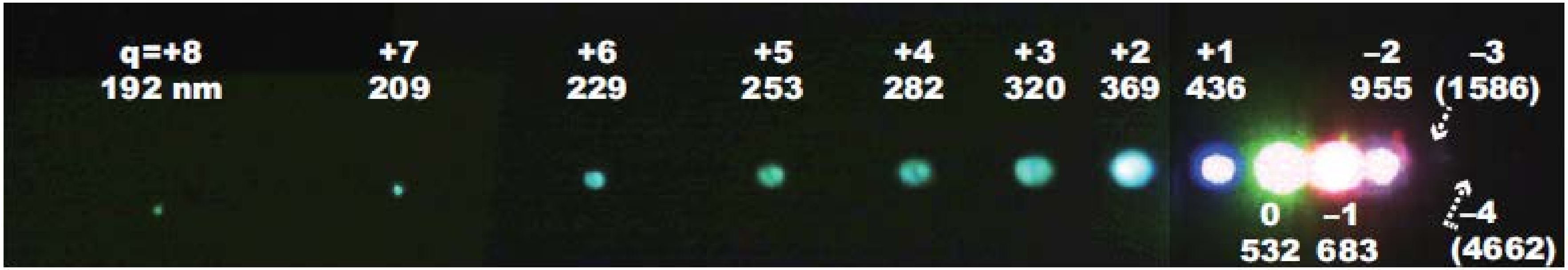
Neutrino Mass Spectroscopy with Atoms

N. Sasao, M. Yoshimura (Okayama U.)

Thank you very much for giving me an opportunity to talk about our project.



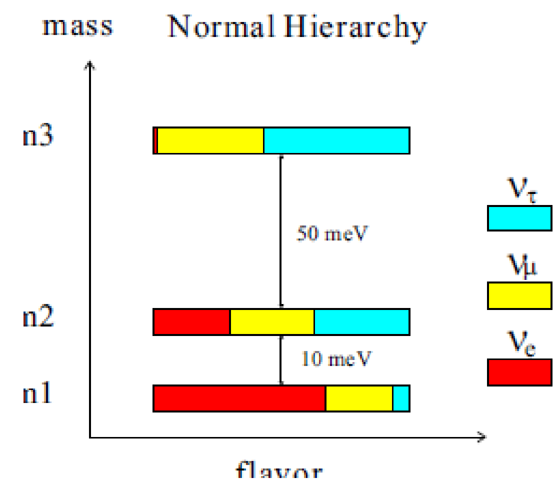
Contents

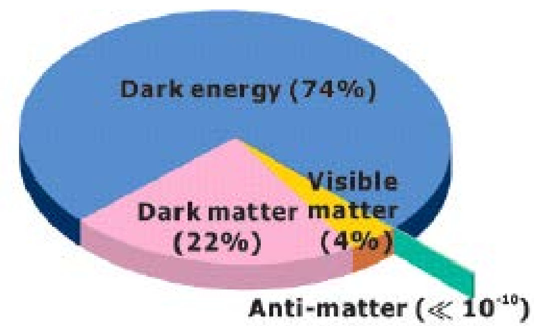
- Physics motivation
  - Open questions on neutrino physics
- RENP: radiative emission of neutrino pairs
  - Experimental principle and RENP rate/spectrum
  - Impact on neutrino physics
- Macro-coherent amplification
  - What is it?
  - How to prove it experimentally?
- PSR: paired super-radiance
  - Way to prove macro-coherence experimentally
- Summary and Future Prospect

吉村さんより

Physics motivation – unknown parameters of neutrino -

- What we know about neutrino:
  - Three flavors with mixing
  - Finite masses
- Questions to be answered:
  - Did neutrino play crucial role in making the matter dominated universe?
  - Why neutrinos are so light (<0.5 eV) compared with the other particles?
- Unknown neutrino parameters:
  - Absolute neutrino mass (Lightest mass=m0)
  - Nature of mass (Dirac or Majorana)
  - CP phases (δ,α,β)

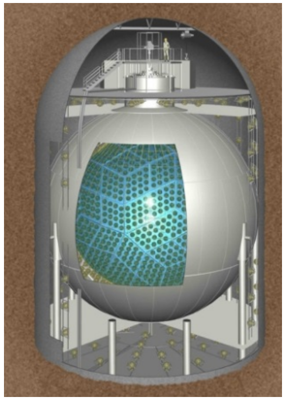




The current composition of the universe

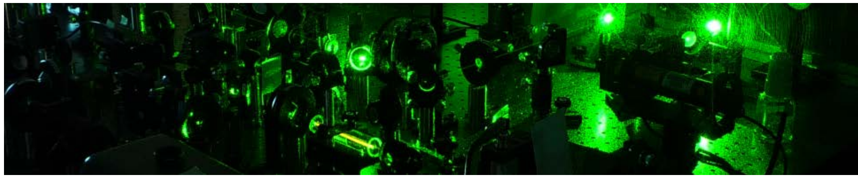
Types of experiments

- Traditional and popular approach.
  - Oscillation experiments
    - To determine mass pattern (NH/IH).
    - To measure CP phase (only delta)
  - Neutrino-less double beta decay
    - Sensitive to M-D distinction
    - Can measure effective neutrino mass



Big accelerators or detectors needed

- Our approach : neutrino spectroscopy with atoms
    - Sensitive to most of unknown parameters
    - Small laboratory experiment with lasers



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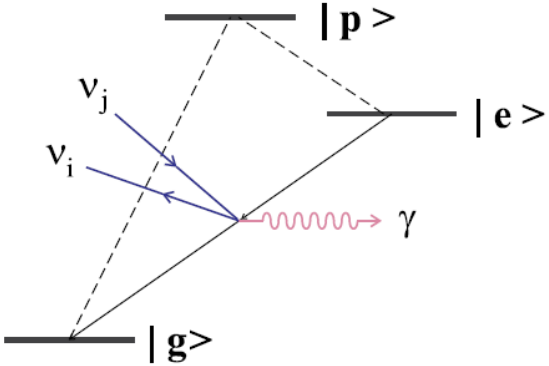
Experimental principle
-- Radiative emission of neutrino pairs --

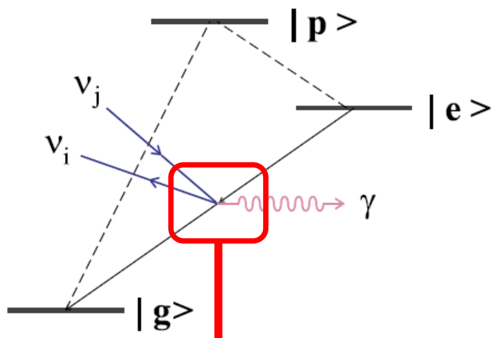
- RENP:
  - Radiative emission of neutrino pair from excited atoms decaying to the ground level.
  - Photon spectrum contains information on neutrino.



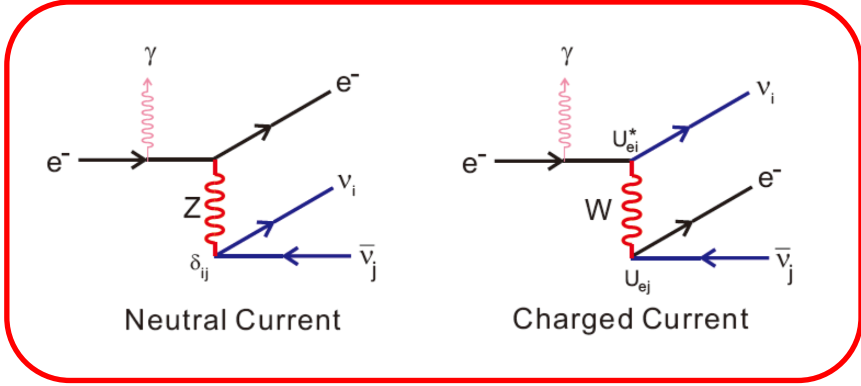
- Advantages/disadvantages using atoms
  - Photon spectrum is sensitive to
    - Absolute mass, NH/IH, Majorana-Dirac distinction, CP phases (α, $\beta-\delta$)
    - thanks to the atomic energy scales close to the expected neutrino mass.
  - Enhancement mechanism needed to overcome smallness of the rate.
    - Macro-coherent amplification

$$\Gamma \approx 1/10^{26} \text{ year for } E_{eg} = 1\,\text{eV}$$

A. Fukumi et.al : Prog. Theor. Exp. Phys. **2012**, 04D002



Expected RENP rate



- RENP rate calculation:
  - RENP process does exist, and its rate and spectrum can be calculated reliably by the Standard Model once ν parameters are given.
- RENP rate formula
  - $$\Gamma = \Gamma_0 \; I(\omega) \;\; \eta(t)$$

Activity factor representing the atomic coherence and strength of supporting fields

Photon spectra containing information on neutrino parameters

Overall rate factor containing the coupling constant, target density etc.

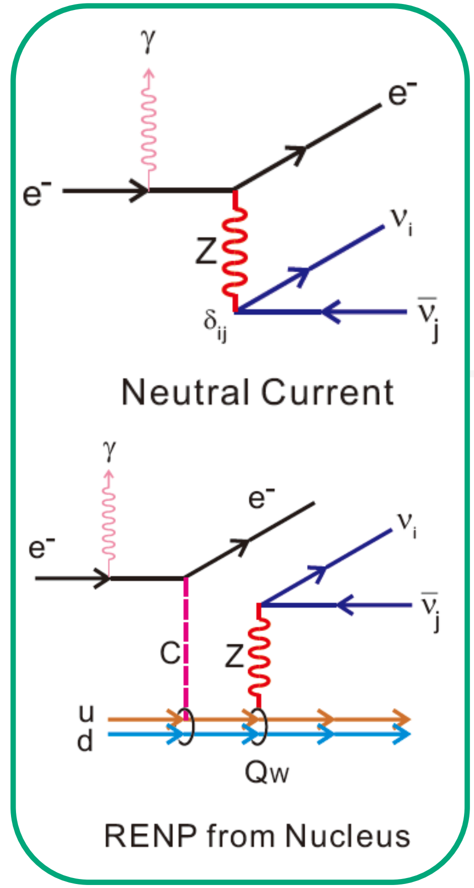
RENP from quarks (nucleus)

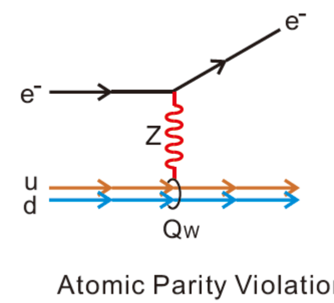
- Atomic Parity Violation:
  - Neutral boson Z interacts with nucleus as a whole (coherently)
  - Weak charge Qw

$$Qw = N - (1 - 4\sin^2\theta_w)Z$$

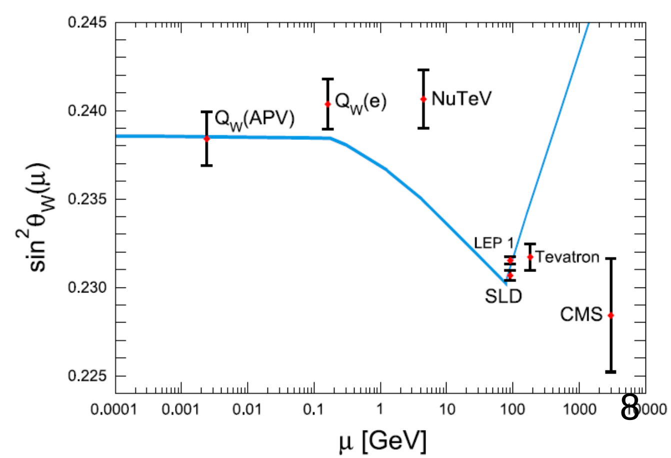
- RENP from nucleus
  - Rate enhancement larger than 10^6 is expected for heavy atoms.

M.Yoshimura and N.Sasao, arXiv:1310.6472v1 [hep-ph] 24 Oct 2013, PRD 89, 053013 (2014)



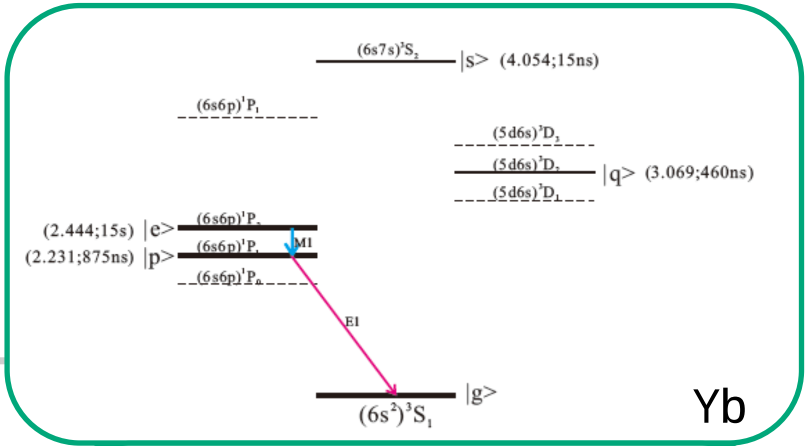


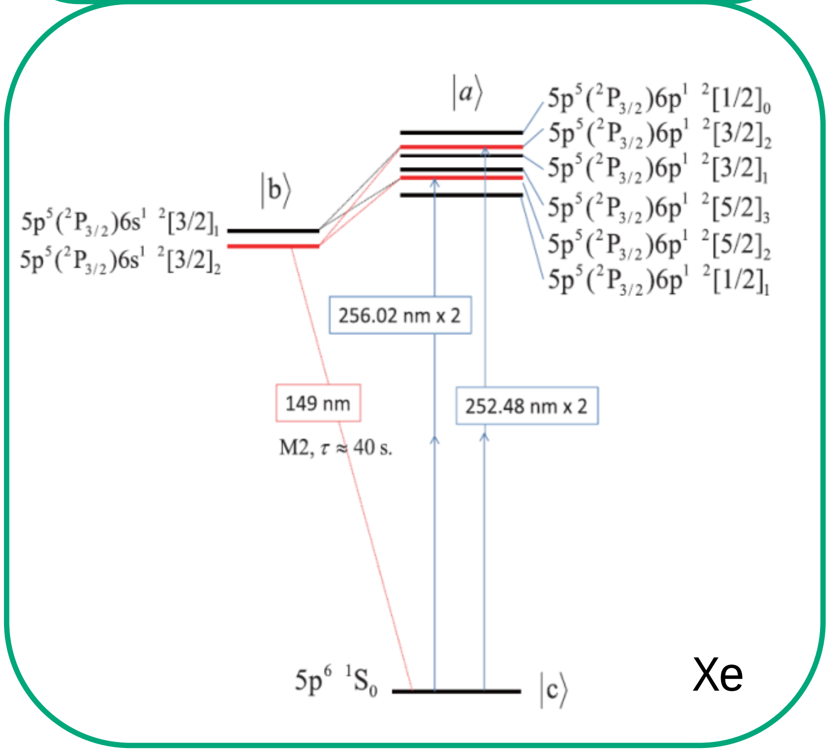
Qw ~ # of neutrons



Examples of RENP target and rate

- Examples of target atoms
  - Xe and Yb
- RENP rate
  - Γ=40 Hz for Xe $^3P_1$ (8.4365eV).
    n=7x 10^19 [cm-3],
    V=100 cm^3, η=10^-3
- Assuming Macro-coherence
  - N^2 amplification
  - Momentum conservation law holds among emitted particles





Absolute mass and mass pattern NH/IH

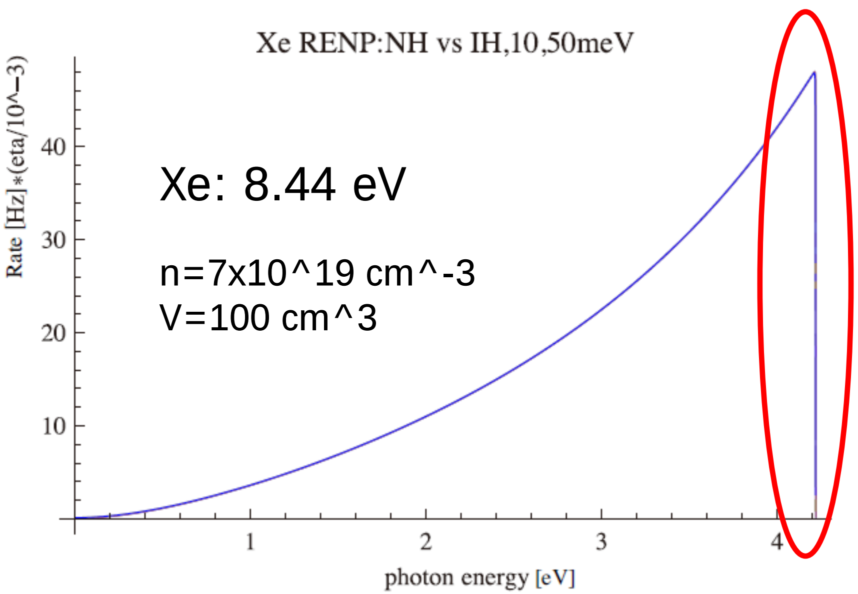
- RENP photon spectrum
  - Overall spectrum is similar to muon decay at rest.

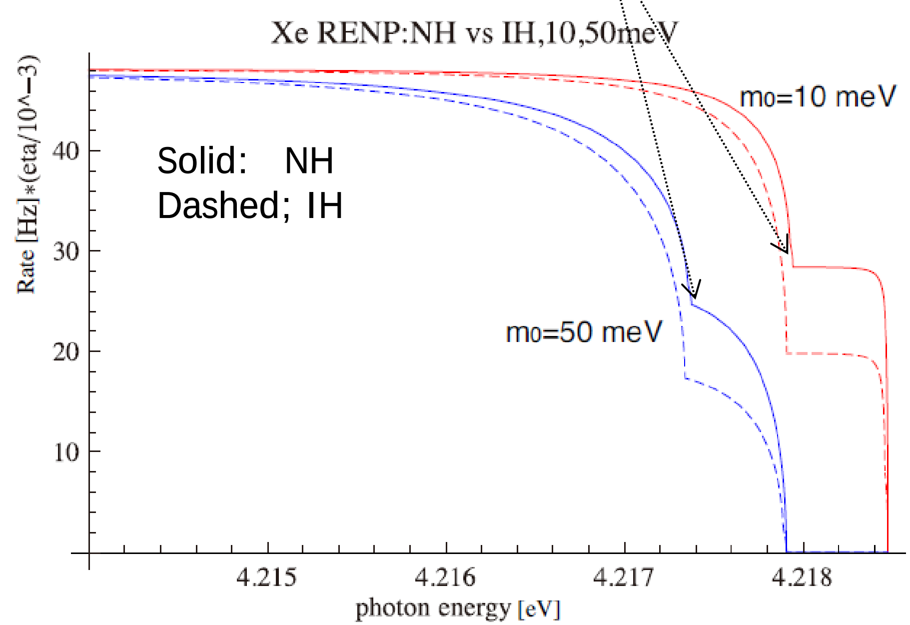
$M_{\mu} \to e\nu\nu$

$E_{eg} \to \gamma\nu\nu$

Thresholds are given by:

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



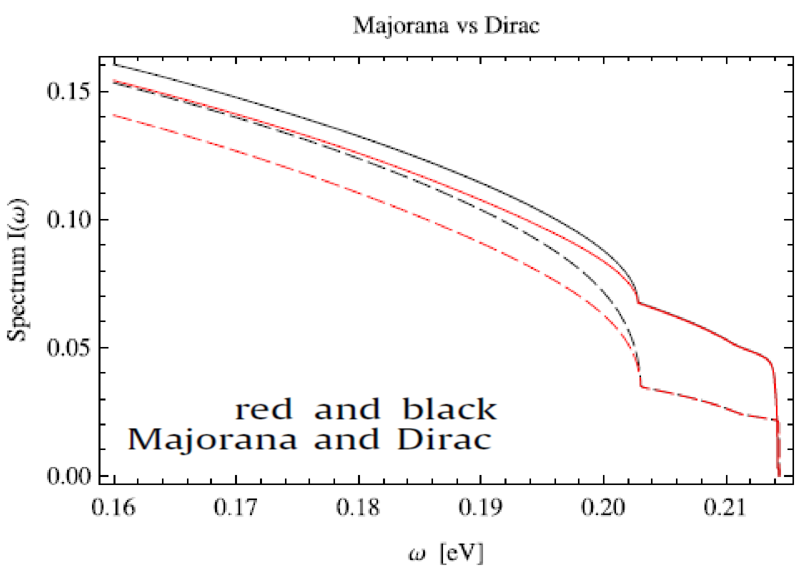


D.N. Dinh, S.T. Petcov, N. Sasao, M. Tanaka, M. Yoshimura
Physics Letters B 719 (2013) 154–163

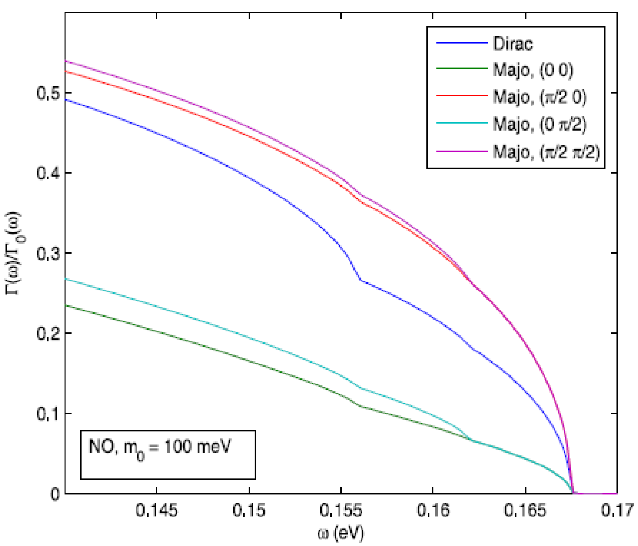
Majorana-Dirac and CP phases

- M-D distinction & CP phase measurements
  - M-D distinction by identical particle effect
  - Need atoms/molecules with energy gap less than 1 eV

$\epsilon_{eg} = \epsilon_{eg}(\mathrm{Yb})/5$ for $m_0 = 2$ meV



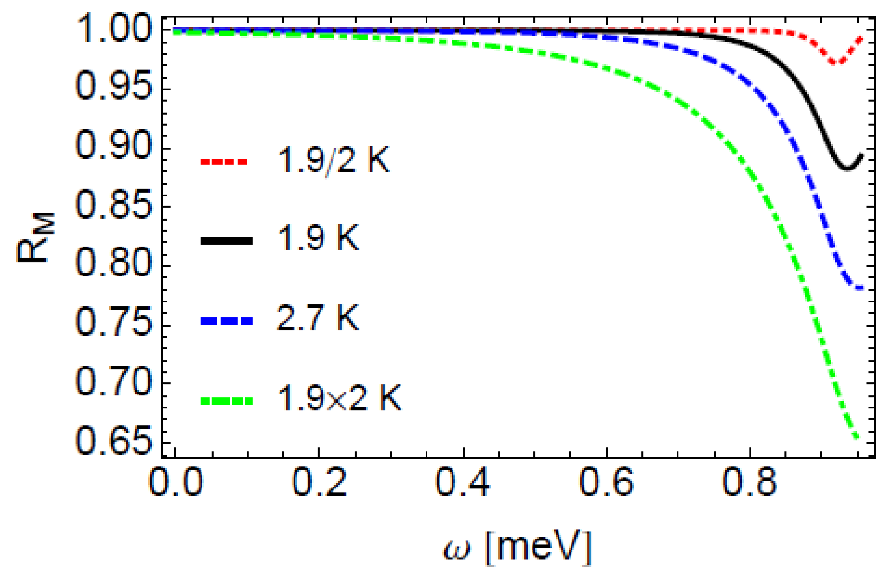
CPV phases $(\alpha, \beta - \delta)$



M. Yoshimura, N. Sasao, and M. Tanaka
arXiv:1409.3648v1 [hep-ph] 12 Sep 2014

Cosmic Neutrino Background (1.9K)

- Our Universe filled with neutrinos as well as photons
  - Temperature: 1.9 K
  - Second after Big-bang
- Pauli Exclusion Principle
  - Spectrum distortion



$m_0 = 5$ meV, $\epsilon_{eg} = 11$ meV

Impact on neutrino physics

- RENP process provides
  - Systematic way of measuring neutrino's unknown parameters:
    - Normal or Inverted Hierarchy
    - Absolute mass
    - Majorana-Dirac distinction
    - CP phases: α and $\beta-\delta$
    - Relic neutrino temperature

easy

hard

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Quantum Coherence in Physics

- Coherent superposition within a single particle:
  - Neutrino oscillation:

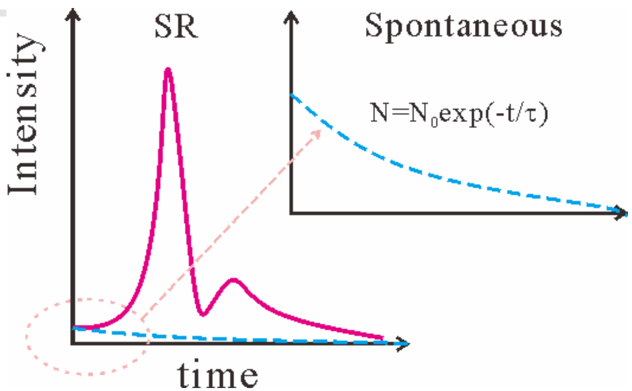
$$|\nu_e\rangle = +\cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

- Coherence among particles
  - Superfluid/BEC
- Coherence among atoms mediated/ supported by radiation fields.
  - Super-radiance
  - Macro coherence

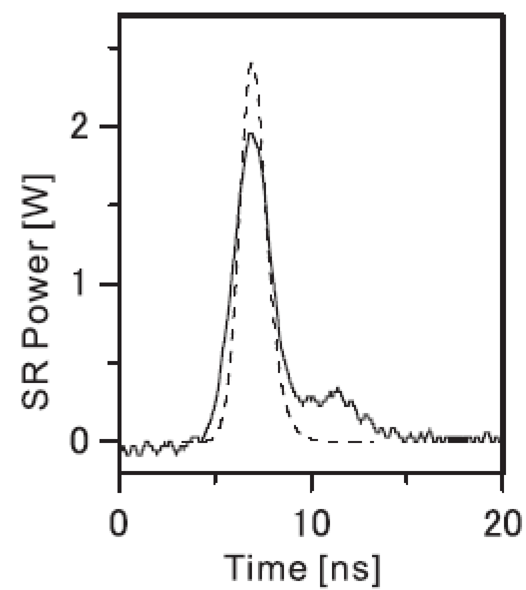
Amplification by Coherence

- Super-radiance (SR)
  - De-excitation via single-photon emission.

$$R_\gamma \propto \left|\sum_a^N \exp(i\vec{k}\cdot\vec{r}_a)\mathcal{M}_a\right|^2 \propto N^2$$



Ba SR experiment



- Macro-coherent amplification
  - De-excitation via multi-particle emission.

$$R_{\gamma\nu\bar{\nu}} \propto \left|\sum_a^N \exp\left(i(\vec{k}_1+\vec{k}_2+\vec{k}_3)\cdot\vec{r}_a\right)\mathcal{M}_a\right|^2$$

$$k_1 + k_2 + k_3 = 0$$

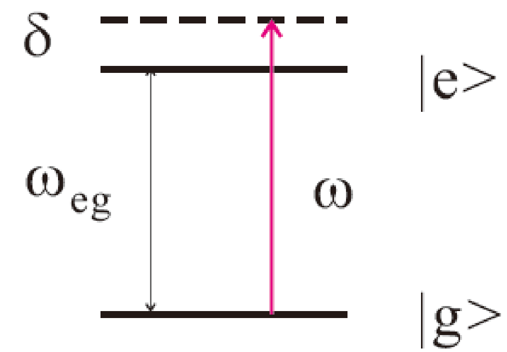
Questions raised from people

- Coherence needs wave-function overlap.
  - Can atoms far apart cooperate?
    - Yes! Radiations mediates coherence among atoms.
    - It has been proved by many SR experiments.
- Momentum conservation law limits available phase space to infinitesimally small region.
  - How can the macro-coherence amplification be initiated from “zero” phase space?
    - By application of trigger fields (laser) to induce the process!

- Wish to answer these questions by the experimental facts, but first try to give easy/intuitive explanation!

Generation of Coherence (simple case)

- Atom with two levels (E1 allowed) irradiated by coherent light: $E = E_0 \cos(\omega t)$



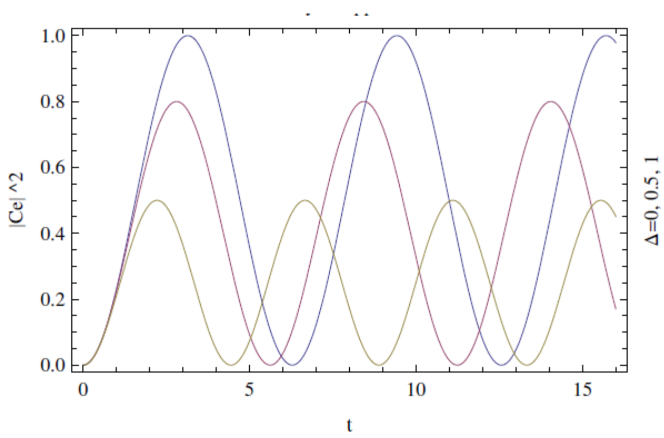
- Atomic state: $| \psi(t) \rangle = \cos\frac{\theta}{2} | g \rangle - i \sin\frac{\theta}{2} | e \rangle$

- Rabi frequency: $\theta = \Omega_R t, \qquad \Omega_R \equiv \frac{E_0 d_{eg}}{\hbar}$

$$d_{eg} = |\langle e | e\vec{x} | g \rangle|$$

- Coherent state (π/2-pulse):

$$| g \rangle \quad \rightarrow \quad \frac{| g \rangle - i | e \rangle}{\sqrt{2}}$$



EM waves generated by coherence

- Excited atoms are a tiny oscillator and oscillators in phase generate EM waves.
- Density matrix operator:

$$\rho \equiv |\psi\rangle\langle\psi| = \rho_{gg}|g\rangle\langle g| + \rho_{ee}|e\rangle\langle e| + \rho_{eg}|e\rangle\langle g| + \rho_{ge}|g\rangle\langle e|$$

$$\rho_{gg} = \cos^2\frac{\theta}{2}, \qquad \rho_{ee} = \sin^2\frac{\theta}{2}, \qquad \rho_{eg} = -i\frac{\sin\theta}{2}e^{ikx} \qquad \left(|\rho_{eg}|_{Max} = \frac{1}{2}\right)$$

Now input laser field:

$E = E_0 \cos(\omega t - kx)$

- Macroscopic polarization P:

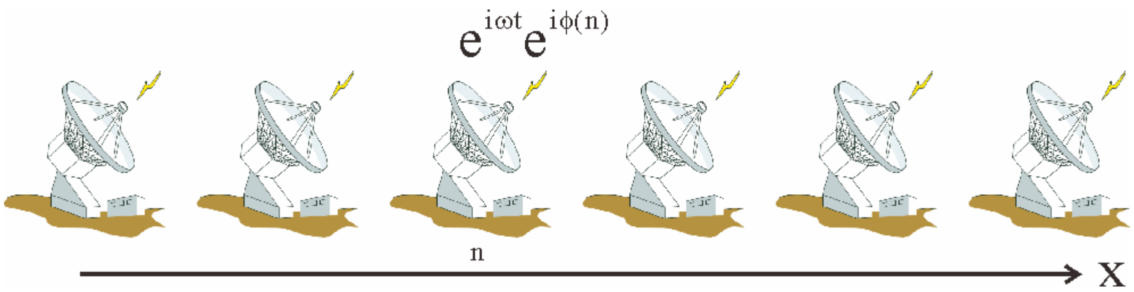
$$\vec{P} \equiv \langle\psi|\vec{d}|\psi\rangle = Tr(\vec{d}\,\rho) = d_{eg}\rho_{ge} + d_{ge}\rho_{eg}$$

- Generation of (classic) EM radiation by P:

$$\frac{\partial^2 E}{\partial t^2} - c^2\frac{\partial^2 E}{\partial x^2} = -\frac{N_0}{\varepsilon_0}\frac{\partial^2 P}{\partial t^2}, \qquad N_0 = \text{number denstiy of atoms}$$

Classic example: Phased antenna array (amplification by N^2 enhancement)

- Phases of individual antenna should be chosen properly to enhance the EM power.



But there are differences.

- Need to take into account reaction of radiation to atoms.

  ⟹ Schrodinger eq.+ Maxwell
  (called Maxwell-Bloch eq.)

- Need trigger fields for weak process (to induce it).

Generation of Coherence (realistic case)

- Atom with 3 levels irradiated by 2 lasers

$$E_0 = E_g \cos(\omega_0 t), \qquad E_{-1} = E_e \cos(\omega_{-1} t)$$

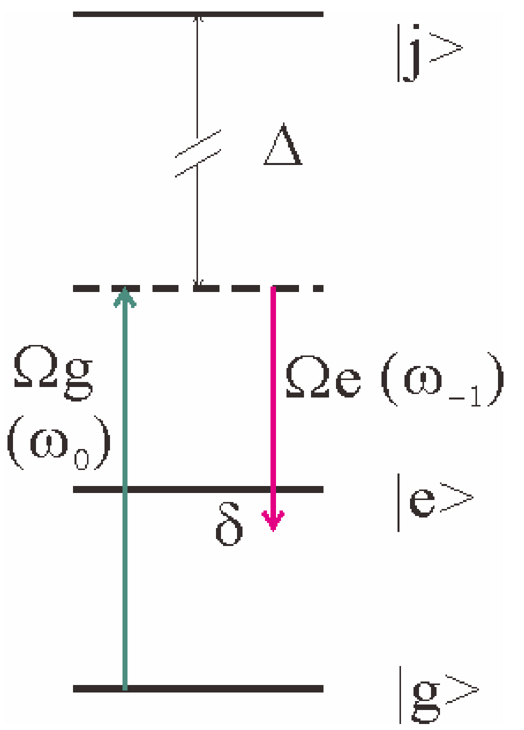
- Atomic state:

$$|\,\psi(t)\,\rangle = \cos\frac{\theta}{2}|\,g\,\rangle + e^{-i\phi}\sin\frac{\theta}{2}|\,e\,\rangle$$

- 2 photon Rabi frequency:

$$\tan\theta \simeq \frac{2|\Omega_{eg}|}{\delta}, \qquad \Omega_{eg} \equiv \frac{\Omega_e\Omega_g}{\Delta}e^{\imath\phi}$$

$$\Omega_g \simeq \frac{E_g|d_{jg}|}{\hbar}, \qquad \Omega_e \simeq \frac{E_e|d_{je}|}{\hbar}$$



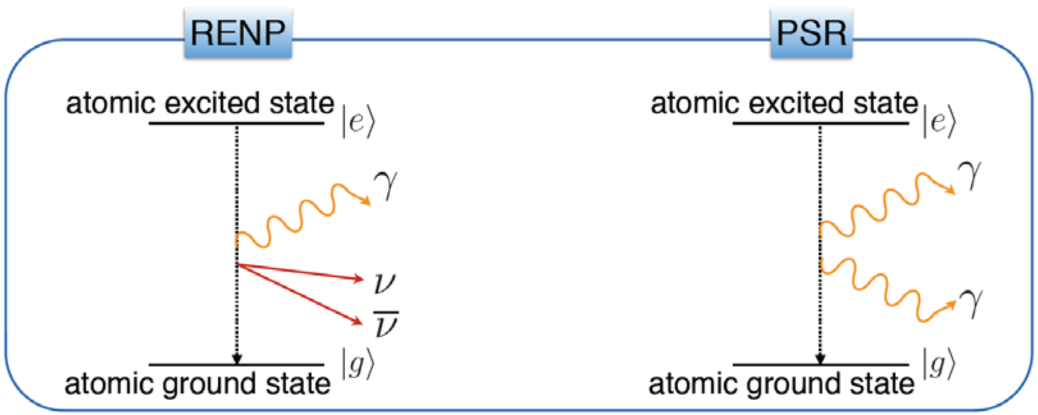
E1 forbidden between e-g

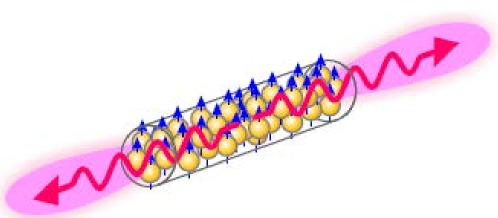
Contents

M. Yoshimura, N. Sasao, and M. Tanaka
PHYSICAL REVIEW A 86, 013812 (2012)

Paired Super-Radiance as an experimental proof of macro-coherence

- PSR (paired super-radiance)
  - Twin process of RENP with the neutrino pair replaced by a photon
  - Two intense photon bursts

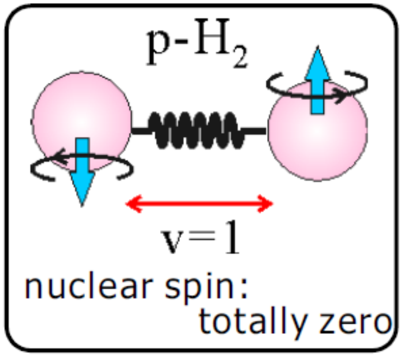




- Best process of proving the principle of macro-coherent amplification.
  - PSR rate >> RENP rate because it is QED process

Yuki Miyamoto et. al.
arXiv:1406.2198v2 [physics.atom-ph]

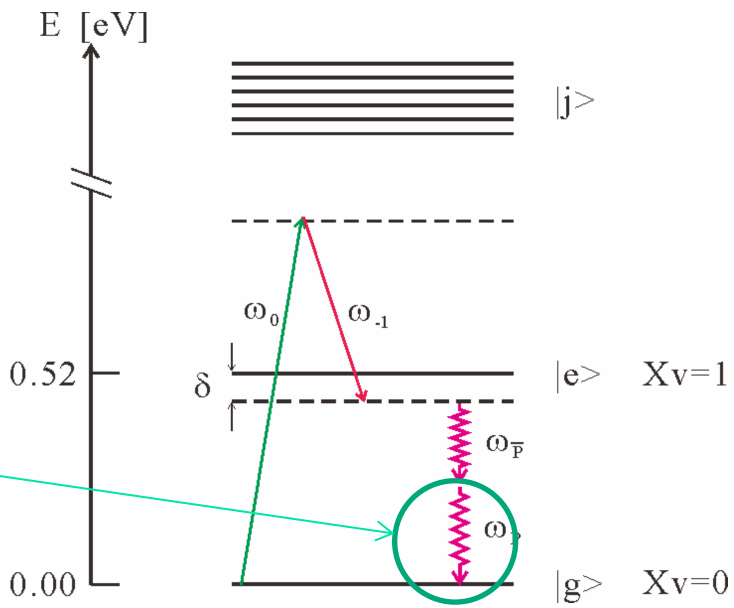
PSR experiment



- Para hydrogen molecule (Spin=0)
  - Vibrationally excited state v=1 to v=0
  - E1 decay forbidden.
  - Two photon decay :

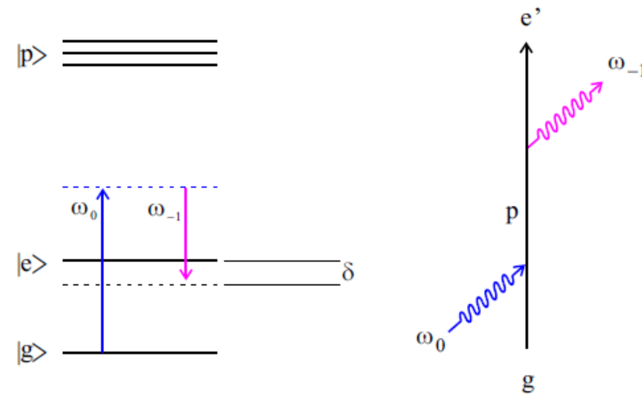
$$\Gamma \approx 1/2\times 10^{12} \text{ sec}$$

- Adiabatic Raman method
  - Two driving lasers injected in the same direction to generate coherence.
  - Lowest Stokes used as a trigger.
  - Two photon emissions detected.



$$\boxed{\omega_q = \omega_0 + q\Delta\omega, \qquad \Delta\omega = \omega_0 - \omega_{-1},}$$

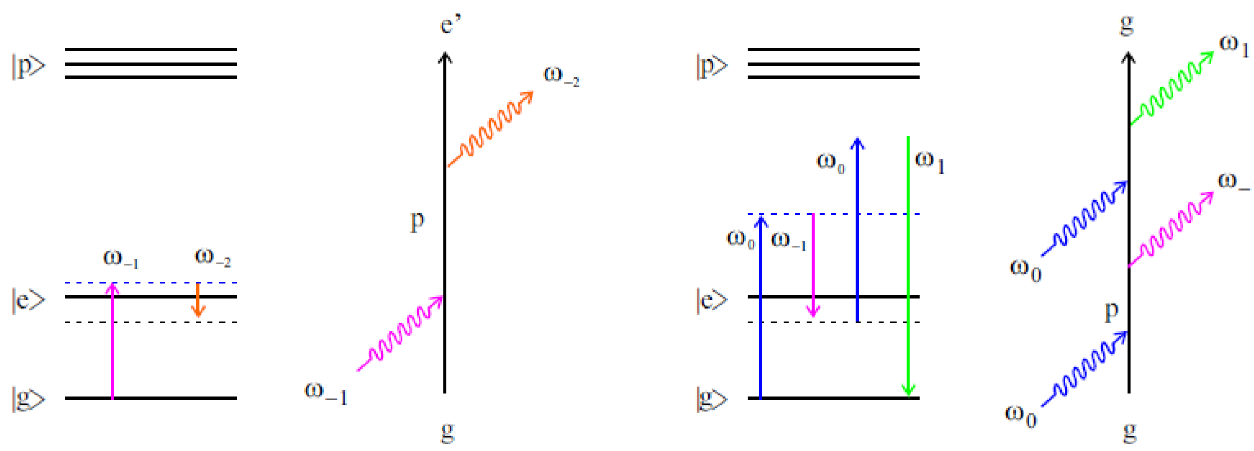
Raman process



- Induced Raman process
  - Inelastic photon scattering induced by external lights.

$$\omega_0 - \omega_{-1} = \omega_e - \omega_g - \delta$$

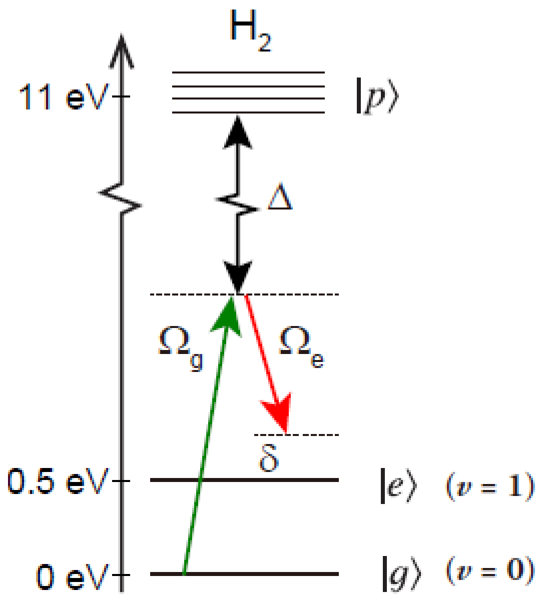
- Higher order process (w/ coherence)
  - Stokes $\quad \omega_{-2} = \omega_{-1} - (\omega_{eg} - \delta) = \omega_0 - 2(\omega_0 - \omega_{-1}) = \omega_0 - 2\Delta\omega$
  - Anti-Stokes $\quad \omega_1 = 2\omega_0 - \omega_{-1} = \omega_0 + (\omega_0 - \omega_{-1}) = \omega_0 + \Delta\omega$



Stokes　　　Anti-Stokes

Adiabatic Raman

- Method to produce large coherence



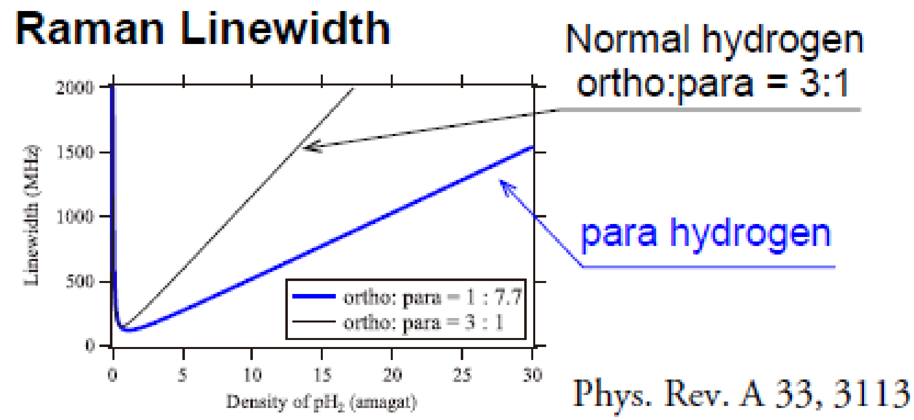
$\delta \neq 0$

Non-degenerate Superposition States:

$$\begin{cases} |+\rangle = \cos\frac{\theta}{2}|g\rangle + e^{-i\varphi}\sin\frac{\theta}{2}|e\rangle \\ |-\rangle = \cos\frac{\theta}{2}|g\rangle - e^{-i\varphi}\sin\frac{\theta}{2}|e\rangle \end{cases}$$

Mixing angle	Two photon Rabi frequency	Coherence
$\tan\theta \simeq \frac{2\Omega_{ge}}{\delta}$	$\Omega_{ge} \simeq \frac{\Omega_g \Omega_e}{\Delta}$	$\boxed{|\rho_{ge}| = \frac{1}{2}\sin\theta}$

Why p-H2?



- E1 transition forbidden from v=1-->v=0.
  - For homo-diatomic molecules such as H2.
  - Two-photon transition allowed.
- Para hydrogen?
  - Round wave-function: less residual interaction.
  - Longer phase relaxation time.
- Cooled down to 77 K.
  - All states in the ground v=0 state.
  - Maximum phase relaxation time (Dicke narrowing).

Phase matching condition or momentum conservation law

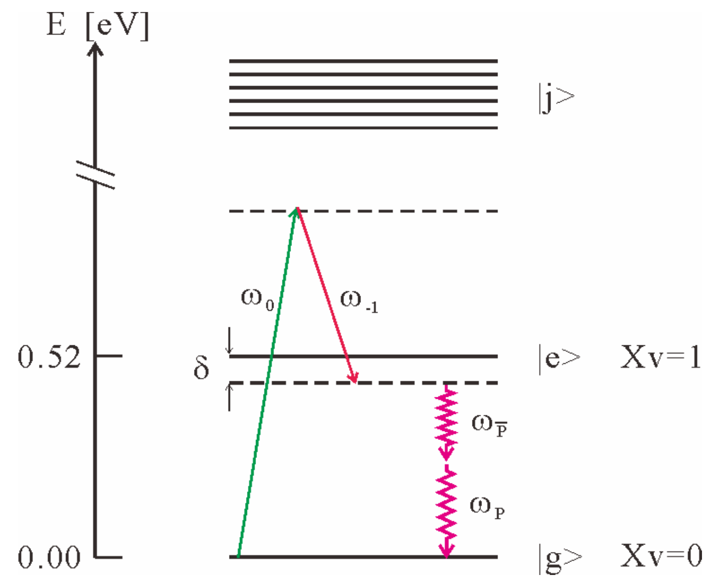
- Energy conservation:

$$\Delta\omega \equiv \omega_0 - \omega_{-1} = \omega_{eg} - \delta,$$

$$\Delta\omega = \omega_p + \omega_{\overline{p}}$$

- Phase imprinted in atom:

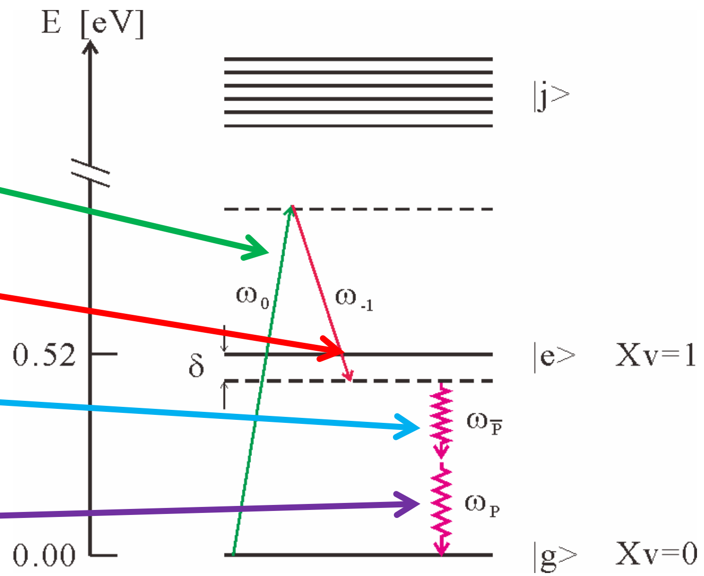
$$e^{i\Delta\omega\cdot x/c}$$



- Two photon pair must be emitted in the same direction to satisfy phase matching condition.

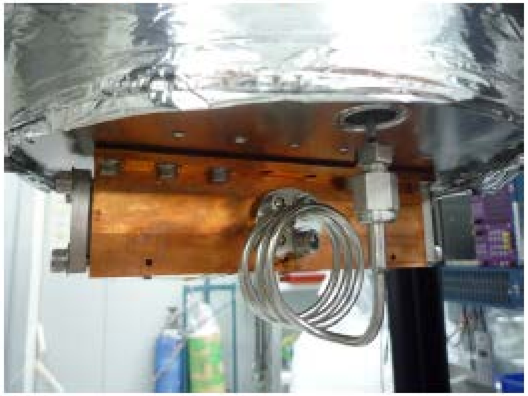
Experiment and results

- Important wavelengths to remember!
  - 532nm
  - 683nm
  - 4.66um (q=-4)
  - 4.96um

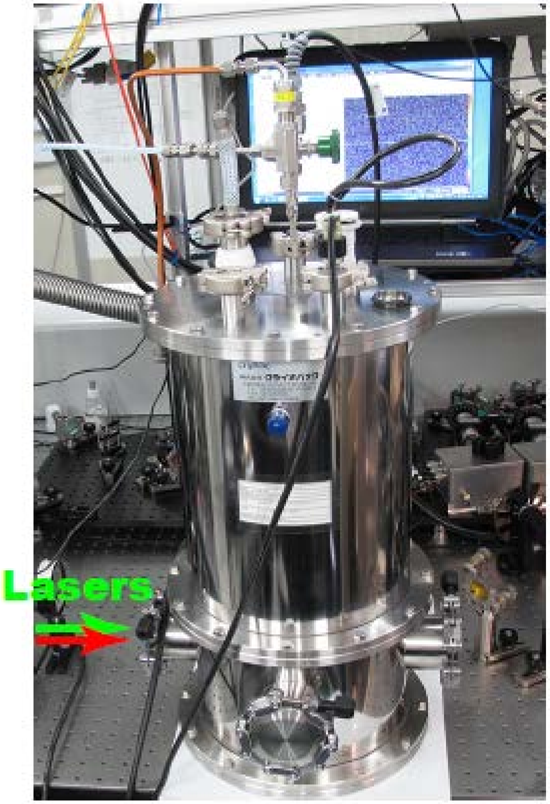


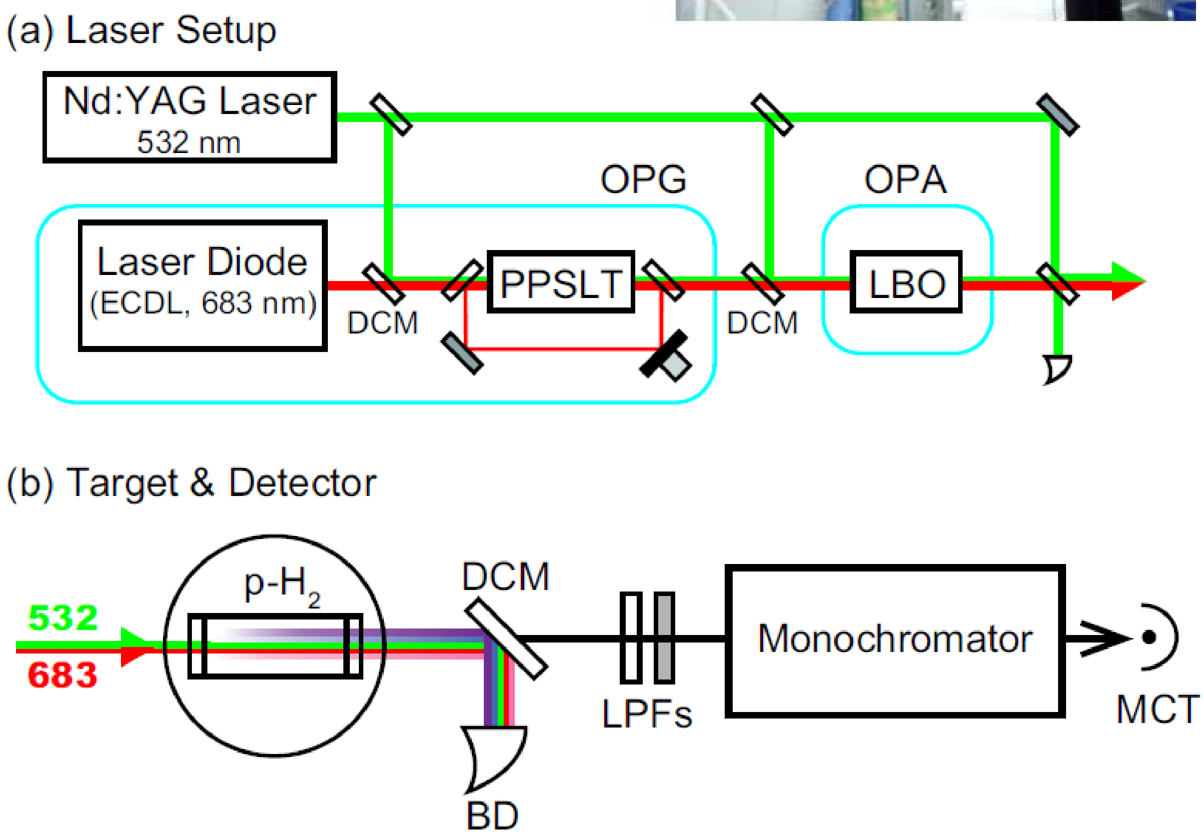
Experimental setup

▶ H_2 gas cell (15 cm long)



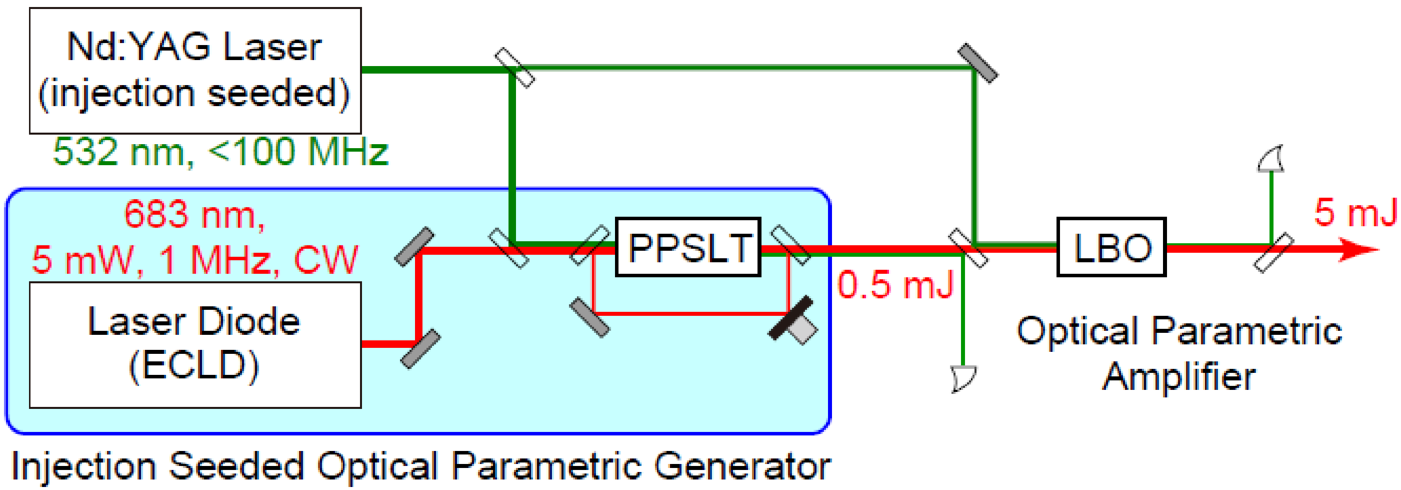
▶ L-N_2 Cryostat

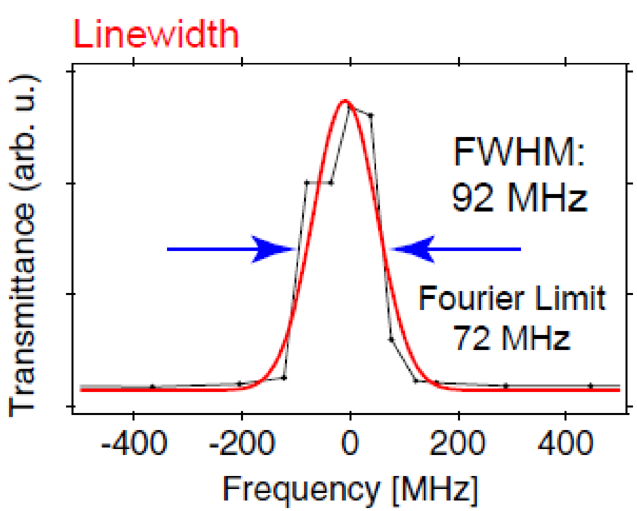


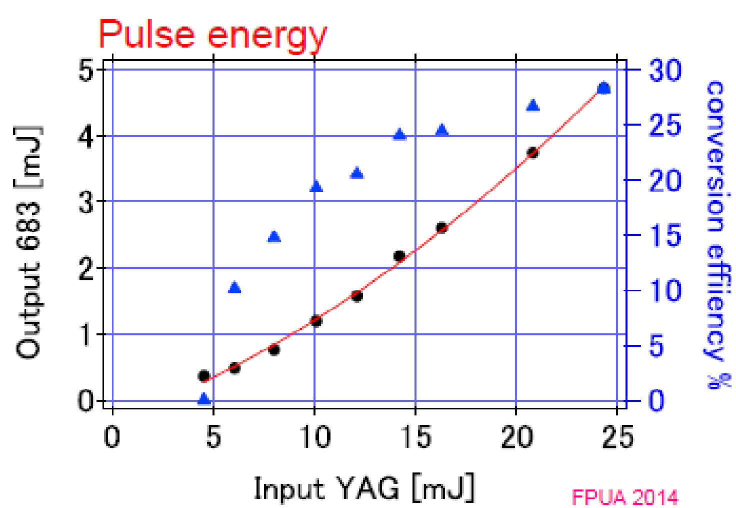


- Pump lasers of 5 GW/cm^2 : $\Omega_{ge} = 2\pi \times 170$ MHz
- 5 mJ, 6 ns pulse, w_0 = 100 μm beam waist → 5 GW/cm^2
- Fourier transform limited linewidth (~100 MHz)

Laser system (setup)

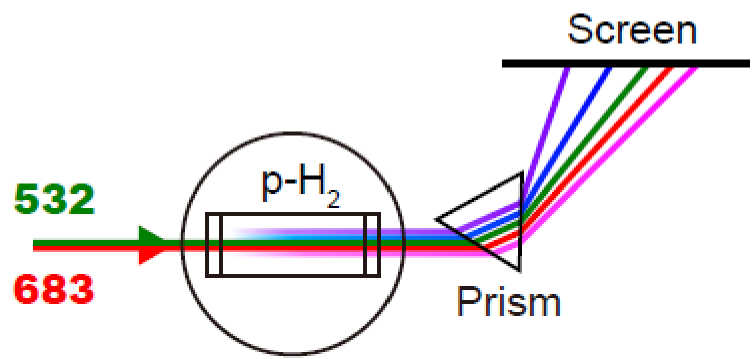


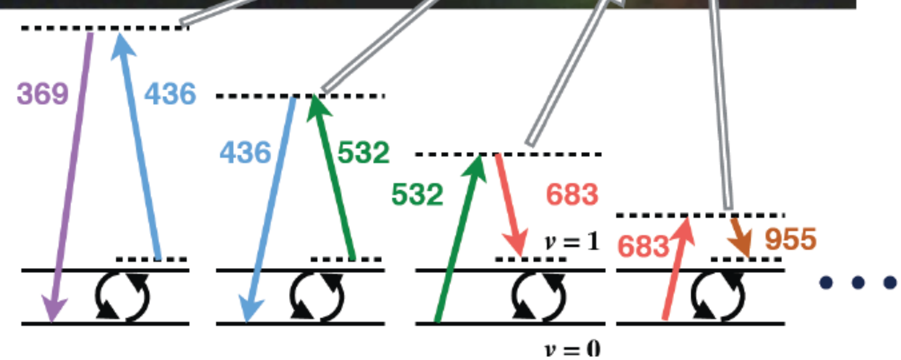


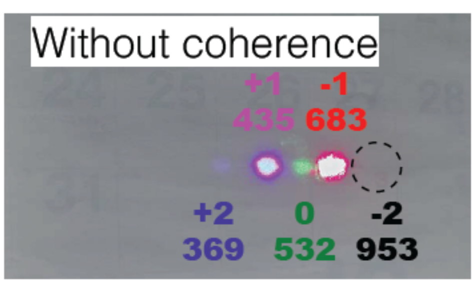


Ultra-broadband Raman sidebands

- Raman sidebands, from 192 to 4662nm, are observed: >24 octaves
- Evidence of large coherence

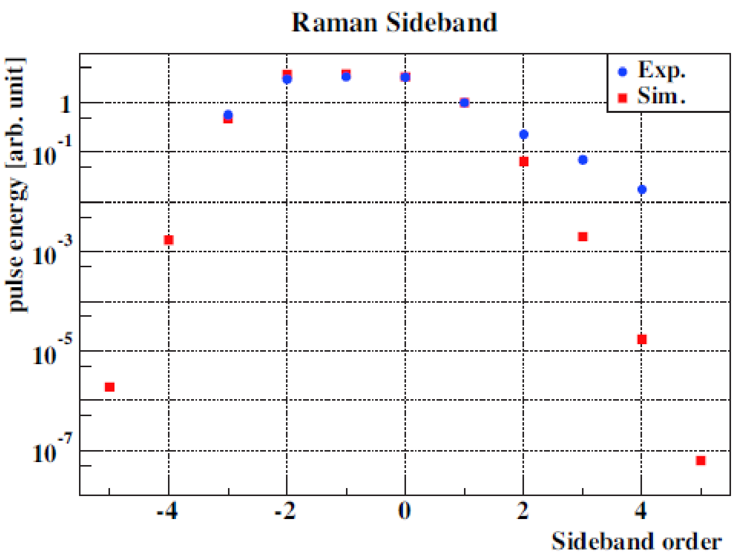






Estimated coherence

- Maxwell-Bloch eq.



$$\frac{\partial \rho_{gg}}{\partial \tau} = i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{gg},$$

$$\frac{\partial \rho_{ee}}{\partial \tau} = i\Big(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}\Big) - \gamma_1 \rho_{ee},$$

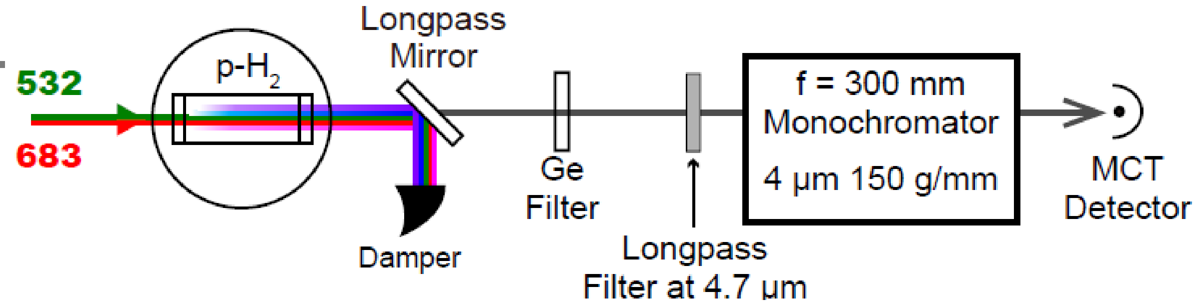
$$\frac{\partial \rho_{ge}}{\partial \tau} = i\Big(\Omega_{gg} - \Omega_{ee} + \delta\Big)\rho_{ge} + i\Omega_{ge}\Big(\rho_{ee} - \rho_{gg}\Big) - \gamma_2 \rho_{ge},$$

$$\frac{\partial E_q}{\partial \xi} = \frac{i\omega_q n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(q)} + \rho_{ee}\alpha_{ee}^{(q)}\Big)E_q + \rho_{eg}\alpha_{eg}^{(q-1)}E_{q-1} + \rho_{ge}\alpha_{ge}^{(q)}E_{q+1}\Big\},$$

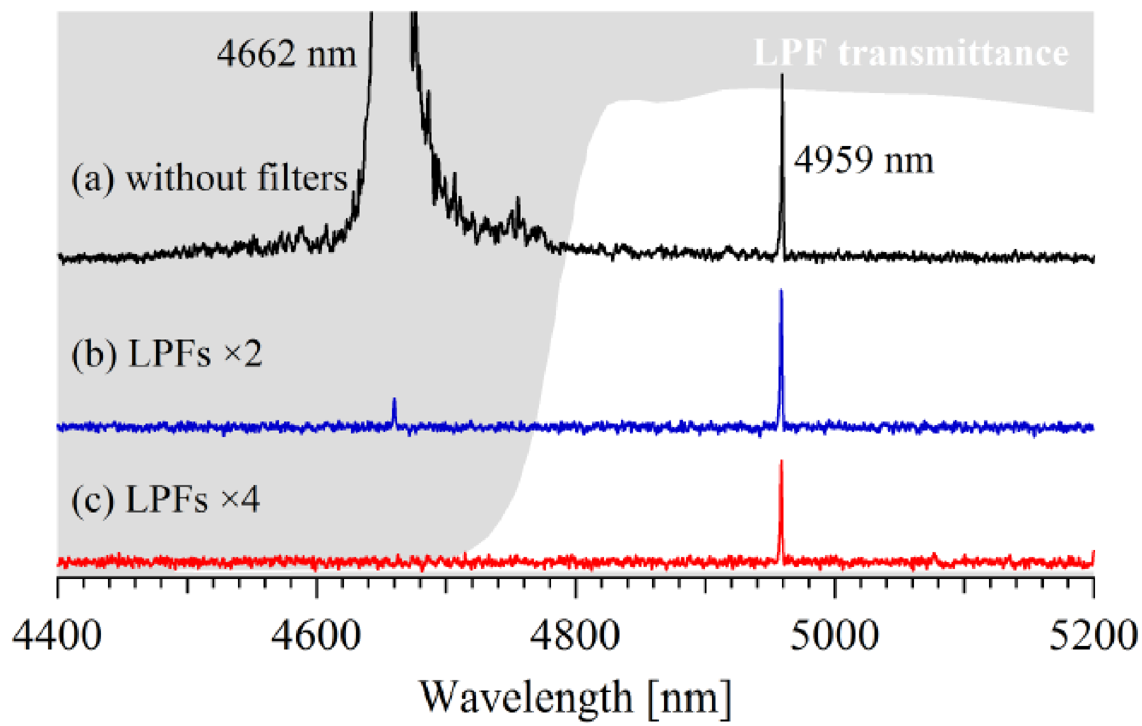
$$\frac{\partial E_p}{\partial \xi} = \frac{i\omega_p n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(p)} + \rho_{ee}\alpha_{ee}^{(p)}\Big)E_p + \rho_{eg}\alpha_{ge}^{(p\overline{p})}E_{\overline{p}}^{*}\Big\}.$$

- Coherence estimated by simulation: $\rho_{ge} \simeq 0.032$

Two-photon emission spectrum

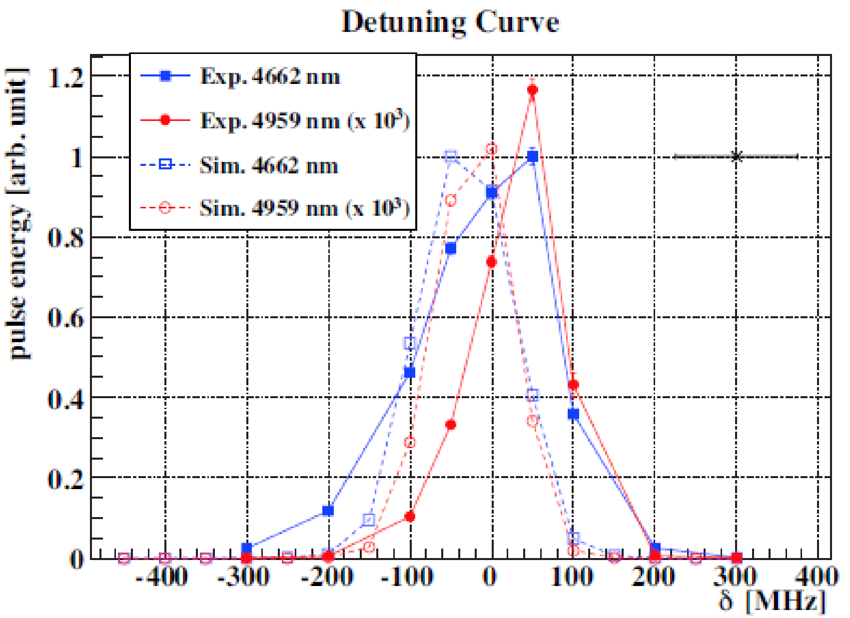


- Both 4.66 and 4.69um signals are observed clearly.
- 4.69um signal unaffected by long-pass filter (4700nm)



Detuning curve and others

- Detuning curve:
  - Resonant around $\delta \sim 0$.
  - Agree with simulation curve.
- Angular distribution
  - Forward peak: 10-20 mrad
- Time profile
  - FWHM ~5ns; narrower than the driving lasers (~8 ns).



Comparison with spontaneous two-photon emission rate

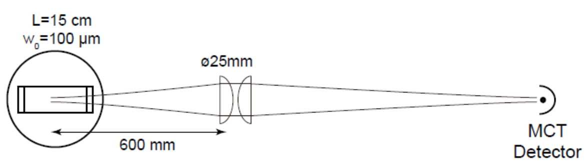
- Number of observed photons=4.4 x 10^7/pulse
- Spontaneous two photon rate

$$\frac{dA}{dz} = \frac{\omega_{eg}^7}{(2\pi)^3 c^6} \left|\alpha_{ge}^{(p\overline{p})}\right|^2 z^3(1-z)^3 \sim 3.2 \times 10^{-11}\ 1/\mathrm{s} \quad (z = \frac{1}{2}) \qquad z = \omega/\omega_{eg}$$

Photon number = $R_0 \cdot \pi w_0^2 L n_0 \cdot A \cdot \frac{\Delta E}{E} \Delta t$ = 1.6×10^{-8}

$$\sim 1.5 \times 10^{16} \quad \Delta\Omega/(4\pi) \sim 1.2 \times 10^{-4} \quad \Delta z \sim 4.9 \times 10^{-3} \qquad \Delta t \sim 80 \ [\mathrm{ns}]$$

- Enhancement factor>10^(15): can only be understood in the presence of macro-coherence.



Contents

Road map to neutrino mass spectroscopy with atoms

- Establish PSR control method
  - Can be a background of RENP
    - Initial-final mutual parity: PSR=even, RENP=odd
  - Switching method
    - AC Stark field/Zeeman field/parametric amplification
- Obtain large activity factor η
  - So far η<10^(-3)
- Find denser target
  - Gas ? Solid?
- Parity violation in RENP

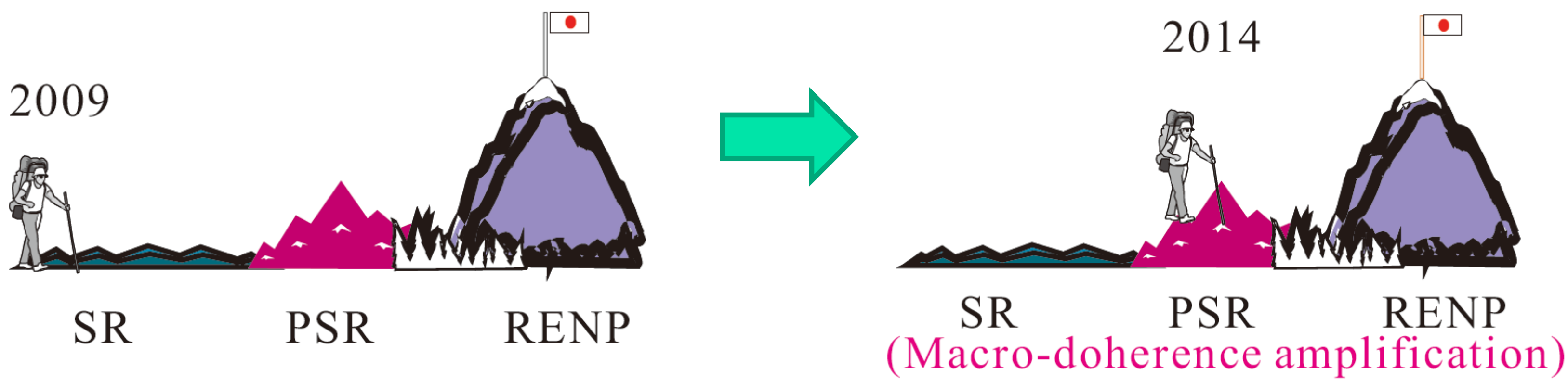
Summary

- Neutrino spectroscopy with atoms
  - A new/systematic approach to the determination of unknown neutrino properties such as absolute mass, M-D distinction, CP-phases and relic neutrinos.
  - RENP: radiative emission of neutrino pairs
  - Macro-coherent amplification is the key concept for RENP.
- PSR
  - A twin process with RENP that can provide experimental proof of the macro-coherent amplification principle.
  - We have actually observed a coherent two-photon process that is consistent with the prediction of the PSR master equation.

Summary (ctn'd)

- RENP
  - RENP from nucleus gives an extra enhancement factor
  - PSR can be controlled by manipulating Hamiltonian structure
    - For example, DC (or AC) Stark effect, Zeeman effect
  - Observation of parity non-conservation provides decisive test for RENP process.
- Future prospects
  - Establish PSR control method
  - Increase the macro-coherence activity factor η
  - Find denser target (gas? Solid?)

Thank you for your attention!!



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