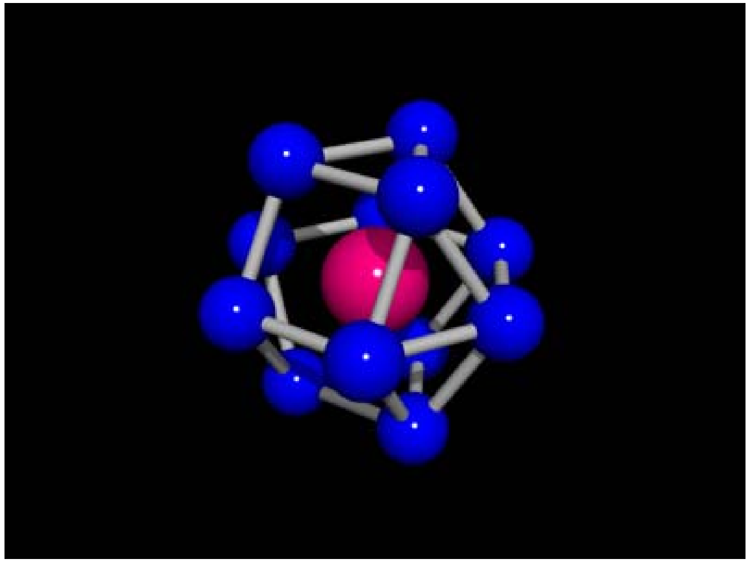


- (top) Pump laser light and SR signal are seen. (Note; life time is 110+51 nsec)

Matrix preparation

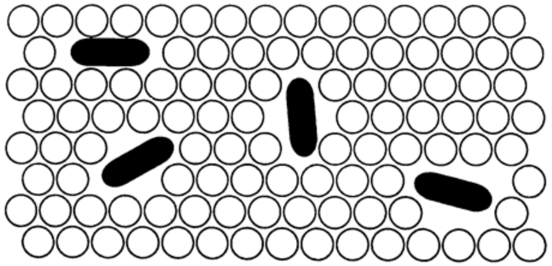
- Xe in Ar
  - With Prof. Wakabayashi （Kinki Univ.）
- Xe in para-H_2
  - With Prof. Momose （UBC）





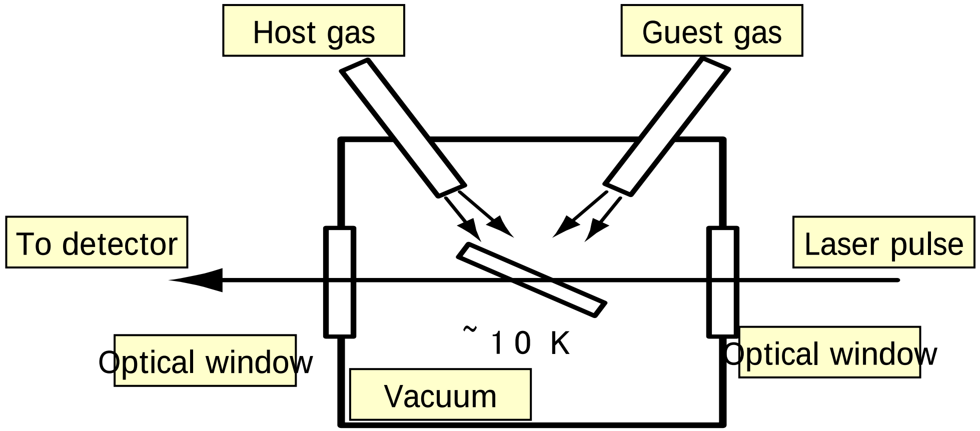
What is matrix？

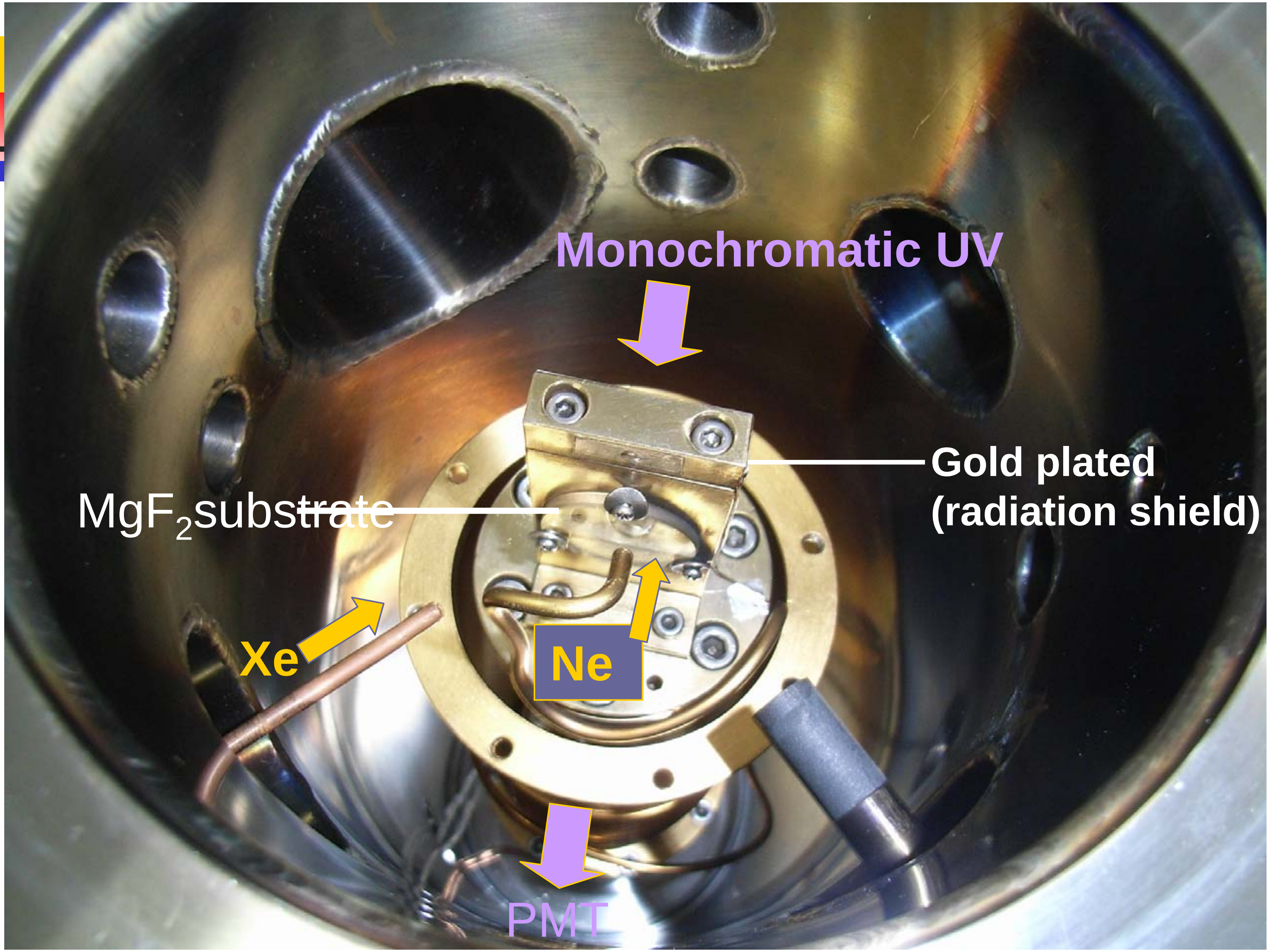
- Matrix is a host material made by molecular crystals of rare gas or p-H2, aiming to confine guest atoms or molecules
  - Interaction with host material is weak.
  - Can suppress rotation.



IAN R. DUNKIN
Matrix-Isolation Techniques

High resolution spectroscopy in chemistry.





Monochromatic UV
Gold plated
(radiation shield)
MgF2substrate
Xe
Ne
PMT

Xe in p-H_2 matrix

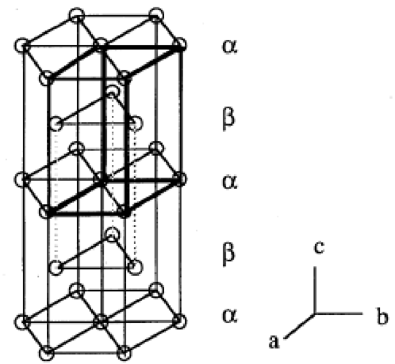
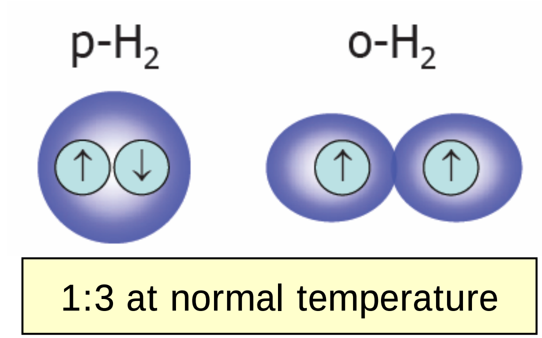
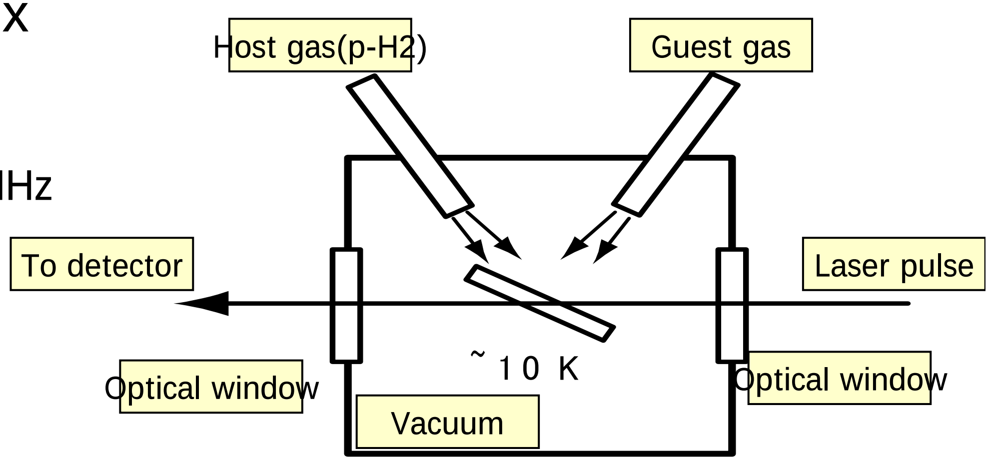


Fig. 1. Hexagonal close packed structure of solid hydrogen.

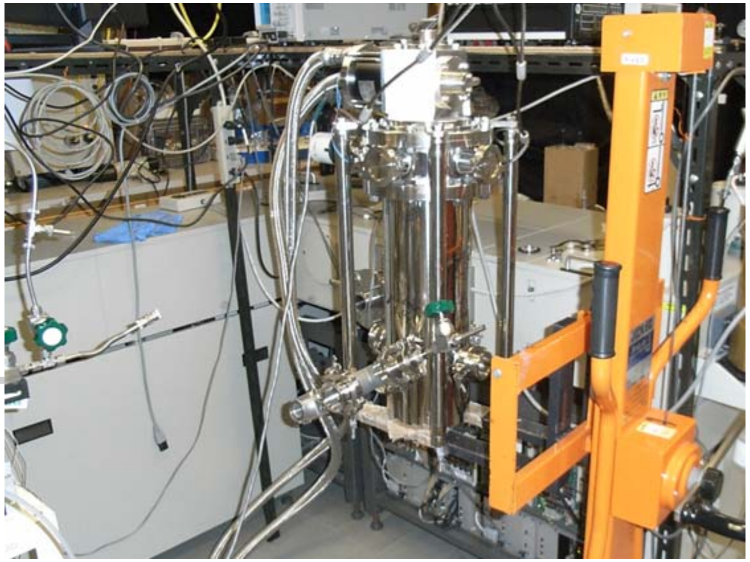
- Why para-H2?
  - Quantum solid
    - Large zero point vibration
    - Large lattice constant
      - Spacing a=3.8 A.
  - Nuclear spin=0
    - Spherical wave functions
    - Less interactive with others.



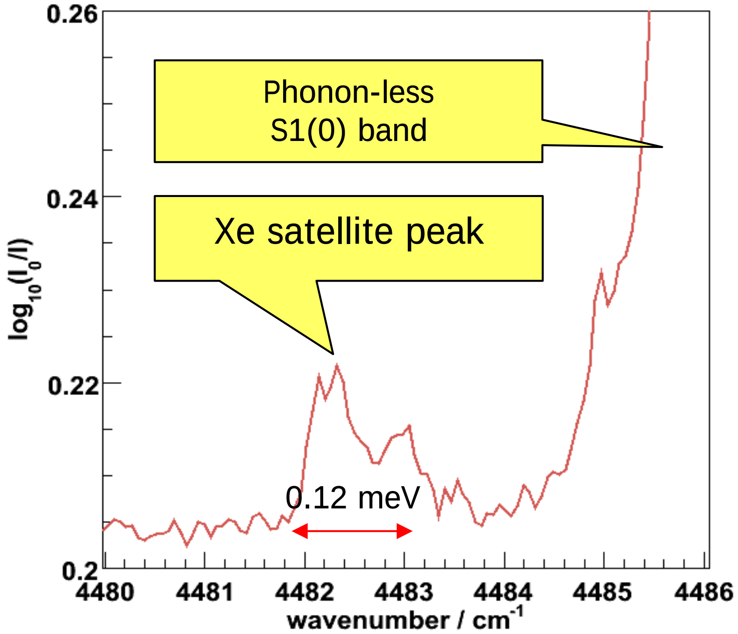
- Infrared spectroscopy using matrix
  - Revival in 1989 by Oka.
  - Examples;
    - $J=6 \leftarrow 0$ transition line width 90MHz (hwhm)
    - Deuterated hydrogen's rotation-vibration width is smaller than Doppler width by x10. (2 MHz!)

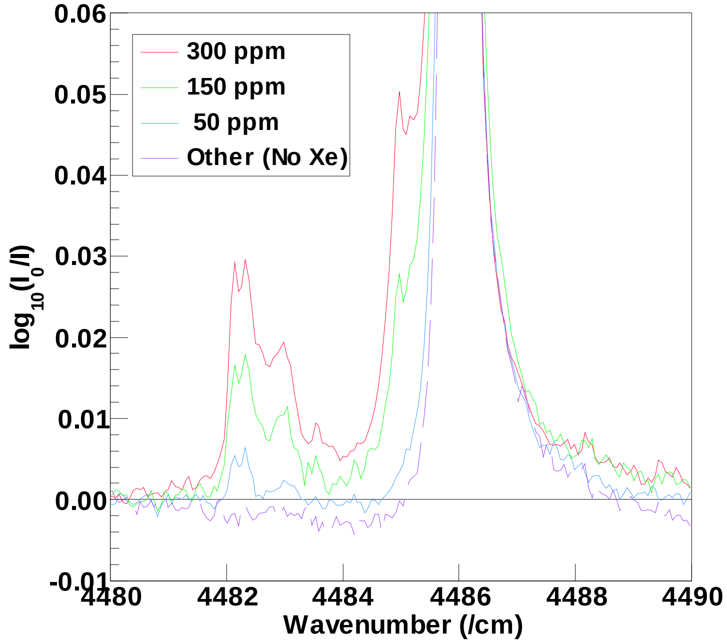


Xe in p-H_2 matrix



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).

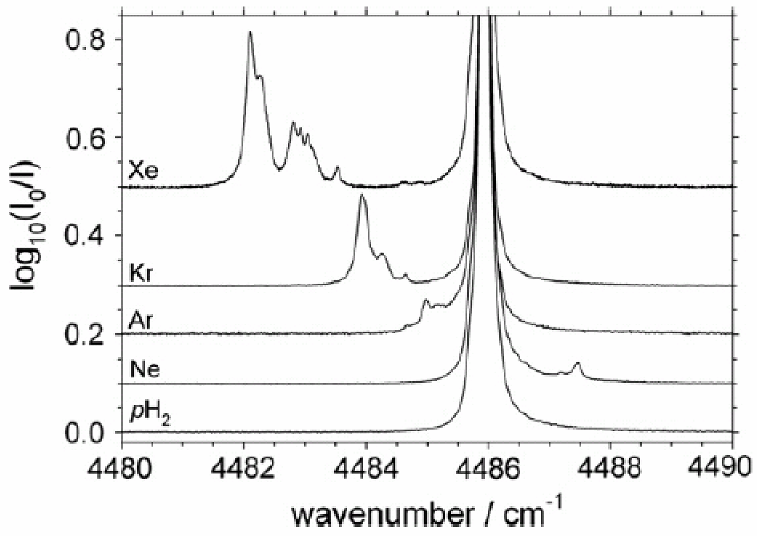


Fig. 2. Infrared absorption spectra in the 4480–4490 cm^{-1} region recorded at 2.0 K for as-deposited samples. Trace (pH_2) is for a 2.8(1) mm thick neat pH_2 solid containing 100 ppm of oH_2. The other spectra are Rg atom doped samples with thicknesses and Rg atom concentrations as follows (Ne) 2.8(1) 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.

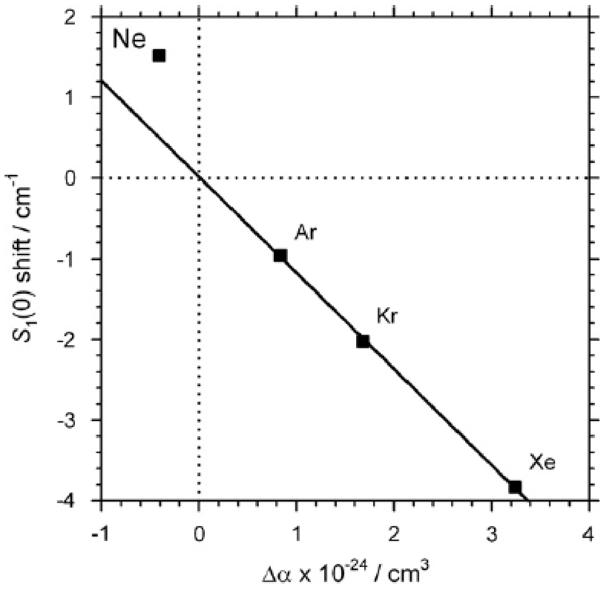


Fig. 3. The wavenumber shift of the Rg $S_1(0)$ satellite line from the unperturbed value as a function of the difference in polarizability between the Rg atom and pH_2.

Research group

現在
人事公募中

(A01)　マクロコヒーラント増幅機構を用いたニュートリノ対生成の検出

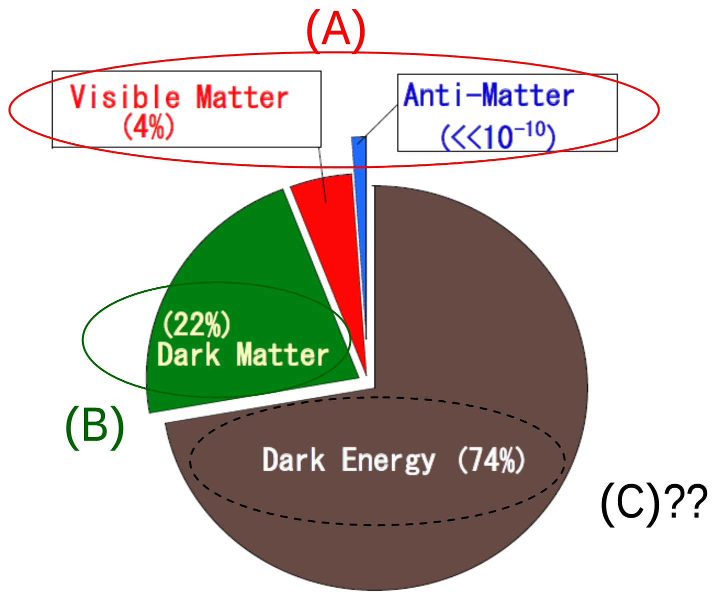
(A02)　ナノ空間貯蔵標的の量子干渉性研究

(A01)	(A02)
SPAN-group 笹尾（岡山）、吉村（岡山）、中野（岡山） 福見（岡山）、南條（京都）、中嶋（岡山） 谷垣（東北） (注）	川口（岡山）、唐（岡山）、中嶋（岡山）、 百瀬（UBC）、加藤（東京理）、 宮本（環境研）、若林（近畿大） 久保園(岡山)
現在進行中の課題・実験 1)　Rb cascade super-radiance Doctor student (S) 2)　Ba Raman super-radiance Doctor student (O)	現在進行中の課題・実験 1) CH4 in matrix (Master student O) 2) Xe in p-H2 matrix (Master student U） 3) Xe in Ar(Ne) matrix (same as above) 4) N@C60 e-excitation (Master student Y)

(注）　オーバーラップしている「連携研究者」（科研費）は除く。

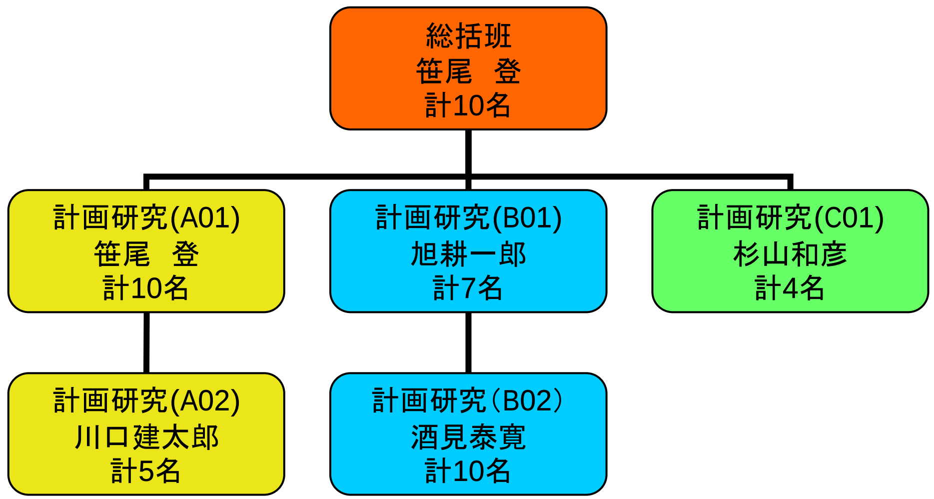
新学術領域「原子が切り拓く極限量子の世界」
—素粒子的宇宙像の確立を目指して—

目的:宇宙史に残された最大の謎3つに焦点を絞り、素粒子的立場から解明する

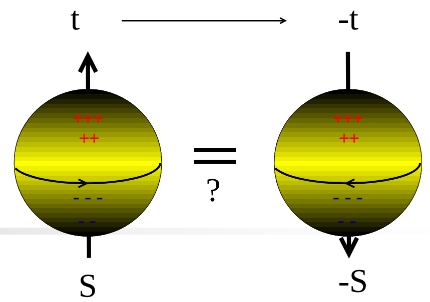


宇宙の組成

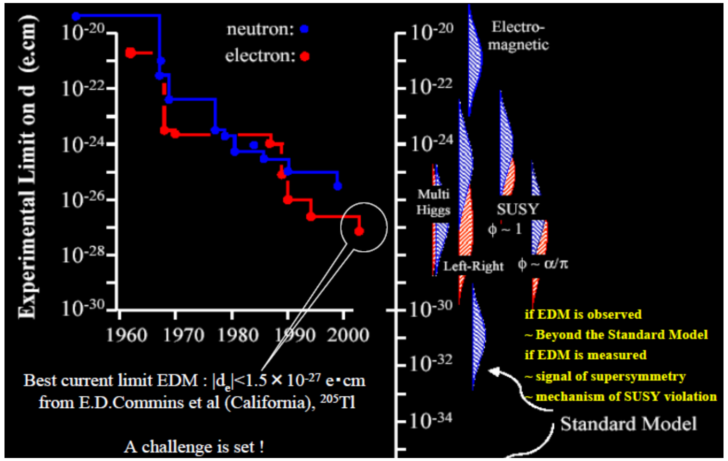
研究体制:6研究班、岡山大学、九州大学、近畿大学、大阪大学、立命館、大阪電通、京都大学、東京工業大学、理化学研究所、東京大学、東京理科大学、東北大学など総計延46名

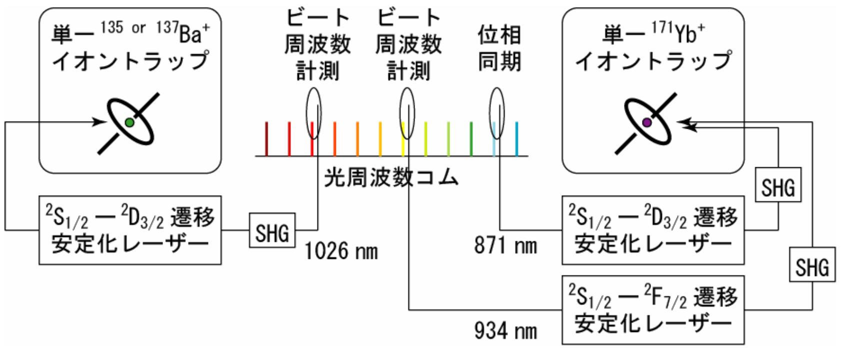


領域の具体的目標
（平成21年度―25年度）



- 計画研究（A）
  - 日本発の新原理、マクロコヒーランス増幅機構を実験的に確立・解明。
  - 世界で初めて原子ニュートリノを観測。
  - 量子干渉性に優れたナノ空間貯蔵原子(分子)を実現
    - 境界分野の開拓・工業的実用化
- 計画研究（B）
  - 世界最高感度で永久電気双極子の測定を実施
    - Xe についてはd(Xe)<4x10^{-30}ecm
    - Frについてはd(e)< 2x10^{-29}ecm実験着手。
- 計画研究（C）
  - 世界最高感度で微細構造定数時間変化を測定
    - $\dot{\alpha}/\alpha < 10^{-17}$ (/yrs)





Summary

- New method of neutrino mass spectroscopy
  - Use of atomic levels
  - Use of a new mechanism;
    - Macro-coherent amplification
  - Project partially supported by Grant-in-Aid for Scientific Research on Innovative Areas （新学術領域）
- Preliminary experiments in progress
    - Super-radiance from Rb cascades
    - Xe in matrix
- Future prospects (2009 → 2013)
  - Observe super-radiance from matrix
  - Observe two-photon super-radiance
    - Proof-of-principle experiment for macro-coherent amplification
  - Observe atomic neutrino