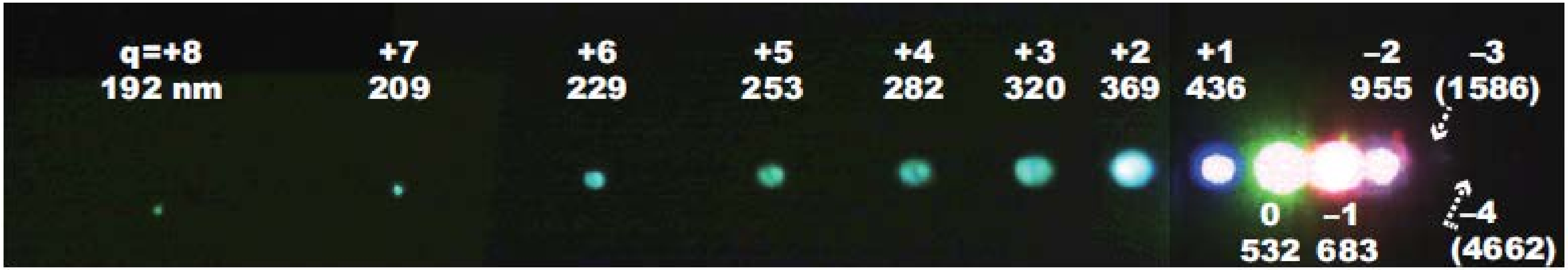
Neutrino mass spectroscopy with atoms

—Experimental aspects—

N. Sasao and M. Yoshimura (Okayama U.)
for SPAN collaboration



Contents

- Physics motivation

  Key word 1: RENP (radiative emission of neutrino pairs)

  Key word 2: Macro-coherent amplification

- Macro coherent amplification and its experimental proof

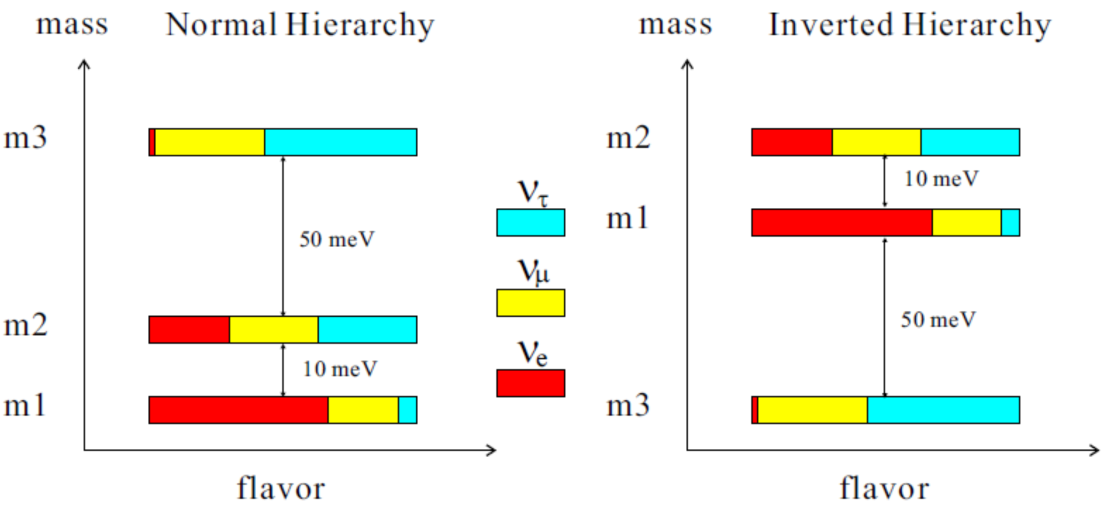
  Key word 3: PSR (paired super-radiance)

- Future prospects
- Summary

Neutrino physics at present

unknown parameters of neutrino

- Absolute mass and mass hierarchy
- Nature of mass
  - Dirac(4-component) vs Majorana(2-component)
- CP-violating phases
  - CP phases (δ,α,β)

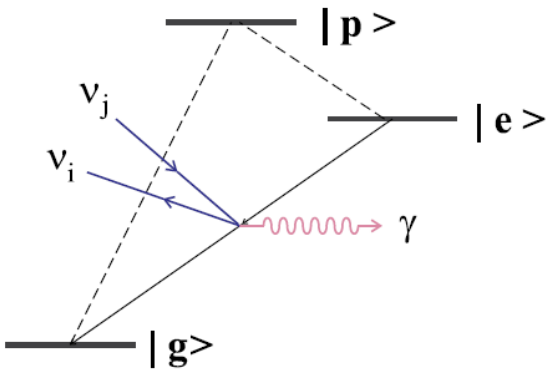


Physics beyond Standard Model
Matter-dominated universe

Experimental principle and its characteristics

- Experimental principle
  - Radiative emission of ν-pair $|e\rangle \rightarrow |g\rangle + \gamma\nu\bar{\nu}$
  - Measure photon energy spectrum

RENP(Radiative Emission of Neutrino Pair)

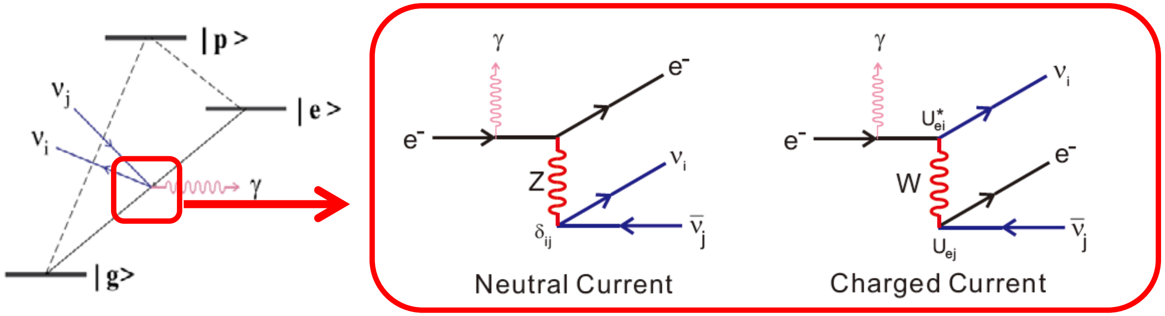


- Merit and demerit using atoms
  - （energy scale of atoms）～（neutrino mass scale）
    - Sensitivity to ν absolute mass, hierarchy, M-D, CP-phases (α, β–δ)
  - Small rate -> need amplification: e.g. Γ ~1/10^26 year for Q=1 eV
    - 「Macro-coherent amplification mechanism」

“Neutrino Spectroscopy with Atoms and Molecules”,
A. Fukumi et.al : Prog. Theor. Exp. Phys. **2012**, 04D002

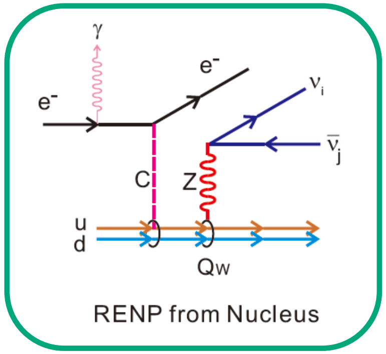
Expected RENP rate

- RENP rate calculation:
  - RENP spectrum can be calculated by the standard model.



Neutral Current

Charged Current



RENP from Nucleus

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

- RENP rate example
  - Γ=50 Hz for Xe $^3P_1$ (8.4365eV).
  - n=7x 10^20 [cm-3],
  - V=100 cm^3, η=10^-3

Macro-coherent amplification
･N^2
･momentum conservation

impact on neutrino physics (1)

Absolute mass and hierarchy

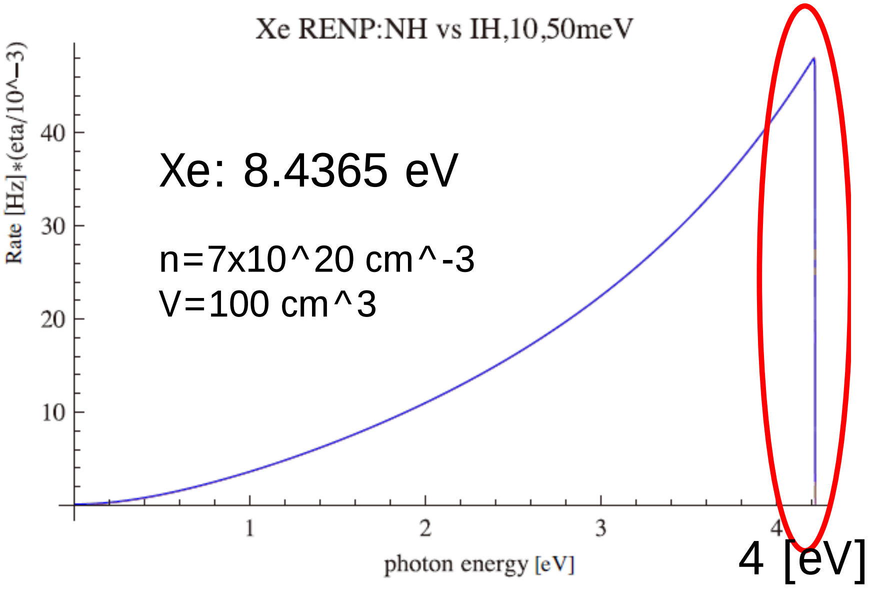
- Example of RENP spectrum（Xe)
  - Similar to muon decay spectrum

$$M_\mu \to e\nu\nu$$

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

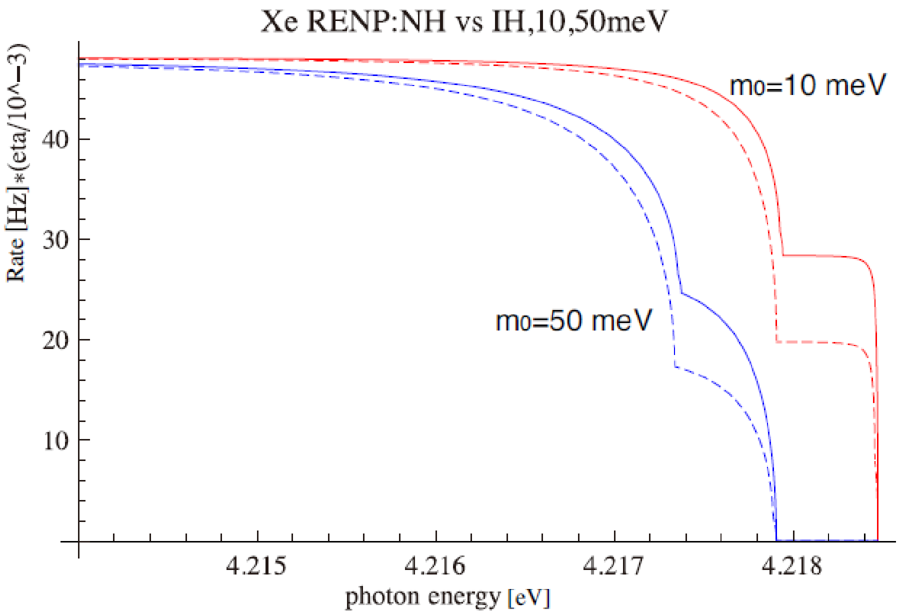
thresholds:

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



Xe: 8.4365 eV

n=7x10^20 cm^-3
V=100 cm^3

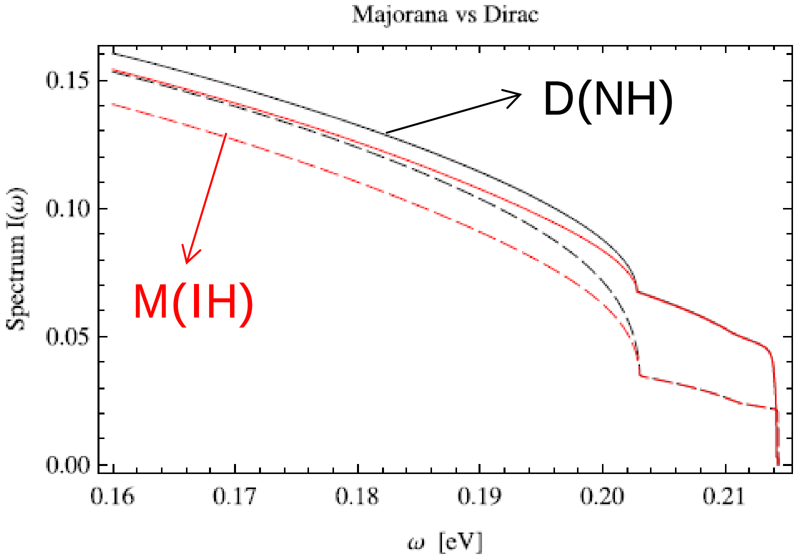


$$m_0 = Min(m_1, m_2, m_3)$$

"Observables in Neutrino Mass Spectroscopy Using Atoms",
D.N. Dinh, S.T. Petcov, N.S, M.Tanaka, M.Yoshimura, Phys. Lett. B 719 (2013) 154–163

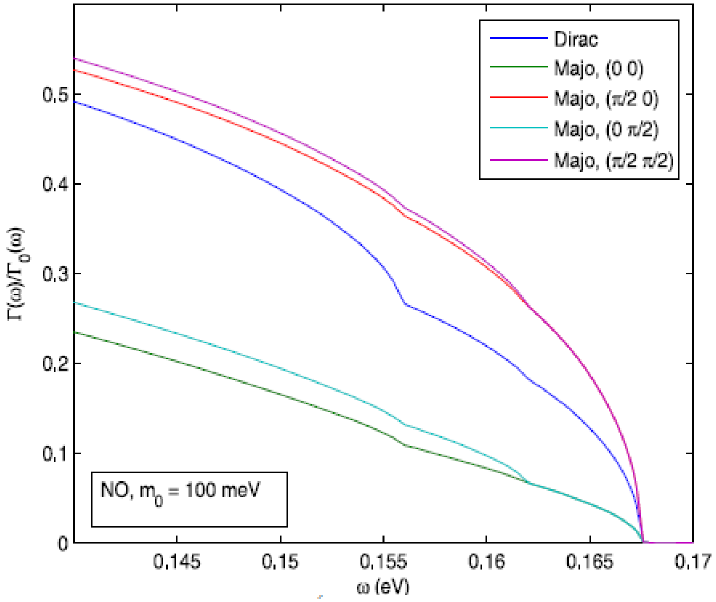
impact on neutrino physics (2)
Majorana-Dirac & CP-phases

- Majorana-Dirac distinction
  - Identical particle effect
- CP-phase measurements
  - Difference in spectrum



$$E_{eg} = E_{eg}(Yb)/5 \simeq 0.428 \ \ [\mathrm{eV}],$$

$$m_0 = 2 \ \ [\mathrm{meV}]$$



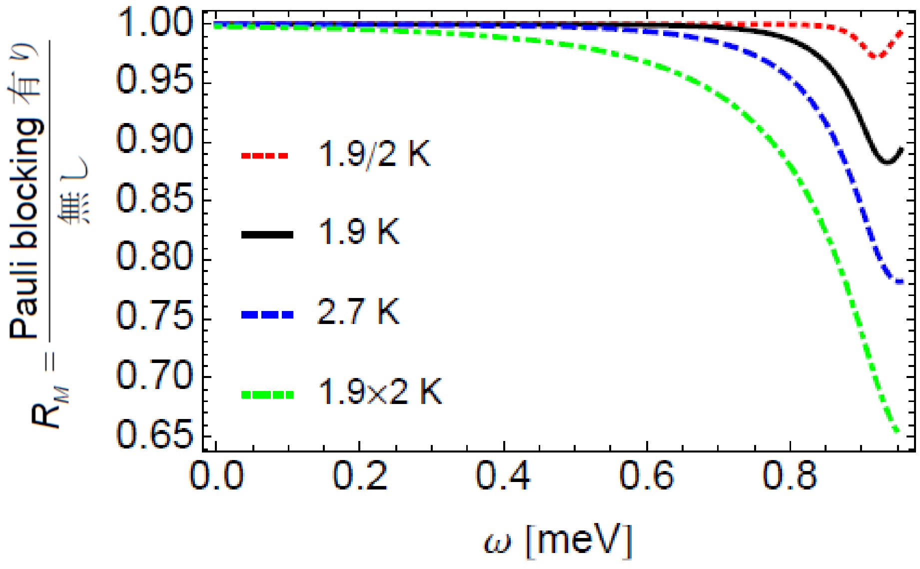
CPV phases $(\alpha, \beta - \delta)$

“Experimental method of detecting relic neutrino by atomic de-excitation”
M. Yoshimura, N.S, and M. Tanaka, Phys. Rev D 91, 063516 (2015)

impact on neutrino physics (3)

Cosmic neutrino background（1.9K）

- Our universe is filled with 1.9K neutrinos at present.
  - Information after 1-2sec of Big-bang
  - Yet to be observed!
- Observation principle
  - Spectrum change due to Pauli exclusion principle



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

$$\boxed{T_\nu / T_\gamma = \left(4/11\right)^{1/3} \quad ?}$$

Contents

- Physics motivation

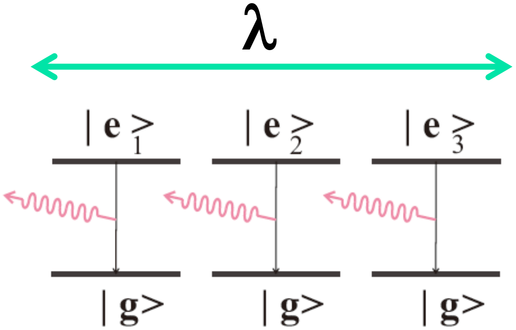
- Macro coherent amplification and its experimental proof

  Key word 3: PSR (paired super-radiance)

- Future prospects

- Summary

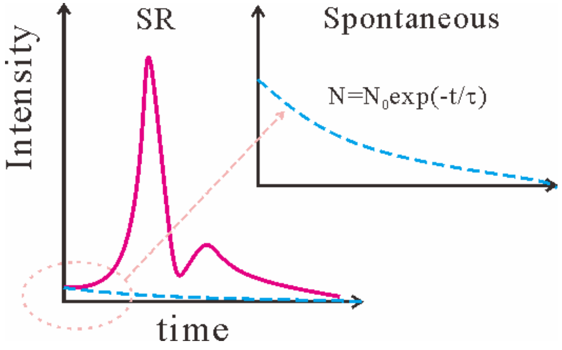
“Production of Ba Metastable State via Super-Radiance”,
C. Ohae et.al, JPSJ 83,044301 (2014)



Amplification by coherence among atoms

- Super-Radiance
  - De-excitation via single photon emission

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

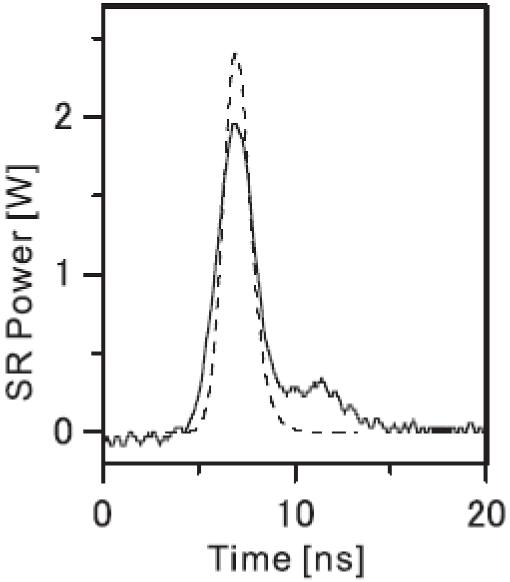


- Macro-coherent amplification
  - De-excitation via multi-particle emission

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

$$k_1+k_2+k_3=0$$

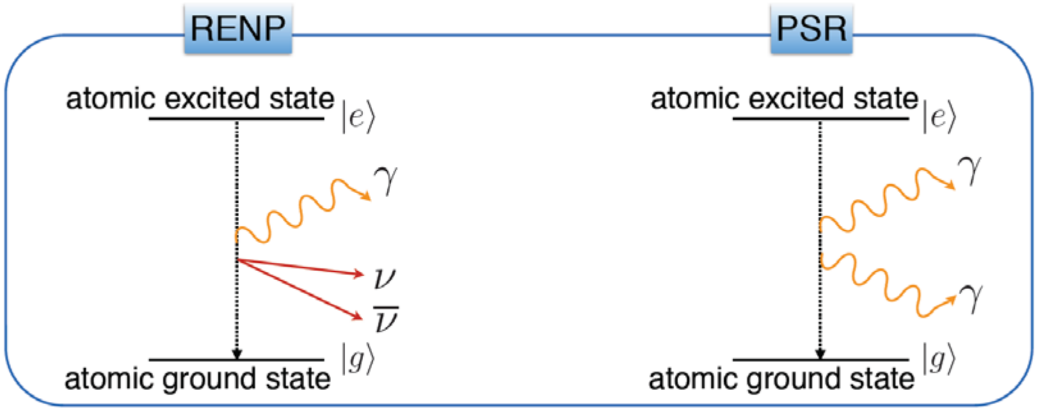
Ba SR experiment

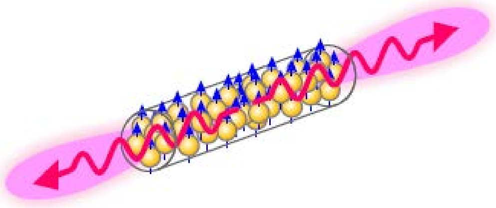


“Dynamics of two-photon paired superradiance”,
M. Yoshimura, N. S, and M. Tanaka, PHYSICAL REVIEW A 86, 013812 (2012)

Experimental proof of macro-coherent amplification

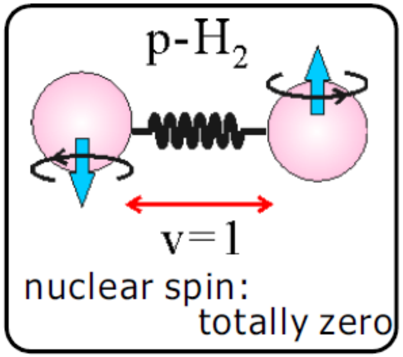
- PSR (paired super-radiance)
  - QED process where ν-pair is replaced with a photon.
  - A pair of strong light pulses (SR) will be emitted.



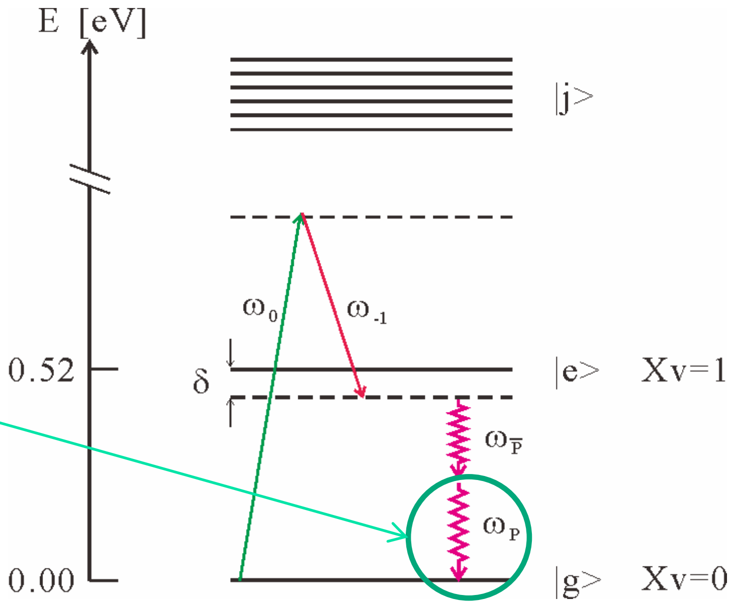


“Observation of coherent two-photon emission from the first vibrationally-excited state of hydrogen molecules”, Yuki Miyamoto et. al. Prog. Theor. Exp. Phys. **2014**, 113C01

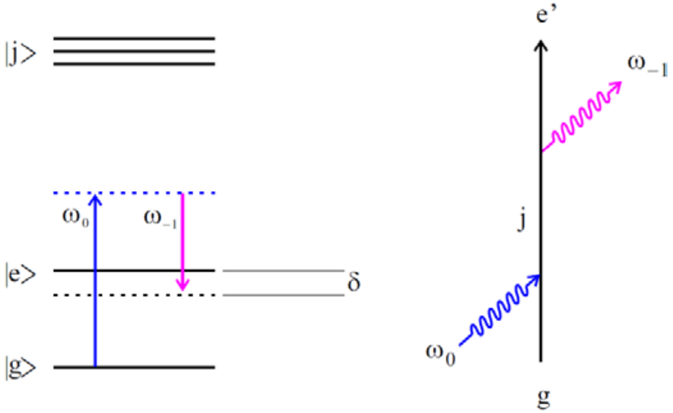
PSR experiment



- Para-hydrogen molecule (Spin=0)
  - Vibrational level (v=1) to ground level(v=0)
  - E1 forbidden.
  - Small 2-photon emission rate:
    $$\Gamma \approx 1/2\times10^{12}\ \text{sec}$$
- Excitation by adiabatic Raman
  - Irradiation by 2 lasers from one side
  - Use Stokes sideband (q=-4) as trigger
  - Detect 2-photon emissions



Features of adiabatic Raman process



- Why we use Raman process?
  - Creation of coherence among two levels |e> and |g>
  - Generation of higher side-bands

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

Eigenstates:

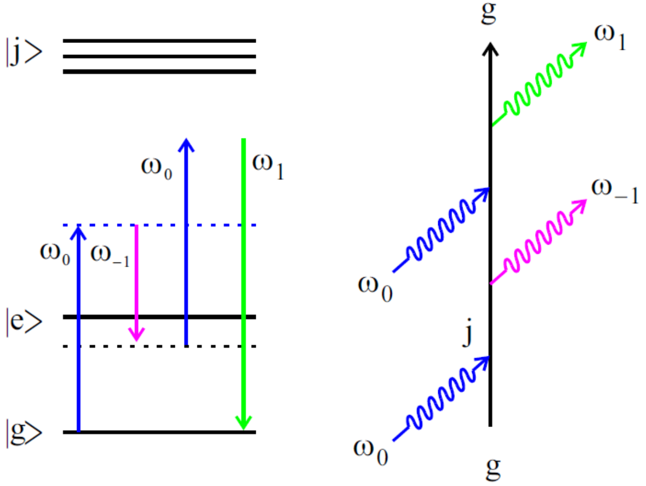
$$|+\rangle = \cos\theta|g\rangle + \sin\theta e^{-i\varphi}|e\rangle$$

$$|-\rangle = \cos\theta e^{-i\varphi}|e\rangle - \sin\theta|g\rangle$$

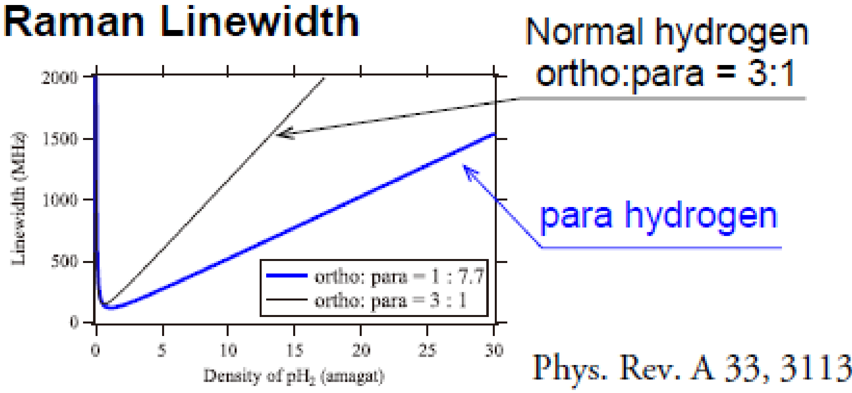
$$\tan 2\theta = \frac{|\Omega_{eg}|}{\Omega_{gg} - (\Omega_{ee} - \delta)}, \qquad \Omega_{eg} = |\Omega_{eg}|e^{i\varphi}$$

Density matrix ρ=|ψ><ψ|

$$\rho_{ge} = \cos\theta \sin\theta\, e^{i\varphi} = \frac{1}{2}\sin 2\theta\, e^{i\varphi}$$



Why para-hydrogen？
Characteristics of p-H2


Raman Linewidth

Normal hydrogen ortho:para = 3:1

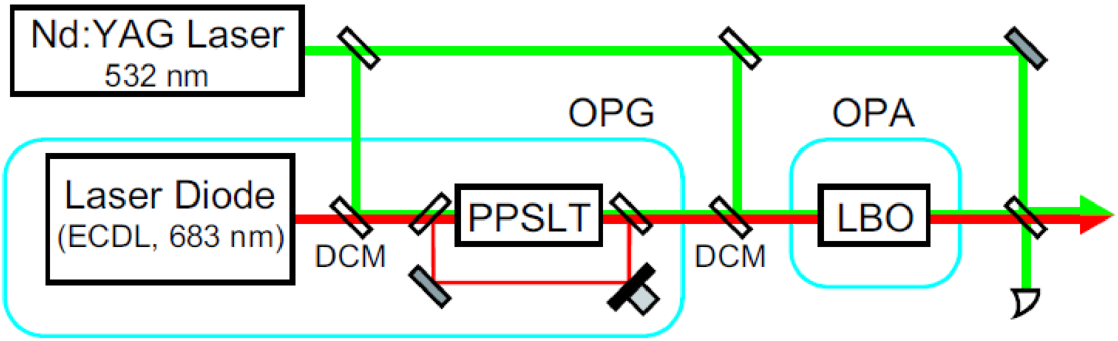
para hydrogen

Phys. Rev. A 33, 3113

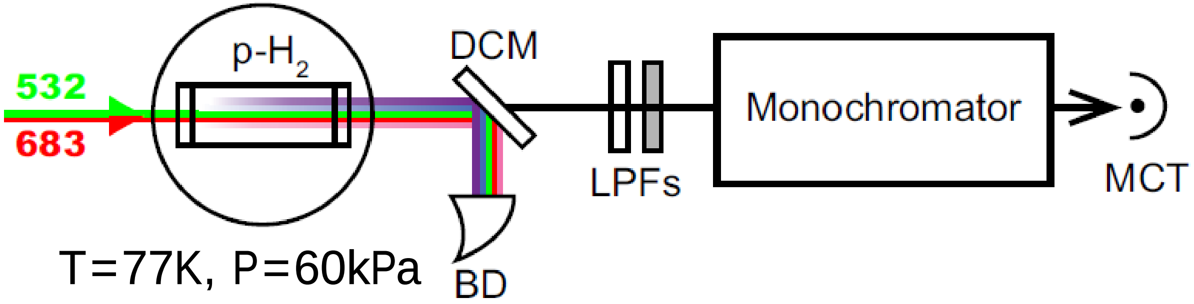
- E1 forbidden v=1-->v=0.
  - Because homo-nuclear diatomic molecule
  - Two photon emission process allowed.
- Para-hydrogen (not ortho-hydrogen)
  - Round wavefunction (less residual interaction).
  - Long coherence time.
- Cooled down(77 K).
  - All ground state(v=0).
  - Longest coherence time (Dicke narrowing).

Experimental setup

(a) Laser Setup



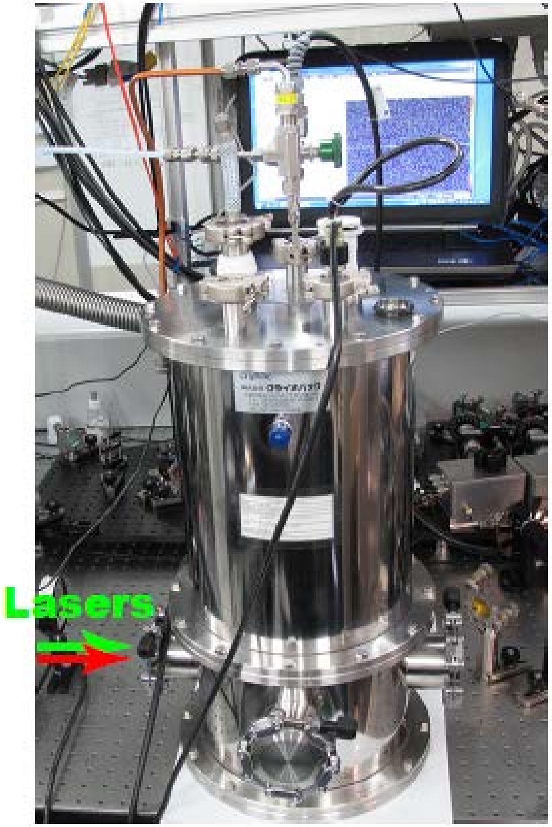
(b) Target & Detector



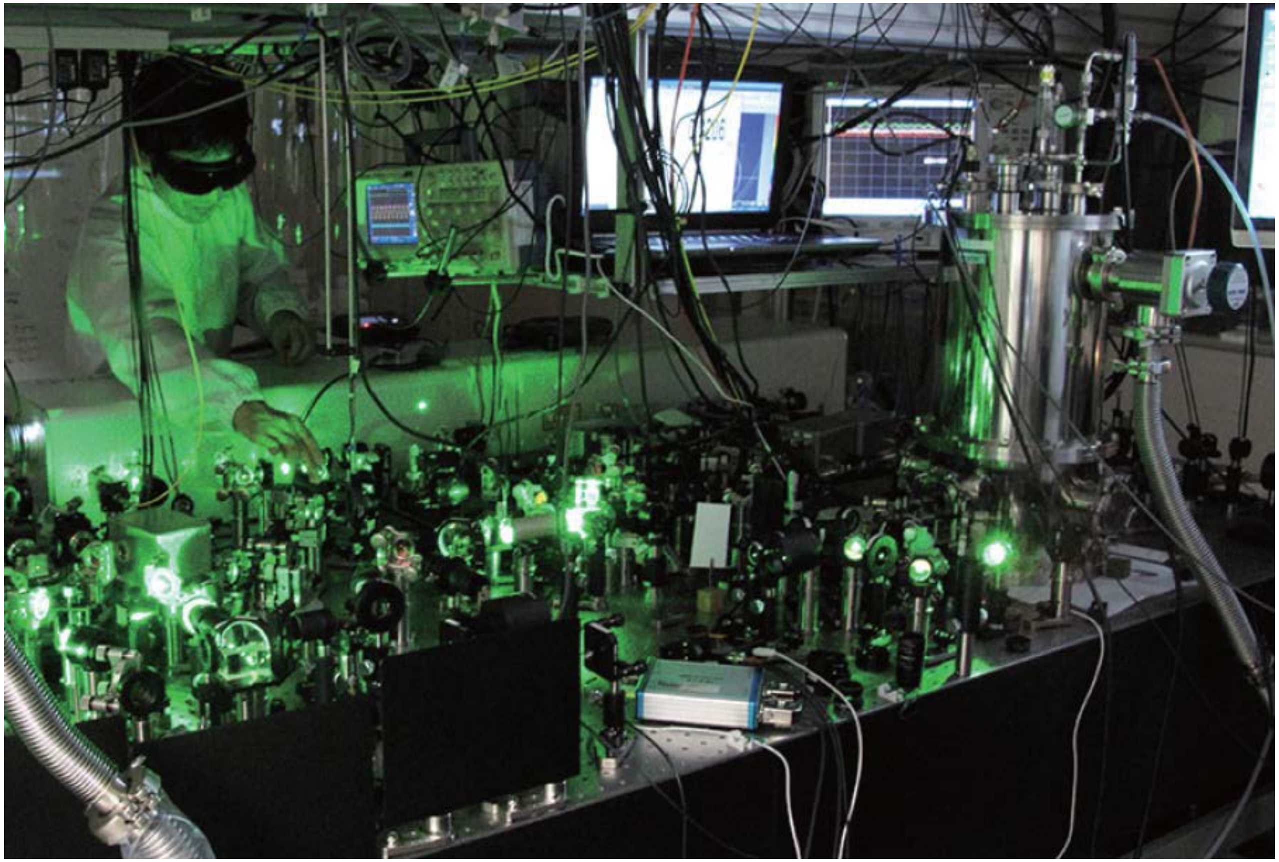
T=77K, P=60kPa
D=2cm, L=15cm

▶ H_2 gas cell (15 cm long)

▶ L-N_2 Cryostat

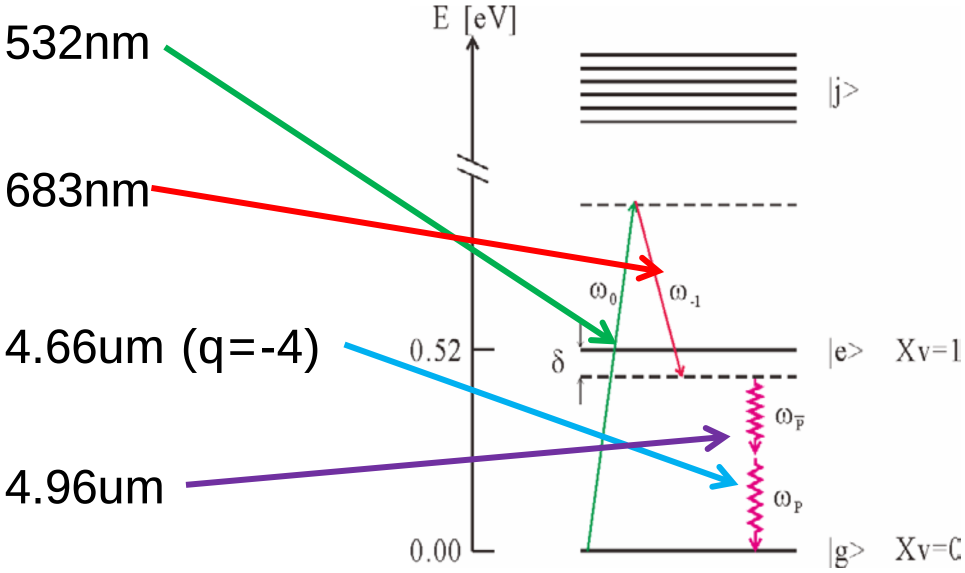


Photograph of whole setup



Wavelengths to be remembered and comments

- Important wavelengths



532nm

683nm

4.66um (q=-4)

4.96um

- Macro-coherent？
  - Energy conservation

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

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

  - Momentum conservation law is equivalent to energy conservation law.

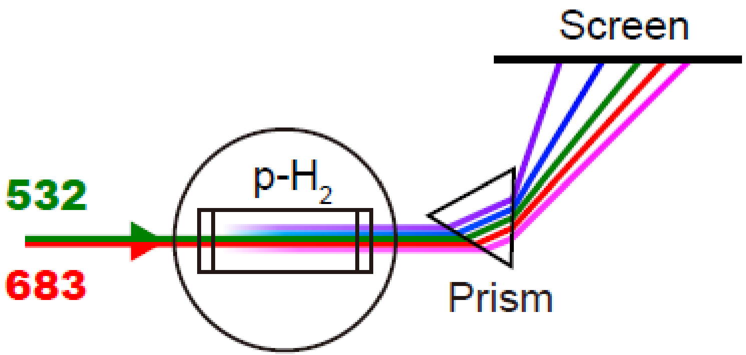
Phase factor added to target

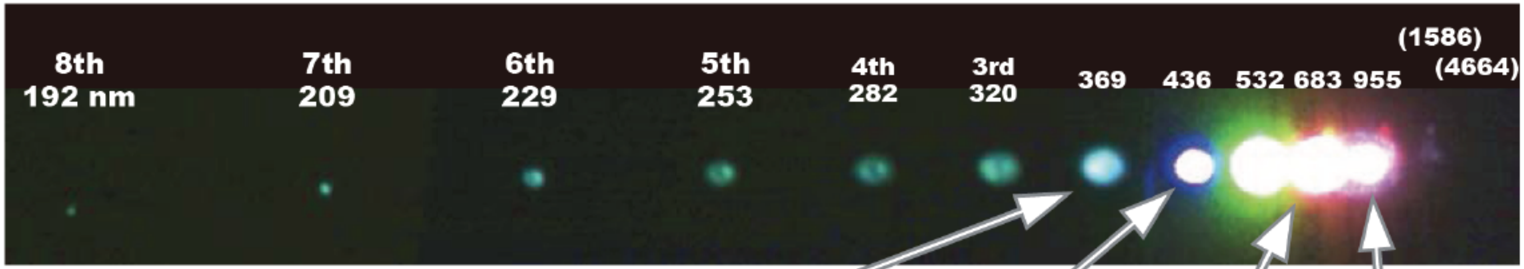
$$e^{i\Delta\omega\cdot x/c}$$

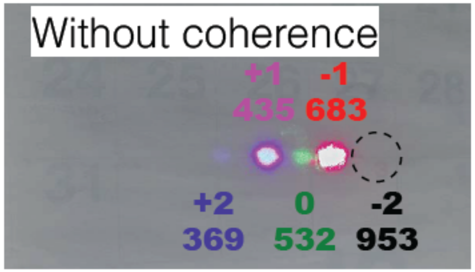
$$\boxed{R = \left|\sum_a^N e^{i(k_1+k_2)x} M_a\right|^2}$$

Observation of Raman sidebands

- 13 sidebands observed (λ=192 - 4662nm)
- Evidence for large coherence







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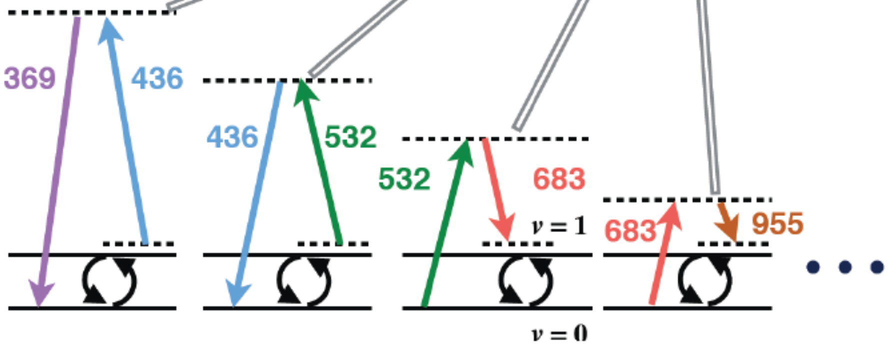

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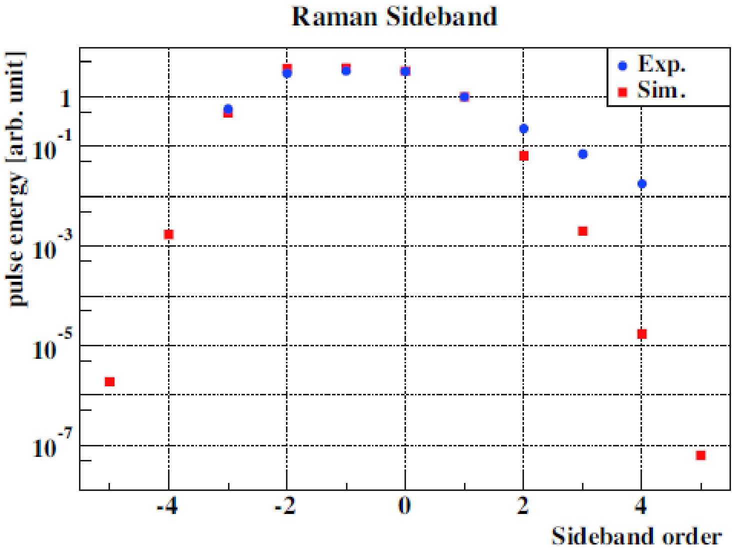
Degree of coherence

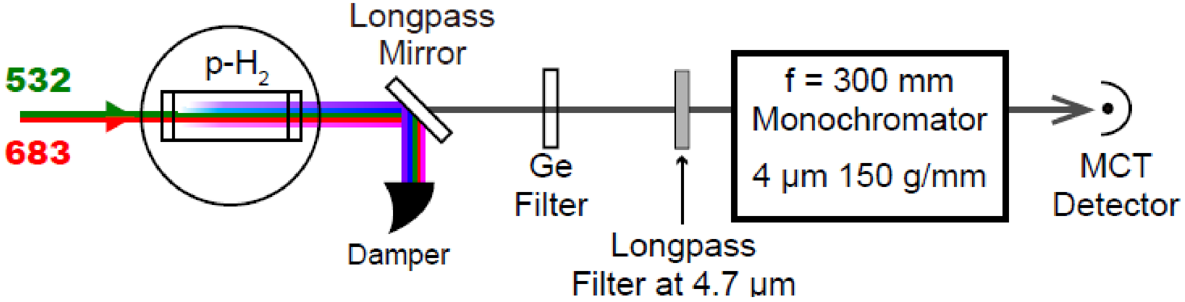
- Maxwell-Bloch eq.



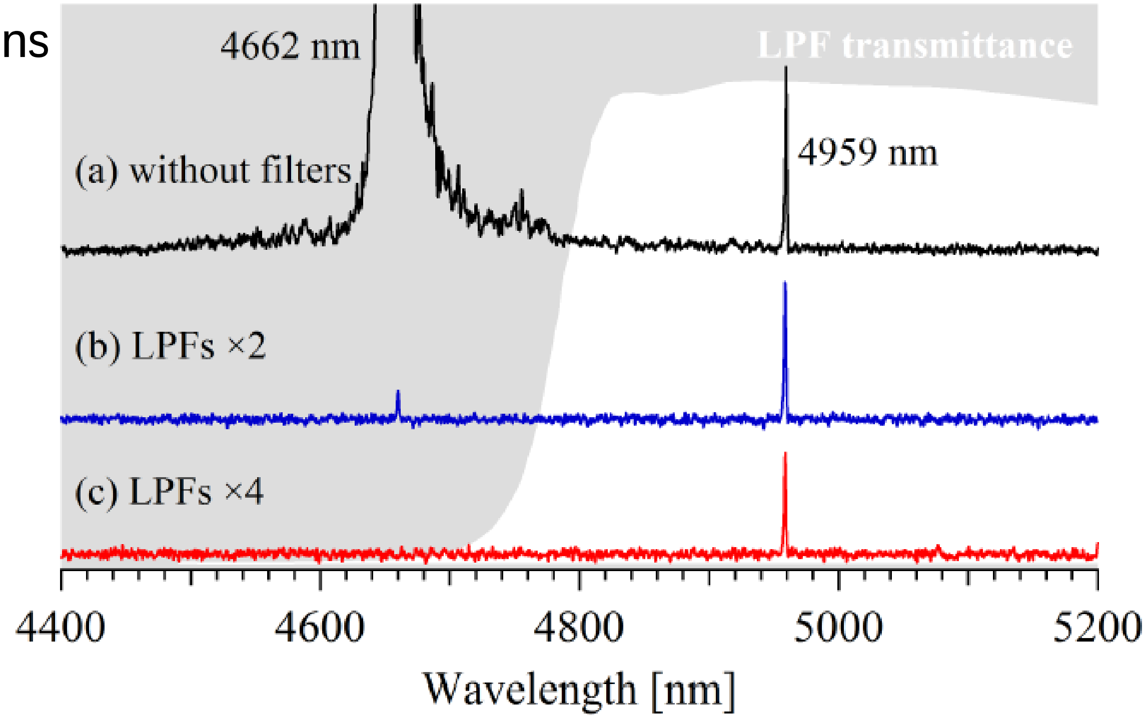
$$
\begin{aligned}
\frac{\partial \rho_{gg}}{\partial \tau} &= i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{gg}, \\
\frac{\partial \rho_{ee}}{\partial \tau} &= i\Big(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}\Big) - \gamma_1 \rho_{ee}, \\
\frac{\partial \rho_{ge}}{\partial \tau} &= i\Big(\Omega_{gg} - \Omega_{ee} + \delta\Big)\rho_{ge} + i\Omega_{ge}\Big(\rho_{ee} - \rho_{gg}\Big) - \gamma_2 \rho_{ge}, \\
\frac{\partial E_q}{\partial \xi} &= \frac{i\omega_q n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(q)} + \rho_{ee}\alpha_{ee}^{(q)}\Big)E_q + \rho_{eg}\alpha_{eg}^{(q-1)}E_{q-1} + \rho_{ge}\alpha_{ge}^{(q)}E_{q+1}\Big\}, \\
\frac{\partial E_p}{\partial \xi} &= \frac{i\omega_p n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(p)} + \rho_{ee}\alpha_{ee}^{(p)}\Big)E_p + \rho_{eg}\alpha_{ge}^{(p\overline{p})}E_{\overline{p}}^{*}\Big\}.
\end{aligned}
$$

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

Observation of two-photon process



- Both 4.66 and 4.96um photons observed.
- 4.66um disappeared when LPFs(4.70um) inserted
- 4.96um remained same with LPF.



Comparison with spontaneous emission

- # of observed photons=4.4 x 10^7/pulse
- # of expected photons due to spontaneous emission

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

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

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

- Huge amplification factor of >10^(15).
- It can only be understood by macro-coherent amplification mechanism.

How far have we reached?

- RENP rate example
  - Γ=50 Hz for Xe $^3P_1$ (8.4365eV).
  - n=7x 10^20 [cm-3]
  - V=100 cm^3, η=10^-3

Γ = n^3 V η (Spectrum function)
η=(average coherence ρ_{eg})x
(stored filed energy)/(n ε_{eg})

- PSR experiment
  - P-H2 (0.52eV).
  - n=6x 10^19 [cm-3],
  - V=1.5x10^-2 cm^3, η=10^-3

Caution: Direct comparison is not allowed because different atoms/molecules and/or different interactions (EM-Weak) are involved.

Contents

- Physics objectives
- Macro-coherent amplification
- Future prospects
- summary

Road map

- Study and control PSR.
  - PSR detailed study
    - PSR by external trigger
    - Counter propagating PSR
  - PSR control
    - Mode switching method

2~3 years

- RENP basic study
    - High density target with coherence
    - Soliton formations
    - Control of background

2~3 years

- RENP experiment

Future (1)

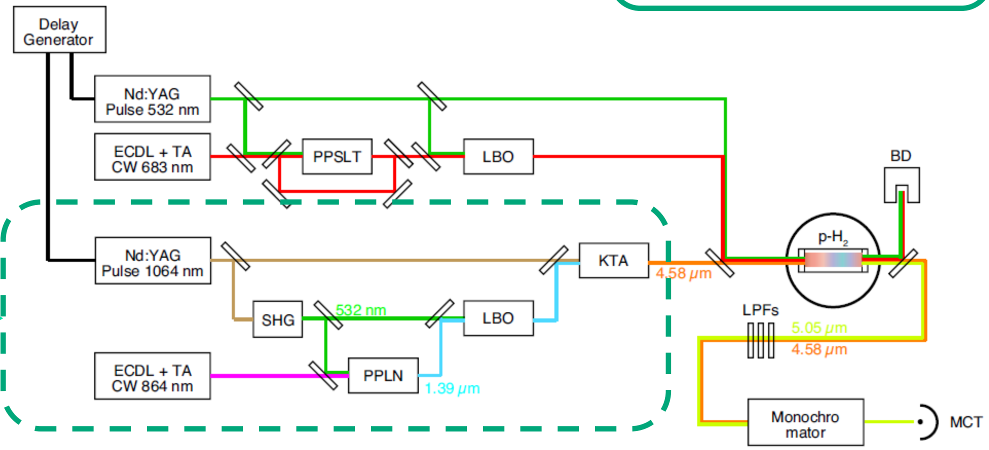
PSR by external trigger

What is new and important?

Raman sideband was used as trigger to induce 2-photon process
Newly built laser is used as trigger

- Study trigger laser power or timing dependence
- Study coherence generation mechanism

Increase amplification



Laser newly built for
External trigger

“Externally triggered coherent two-photon emission from hydrogen molecules”, Yuki Miyamoto et. al. arXiv:1505.07663, accepted for publication in in Prog. Theor. Exp. Phys.

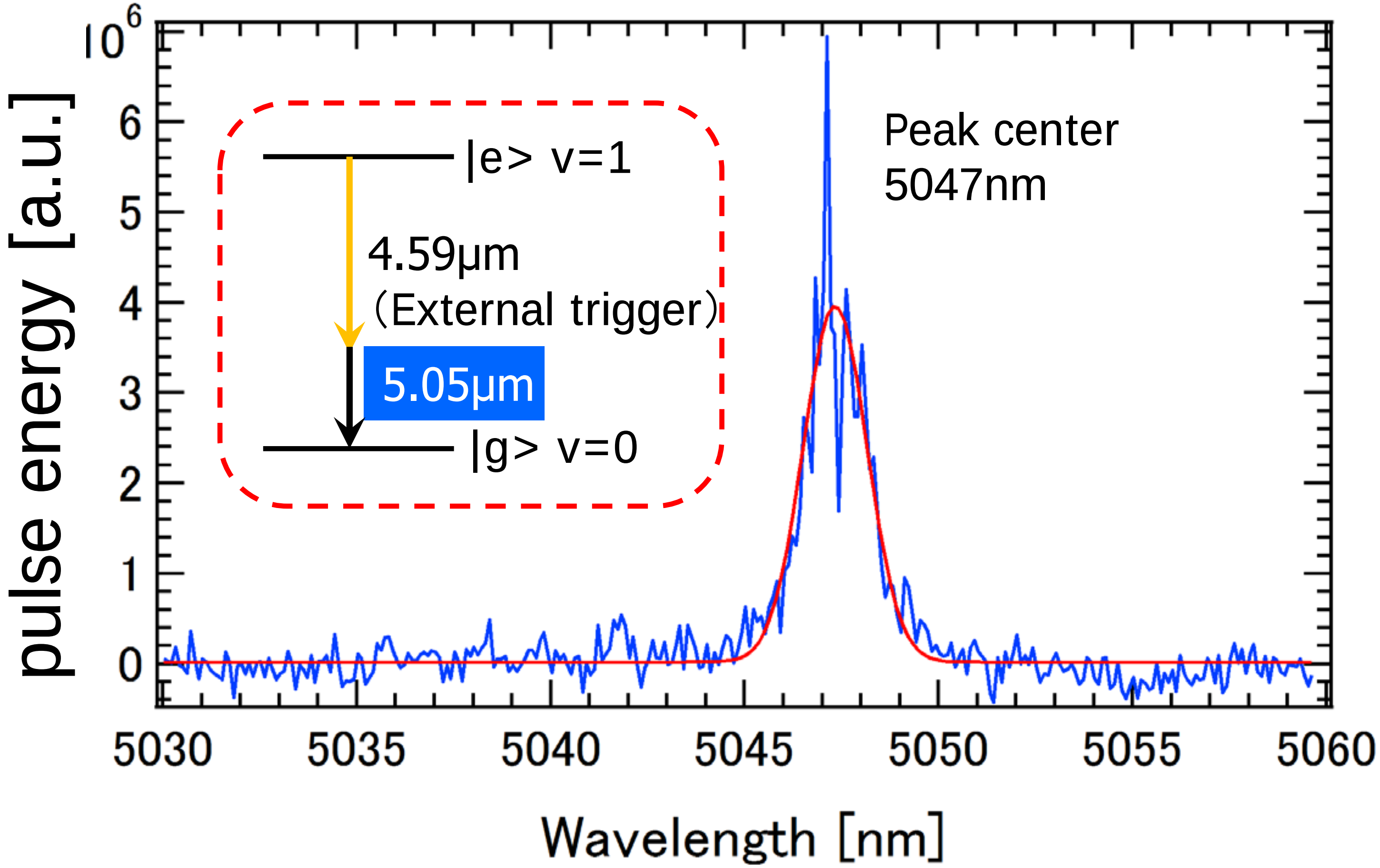
Observed coherent two-photon process by an external trigger

4.96μm（前回）

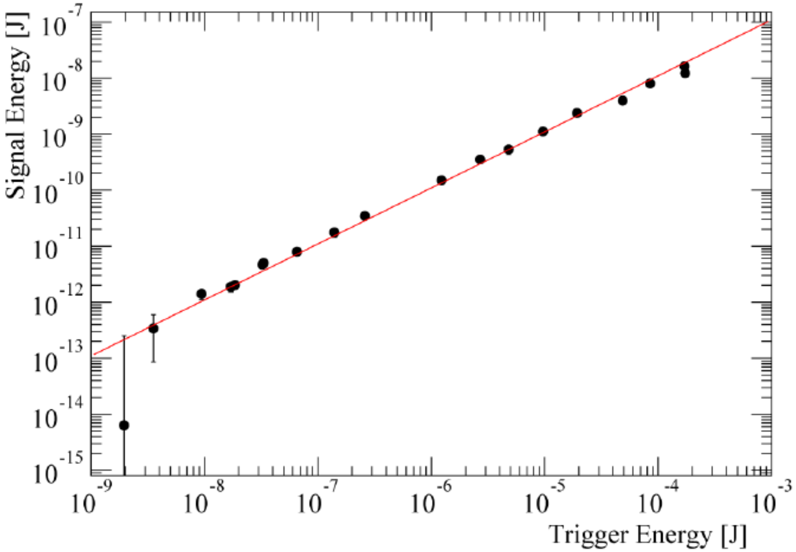
4.4x10^7/pulse

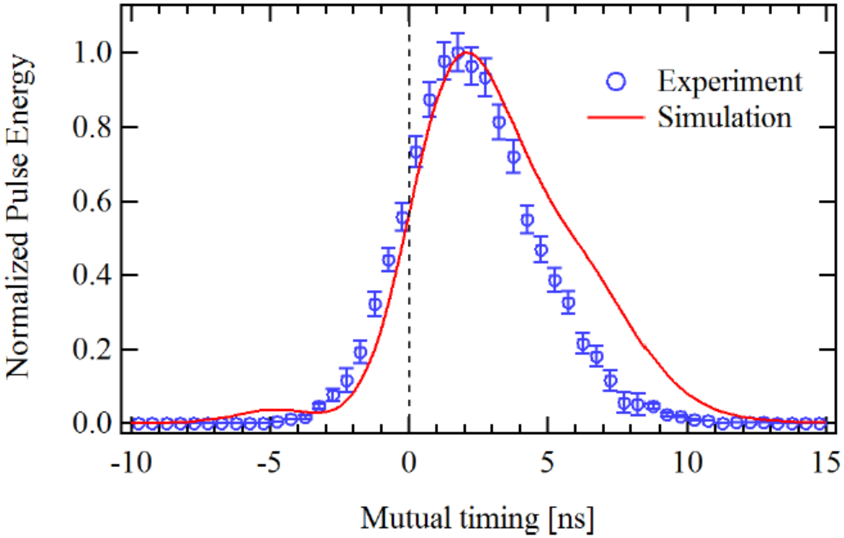
6x10^11/pulse

5.05μm（今回）



Properties of observed signal



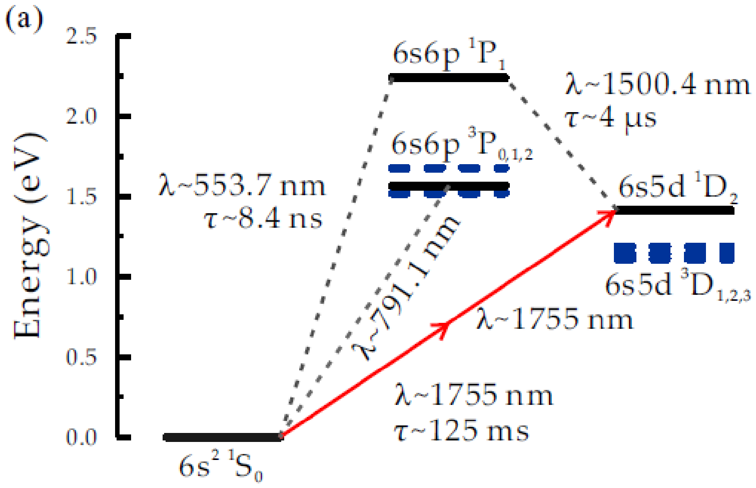


Future (2)

Counter propagating PSR

- Why important?
  - Spatially homogeneous coherence
  - Back-to-back two photons (world first observation!)
  - Soliton may be created only with this configuration
- Candidate atoms
  - Ba, Hg, Xe etc.

（Take Ba as example）



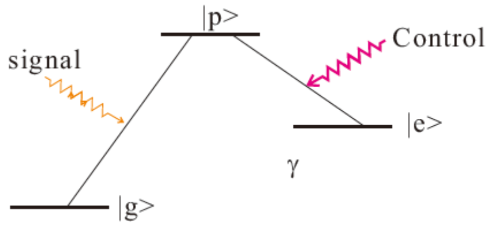
Soliton

PTEP

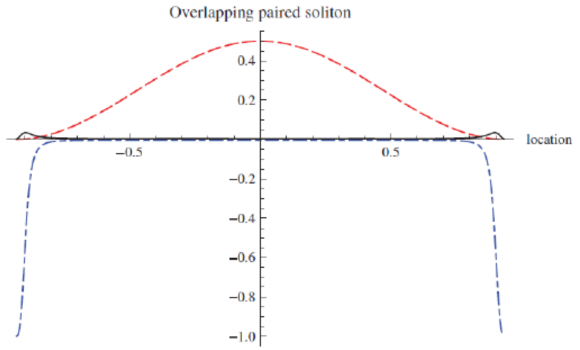
Prog. Theor. Exp. Phys. 2014, 073B02 (14 pages)
DOI: 10.1093/ptep/ptu094

Two-photon paired solitons supported by medium polarization

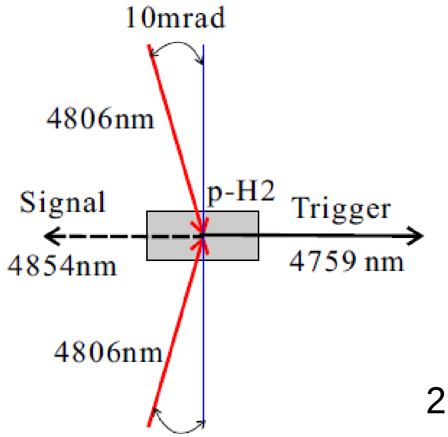
M. Yoshimura[1,*] and N. Sasao[2]



- ”Stopped-light”
  - Control transparency between p-g by irradiating laser lights (control) between p-e
  - Input signal light between p-g, and store information in atomic coherence
  - Retrieve information by control laser
- Two-photon version of ”Stopped-light”
  - Energy condensed state between light field and matter (medium)
  - Existence expected theoretically
  - Created only in counter-propagating PSR
- Need experimental studies
  - Planning to create soliton by irradiating counter propagating lasers with an appropriate intensity structure predicted by theory.

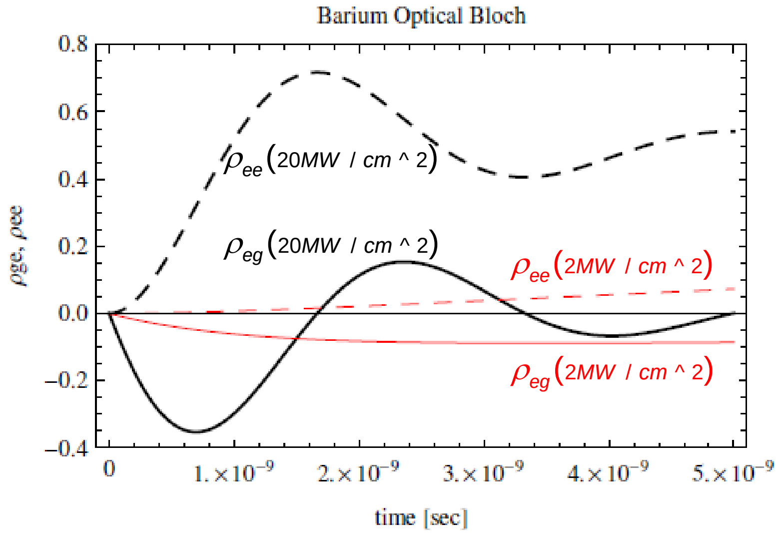


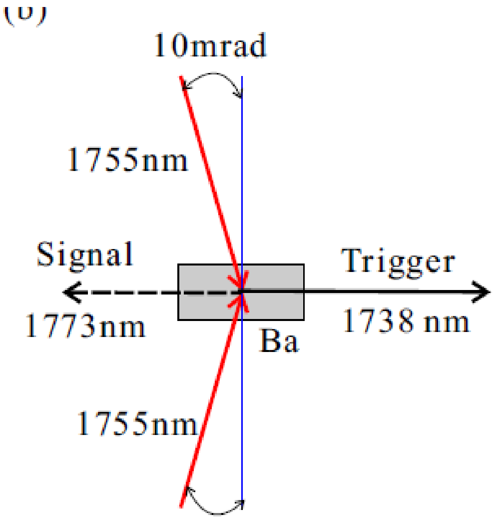
red: field strength
black: coherence
blue: population difference



Example of counter propagating PSR

- Achievable coherence
  - Estimated with optical Bloch eqs
  - Coherence >0.03
- Experimental layout
  - Driving lasers (home made) : 1755nm
  - Counter propagating irradiation
  - Trigger laser (home made) : 1738nm
  - Two photon detection : 1773nm





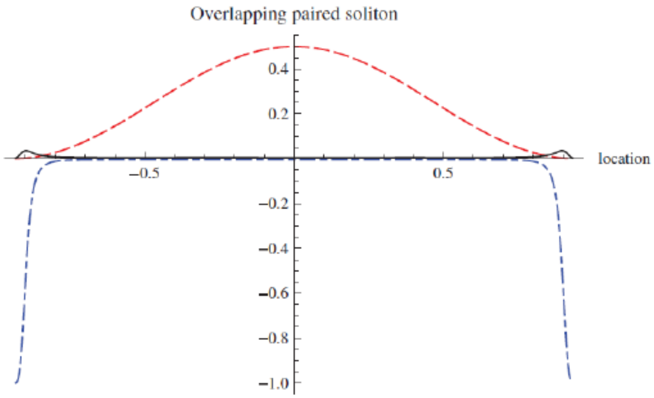
“Two-photon paired solitons supported by medium polarization”,
M. Yoshimura and N. S, Prog. Theor. Exp. Phys., vol. 2014, 073B02 (2014)

Future (3)

RENP basic study

- Soliton formation
- Develop dense coherent target
  - Eg. YSO doped with Eu3+
  - Or Pressurized Xe gas target
  - n > (a few times) 10^20
- Develop high-power laser system
  - Power x10
- Background control

Soliton structure(theory)



Red: Field strength
Black: Coherence
Blue: Population dif.

summary

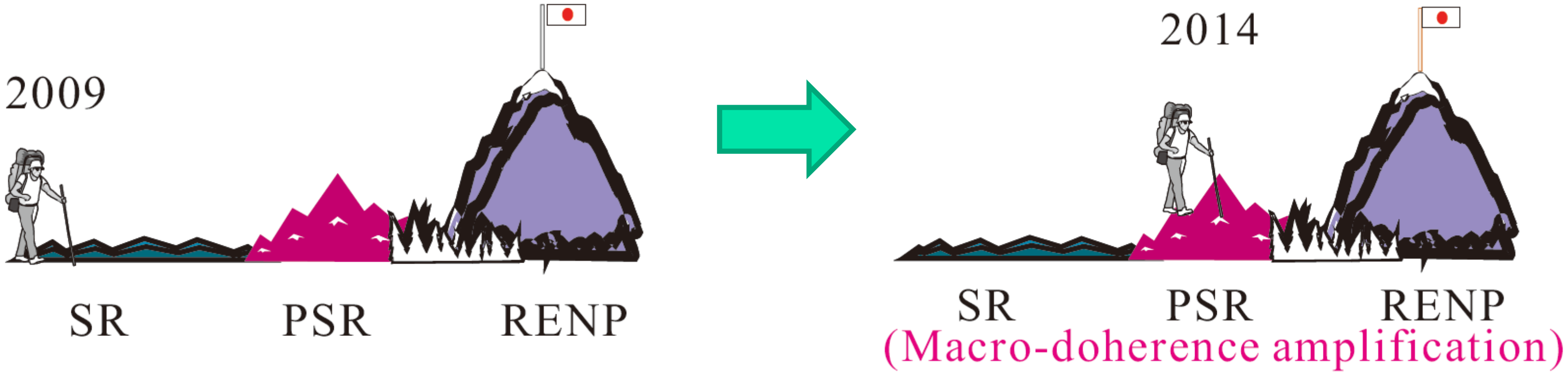
- RENP
  - Systematic way to measure neutrino's undetermined parameters.
  - Absolute mass, M-D distinction, CP-phases
- Macro-coherent amplification
  - Amplification due to coherence among particles
- PSR
  - Huge amplification >10^15 was observed
    using two-photon process from p-H2 vibrational levels.

proves basic part of macro-coherence amplification

- Future prospect
  - PSR Study in more detail
  - RENP basic study
  - RENP experiment

4~6 years

Thank you for your attention



- SPAN group (Spectroscopy with Atomic Neutrino)
- K.Yoshimura, A.Yoshimi, S. Uetake, M. Yoshimura, I. Nakano, Y. Miyamoto. T. Masuda, H.Hara, K. Kawaguchi, J. Tang （Okayama U.）
- M.Tanaka (Osaka U) 、T. Wakabayashi(Kinki U) 、A.Fukumi (Kawasaki)
- S. Kuma(Riken), C. Ohae(UEC) 、K.Nakajima(KEK) 、H.Nanjo (Kyoto)