Physics
OSAKA UNIVERSITY

Neutrino Spectroscopy with Atoms and Molecules

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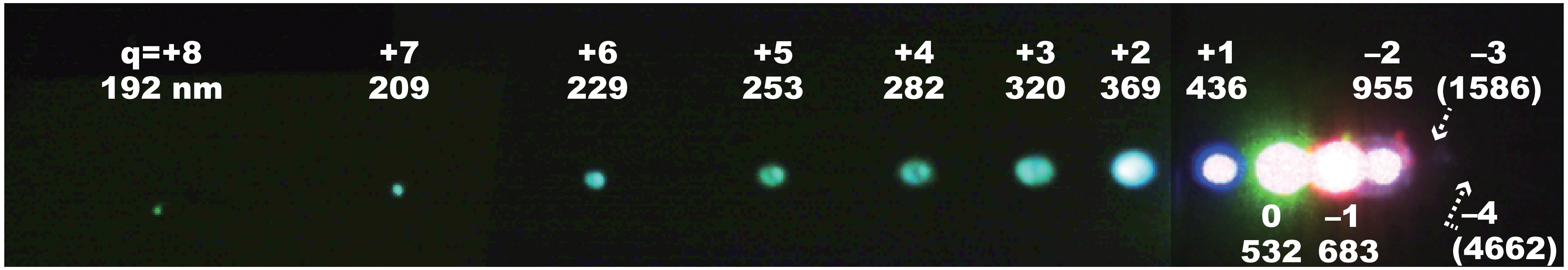


Neutrino Frontier Workshop 2014, Dec. 23, 2014 @ Fuji Calm

SPAN project

SPectroscopy with Atomic Neutrino

Okayama U.

K. Yoshimura, I. Nakano, A. Yoshimi, S. Uetake,
H. Hara, M. Yoshimura, K. Kawaguchi, J. Tang,
Y. Miyamoto

M. Tanaka (Osaka), T. Wakabayashi (Kinki),
A. Fukumi (Kawasaki), S. Kuma (Riken),
C. Ohae (ECU), K. Nakajima (KEK), H. Nanjo (Kyoto)

INTRODUCTION

Unknown properties of neutrinos

Absolute mass

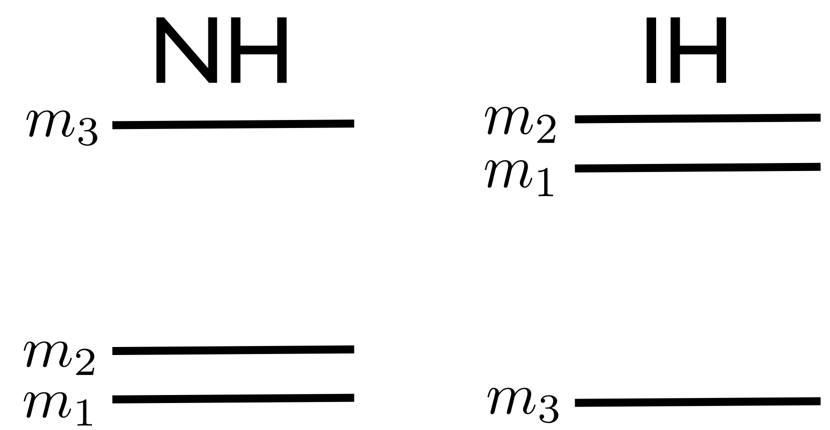
$$m_{1(3)} < 0.19\,\mathrm{eV}\,,\ \ 0.050\,\mathrm{eV} < m_{3(2)} < 0.58\,\mathrm{eV}$$

Mass type

Dirac or Majorana

Hierarchy pattern

normal or inverted



CP violation

one Dirac phase, two Majorana phases

δ $\alpha,\ \beta$

Neutrino experiments

Conventional approach $E \gtrsim O(10\mathrm{keV})$

Neutrino oscillation: SK, T2K, reactors,...

$\Delta m^2, \ \theta_{ij},$ NH or IH, δ

Neutrinoless double beta decays

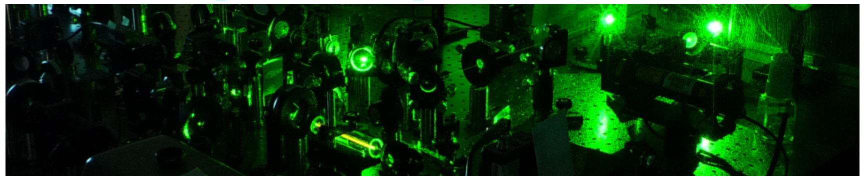
Dirac or Majorana, effective mass $\left|\sum_i m_i U_{ei}^2\right|^2$

Beta decay endpoint: KATRIN

absolute mass

Our approach $E \lesssim O(\mathrm{eV})$ tabletop experiment

Atomic/molecular processes

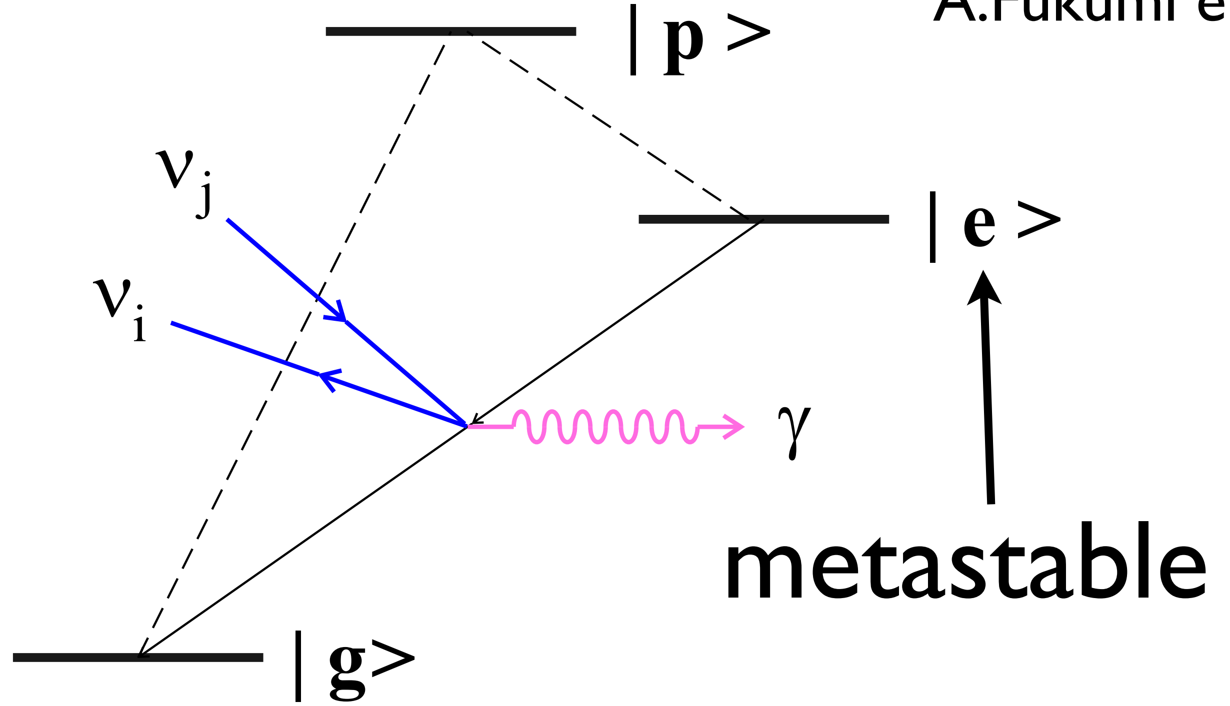


absolute mass, NH or IH, D or M, $\delta, \ \alpha, \ \beta$

RENP

Radiative Emission of Neutrino Pair (RENP)

A.Fukumi et al. PTEP (2012) 04D002, arXiv:1211.4904



$$|e\rangle \to |g\rangle + \gamma + \nu_i \bar{\nu}_j$$

Λ-type level structure

Ba, Xe, Ca+, Yb,...

H_2, O_2, I_2, ...

Atomic/molecular energy scale ~ eV or less

close to the neutrino mass scale

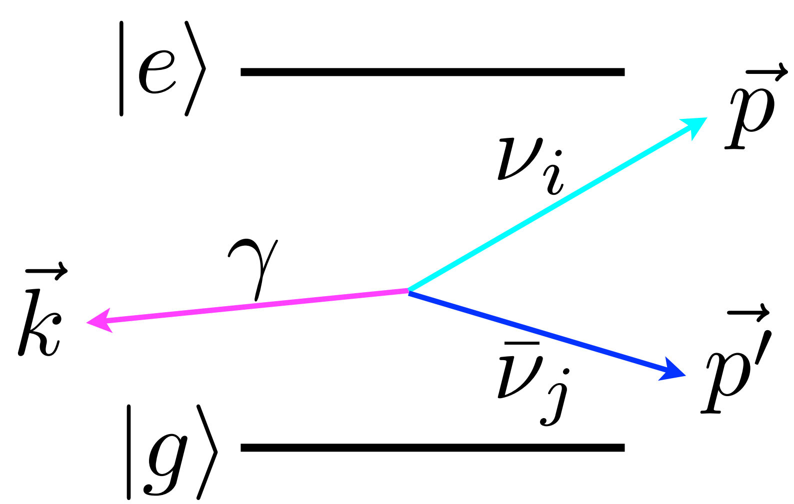
cf. nuclear processes ~ MeV

Rate $\sim \alpha G_F^2 E^5 \sim 1/(10^{33}\,\mathrm{s})$

Enhancement mechanism?

Macrocoherence

Yoshimura et al. (2008)



position of atom

$$\propto e^{-i(\vec{k}+\vec{p}+\vec{p'})\cdot\vec{x}_a}(2\pi)\delta(\epsilon_{eg}-\omega-E_p-E_{p'})$$

$$(\epsilon_{eg}=\epsilon_e-\epsilon_g,\ \omega=|\vec{k}|)$$

Macroscopic target of N atoms, volume V (n=N/V)

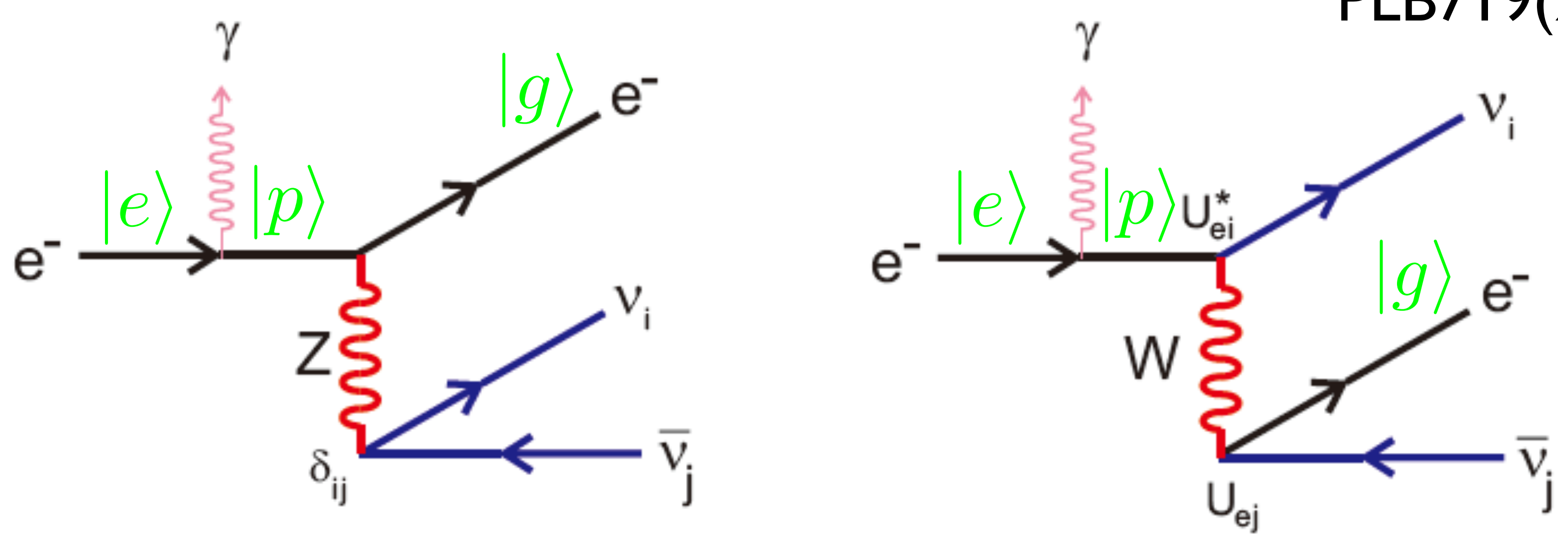
total amp. $\propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p'})\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p'})$

$$d\Gamma \propto \boxed{n^2 V}(2\pi)^4\delta^4(q-p-p') \qquad q^\mu=(\epsilon_{eg}-\omega,-\vec{k})$$

macrocoherent amplification

Neutrino emission from valence electron

D.N. Dinh, S.T. Petcov, N. Sasao, M.T., M.Yoshimura
PLB719(2013)154, arXiv:1209.4808



$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} \sum_{i,j} \bar{\nu}_j \gamma_\mu (1-\gamma_5)\nu_i \, \bar{e}\gamma^\mu (C^V_{ji} - C^A_{ji}\gamma_5) e$$

$$C^V_{ji} = U^*_{ej} U_{ei} + (-1/2 + 2\sin^2\theta_W)\delta_{ji}, \;\; C^A_{ji} = U^*_{ej} U_{ei} - \delta_{ji}/2$$

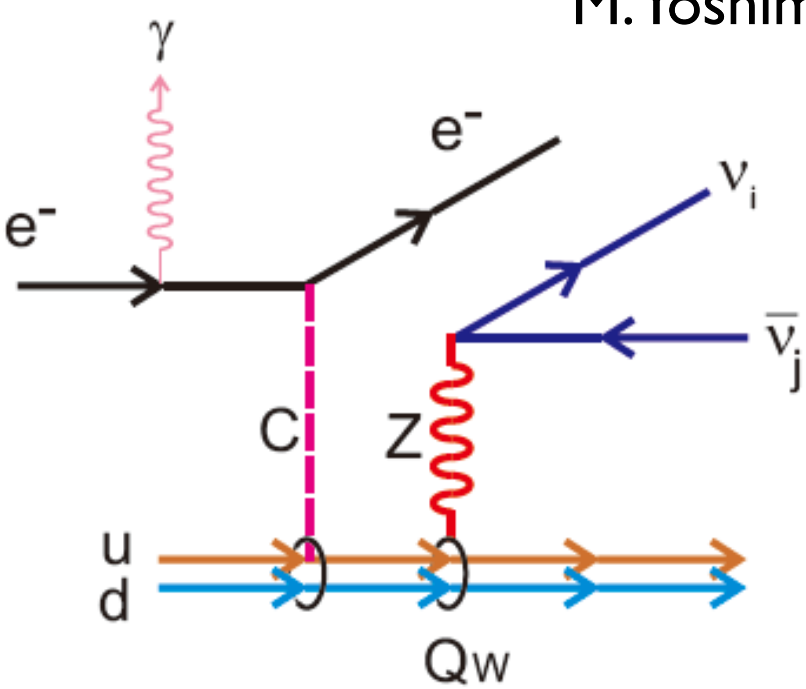
Atomic matrix element in the NR approximation

$$\langle g|\bar{e}\gamma^\mu e|p\rangle \simeq (\langle g|e^\dagger e|p\rangle, \mathbf{0}) = 0$$

$$\langle g|\bar{e}\gamma^\mu \gamma_5 e|p\rangle \simeq (0, 2\langle g|\boldsymbol{s}|p\rangle) \longrightarrow \text{spin current}$$

Neutrino emission from nucleus

M.Yoshimura and N. Sasao, PRD89, 053013(2014), arXiv:1310.6472



flavor diagonal

no PMNS, no phases

weak charge: $Q_W \simeq -(\#\text{ of neutrons})$

cf. atomic parity violation

$$\mathcal{H}_W = 4\frac{G_F}{\sqrt{2}}\sum_{i,q}\bar{\nu}_i\gamma_\mu(1-\gamma_5)\nu_i\,\bar{q}\gamma_\mu(v_q - a_q\gamma_5)q$$

Nuclear matrix element in the NR limit

$$\langle N|\sum_q 4v_q\bar{q}\gamma^\mu q|N\rangle \simeq (Q_W, \mathbf{0})$$

nuclear monopole $\propto Q_W^2 Z^{8/3}$ enhancement

RENP spectrum

Energy-momentum conservation
due to the macro-coherence
→ familiar 3-body decay kinematics

Six (or three) thresholds of the photon energy

$$\omega_{ij} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}} \qquad i, j = 1, 2, 3$$

$$\epsilon_{eg} = \epsilon_e - \epsilon_g$$ atomic energy diff.

Required energy resolution $\sim O(10^{-6})\,\mathrm{eV}$

typical laser linewidth

$$\Delta\omega_{\mathrm{trig.}} \lesssim 1\,\mathrm{GHz} \sim O(10^{-6})\,\mathrm{eV}$$

RENP rate formula

dynamical factor

$$\Gamma_{\gamma 2\nu}(\omega, t) = \Gamma_0 I(\omega) \eta_\omega(t)$$

spectral function

overall rate

Overall rate

macro-coherence

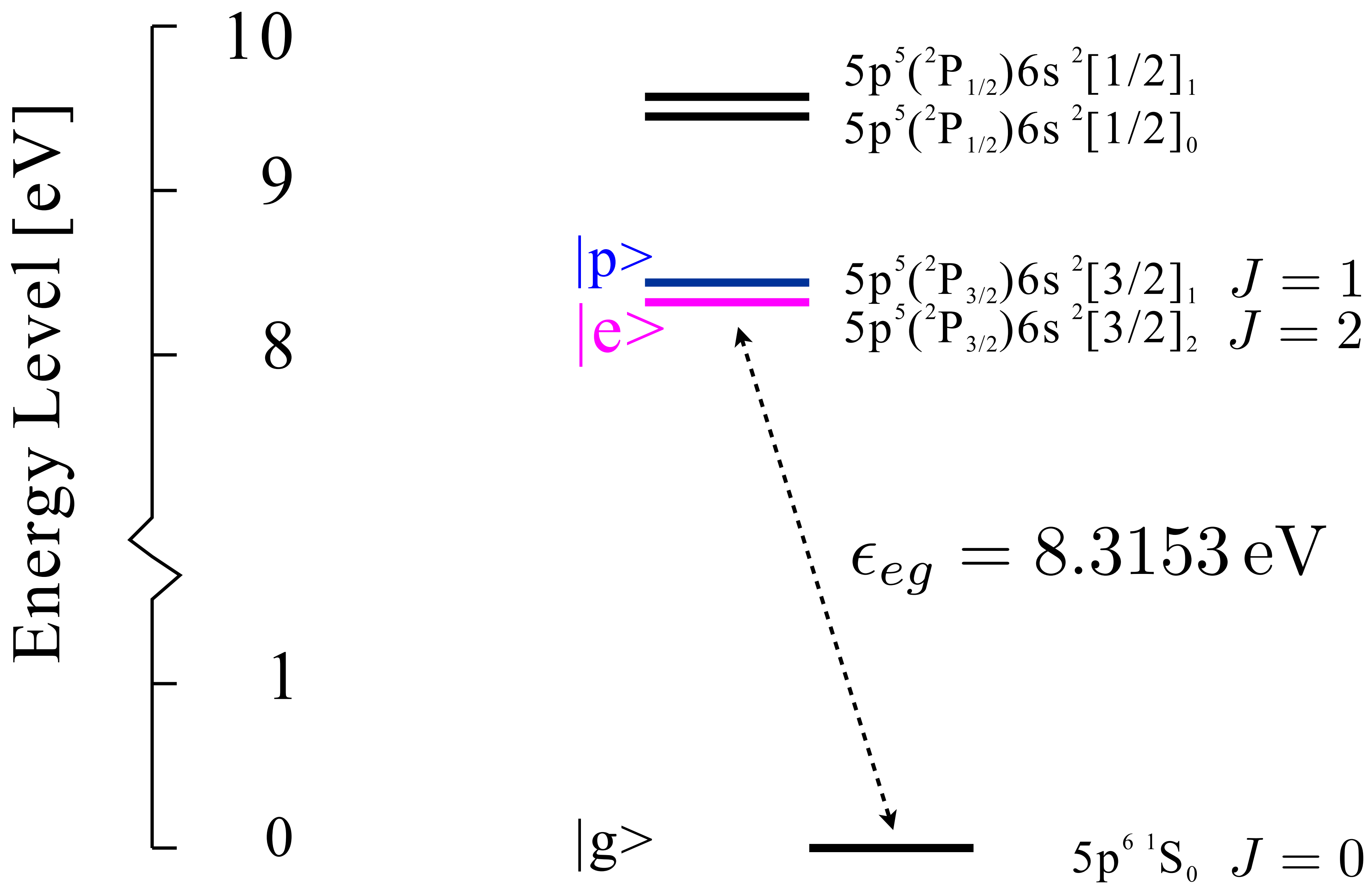
~ field energy density

$$\Gamma_0^{\rm SC} \sim \frac{3n^2 V G_F^2 \gamma_{pg} \epsilon_{eg} n}{2\epsilon_{pg}^3} \sim 1 \ {\rm mHz} \, (n/10^{21} {\rm cm}^{-3})^3 (V/10^2 {\rm cm}^3)$$

$\gamma_{pg} : |p\rangle \to |g\rangle$ **rate**

$$\Gamma_0^M \sim Q_W^2 Z^{8/3} \times \Gamma_0^S \sim 100 \ {\rm kHz}$$

Xe (gas target)

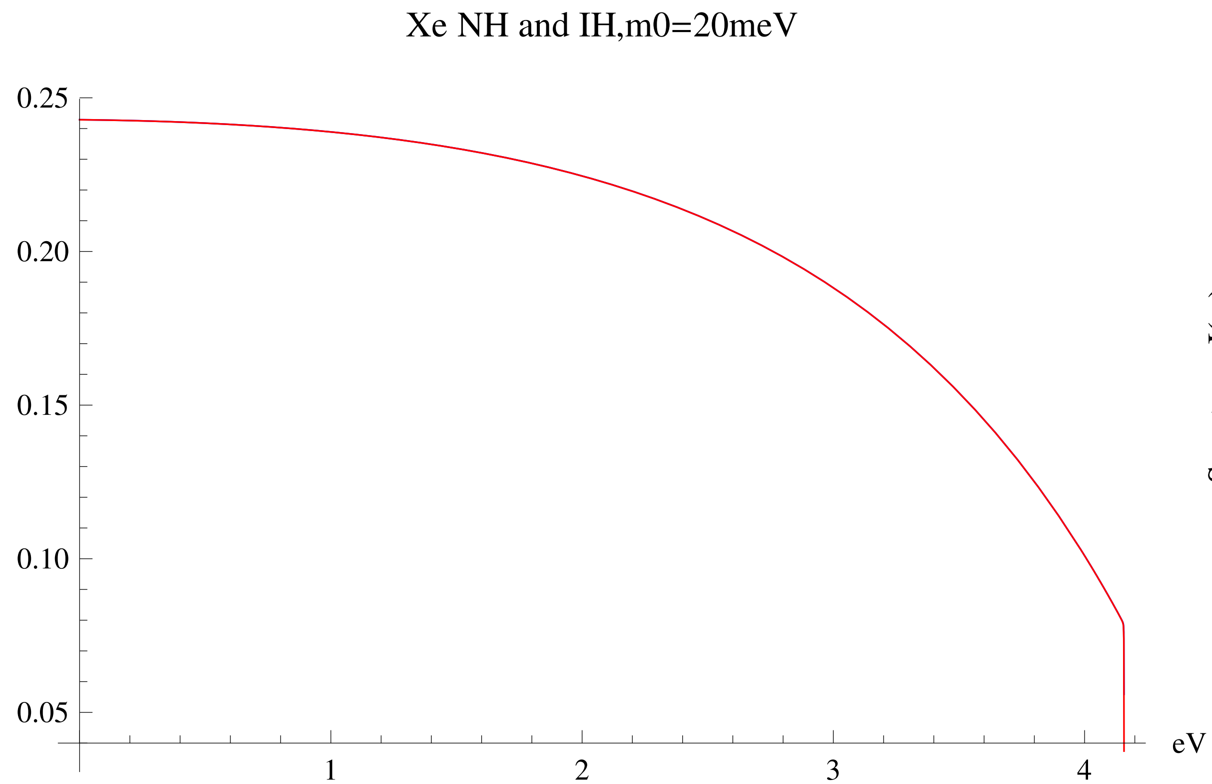


$|e\rangle \leftrightarrow |p\rangle \quad \mathrm{M1}$

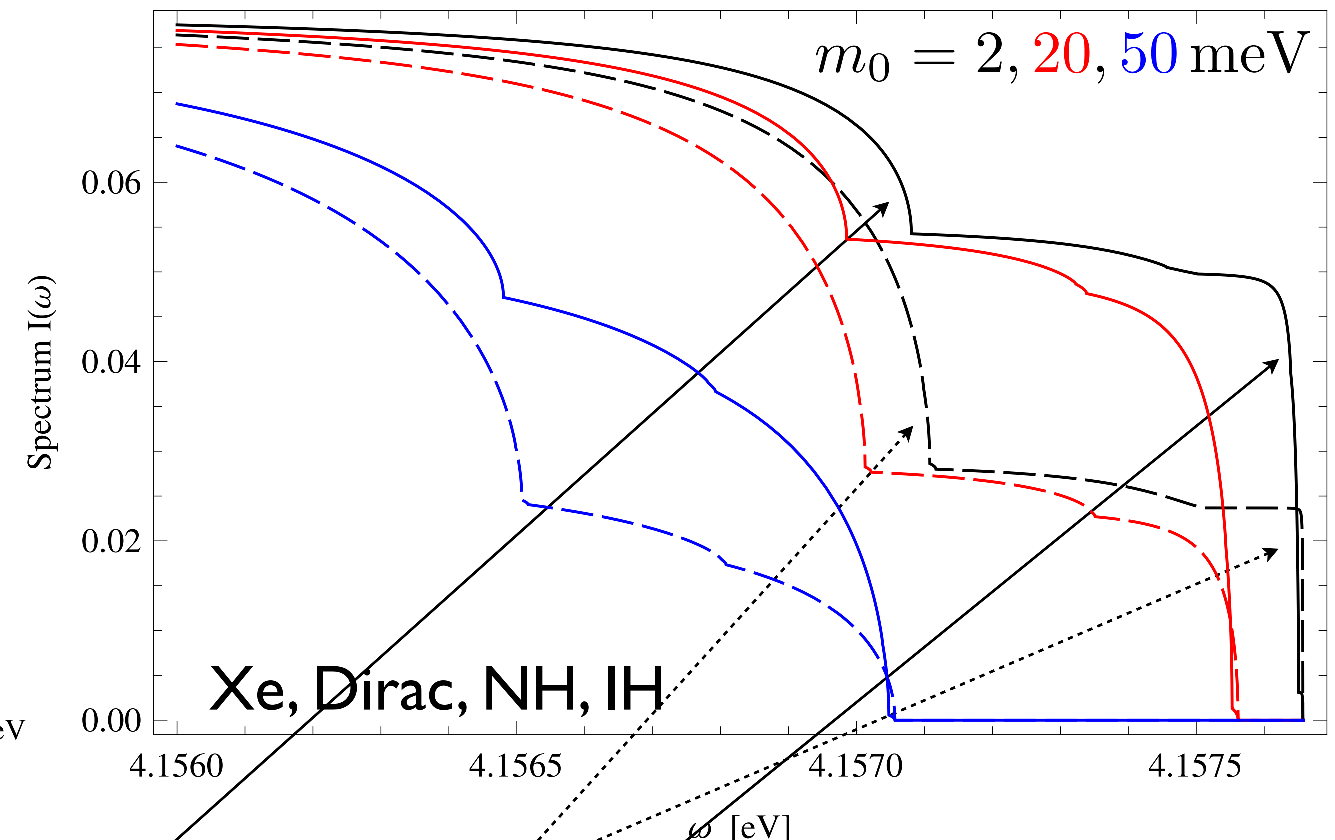
$|p\rangle \leftrightarrow |g\rangle \quad \mathrm{E1}$

Photon spectrum (spin current)

Global shape



Threshold region



The threshold weight factors

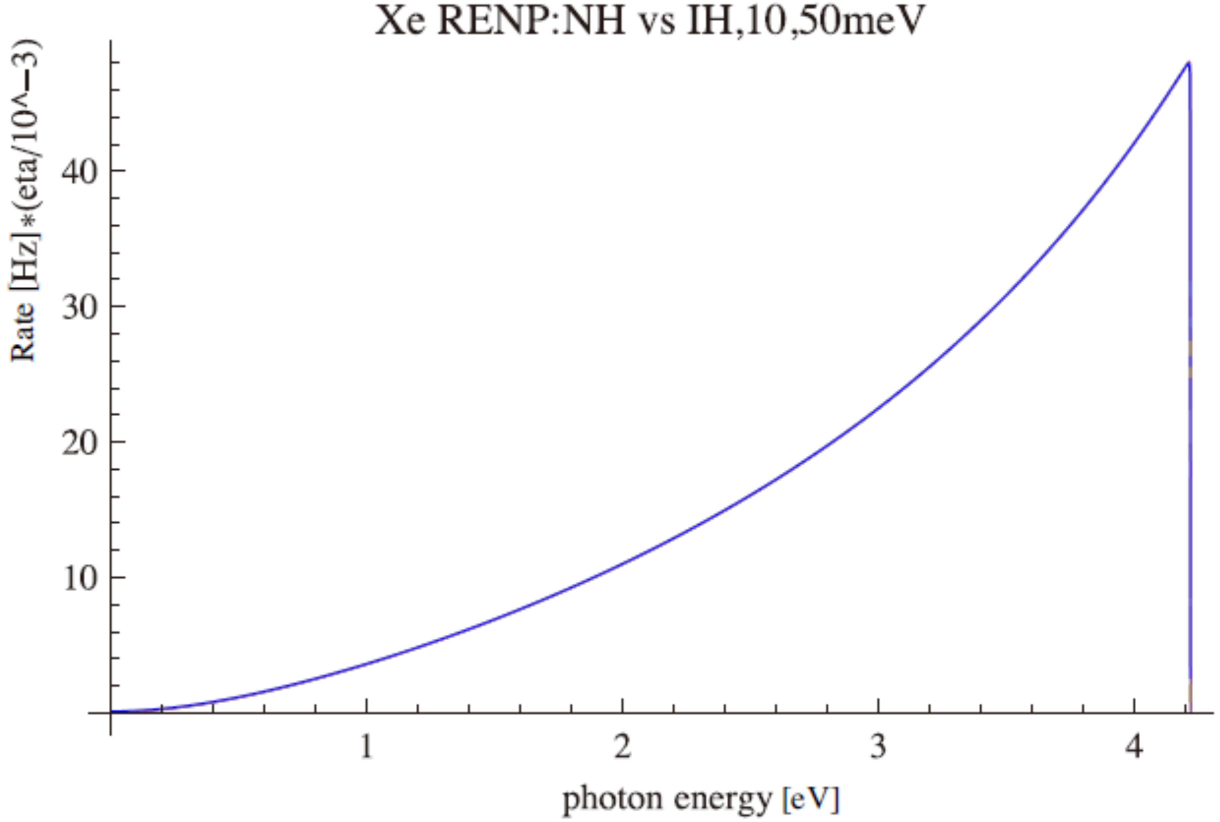
B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2c_{13}^2-1/2)^2$	$(s_{12}^2c_{13}^2-1/2)^2$	$(s_{13}^2-1/2)^2$	$2c_{12}^2s_{12}^2c_{13}^4$	$2s_{12}^2c_{13}^2s_{13}^2$	$2c_{12}^2c_{13}^2s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

Photon spectrum (nuclear monopole)

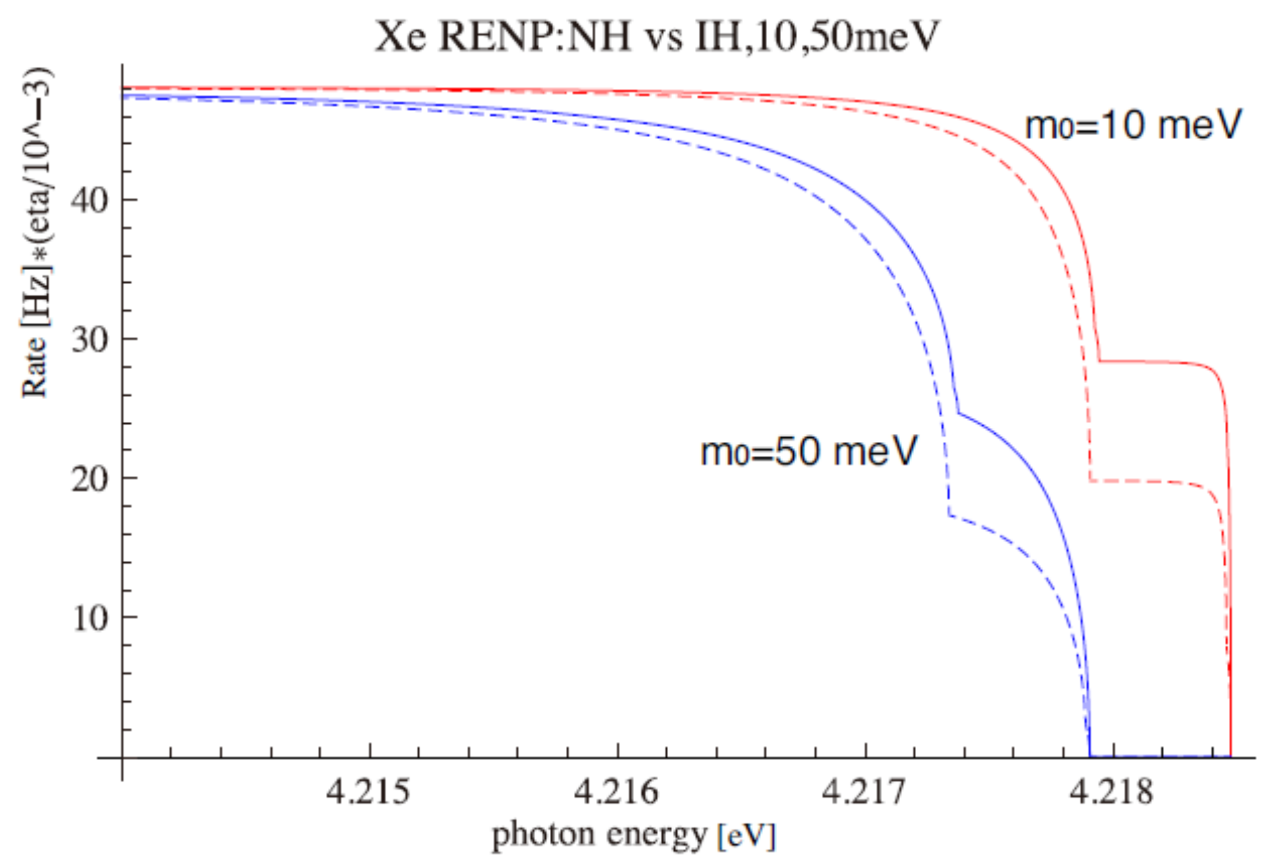
Xe $^3\mathrm{P}_1$ 8.4365 eV

$$n = 7 \times 10^{19}\ \mathrm{cm}^{-3} \quad V = 100\ \mathrm{cm}^3$$

Global shape



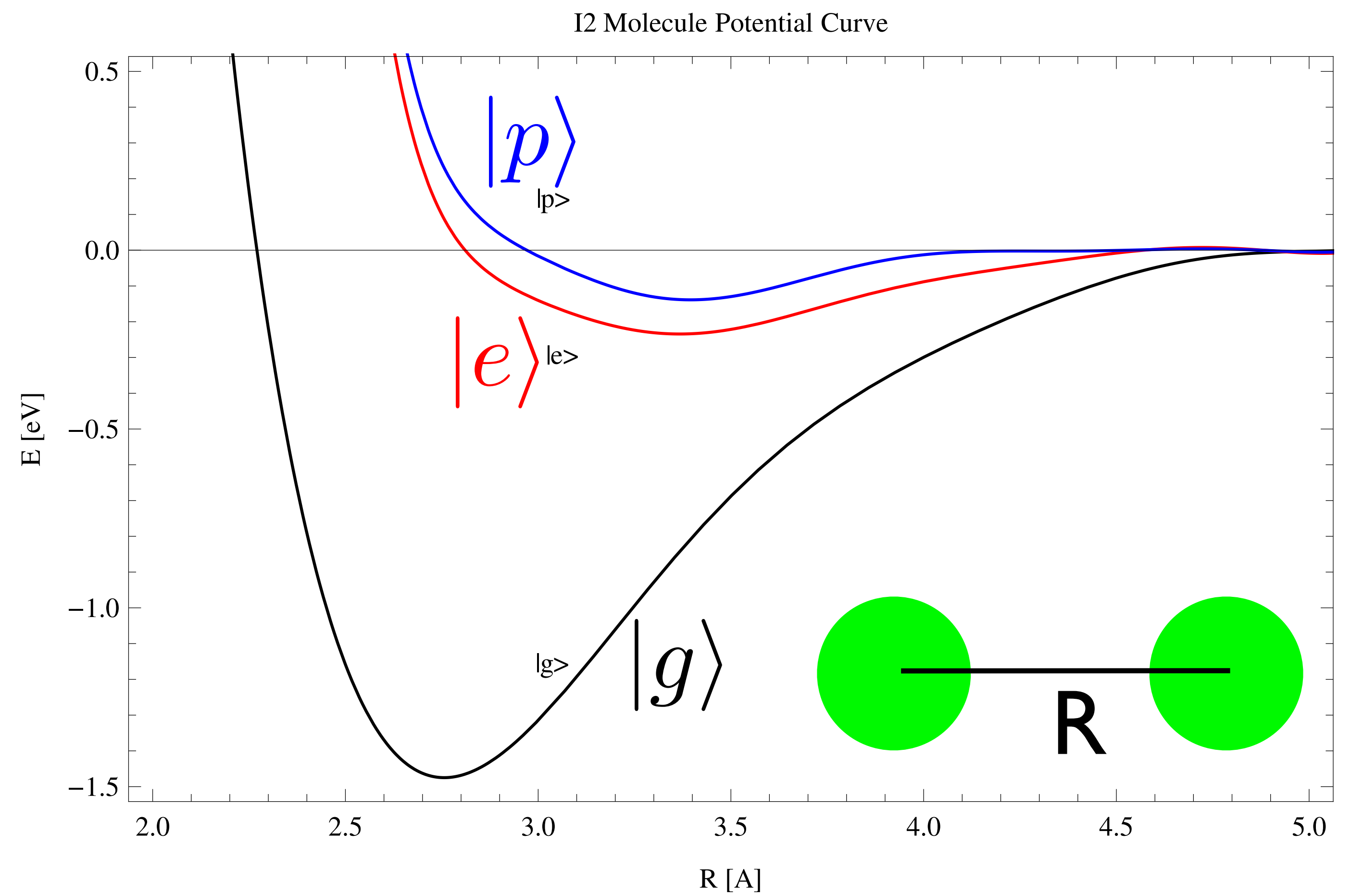
Threshold region

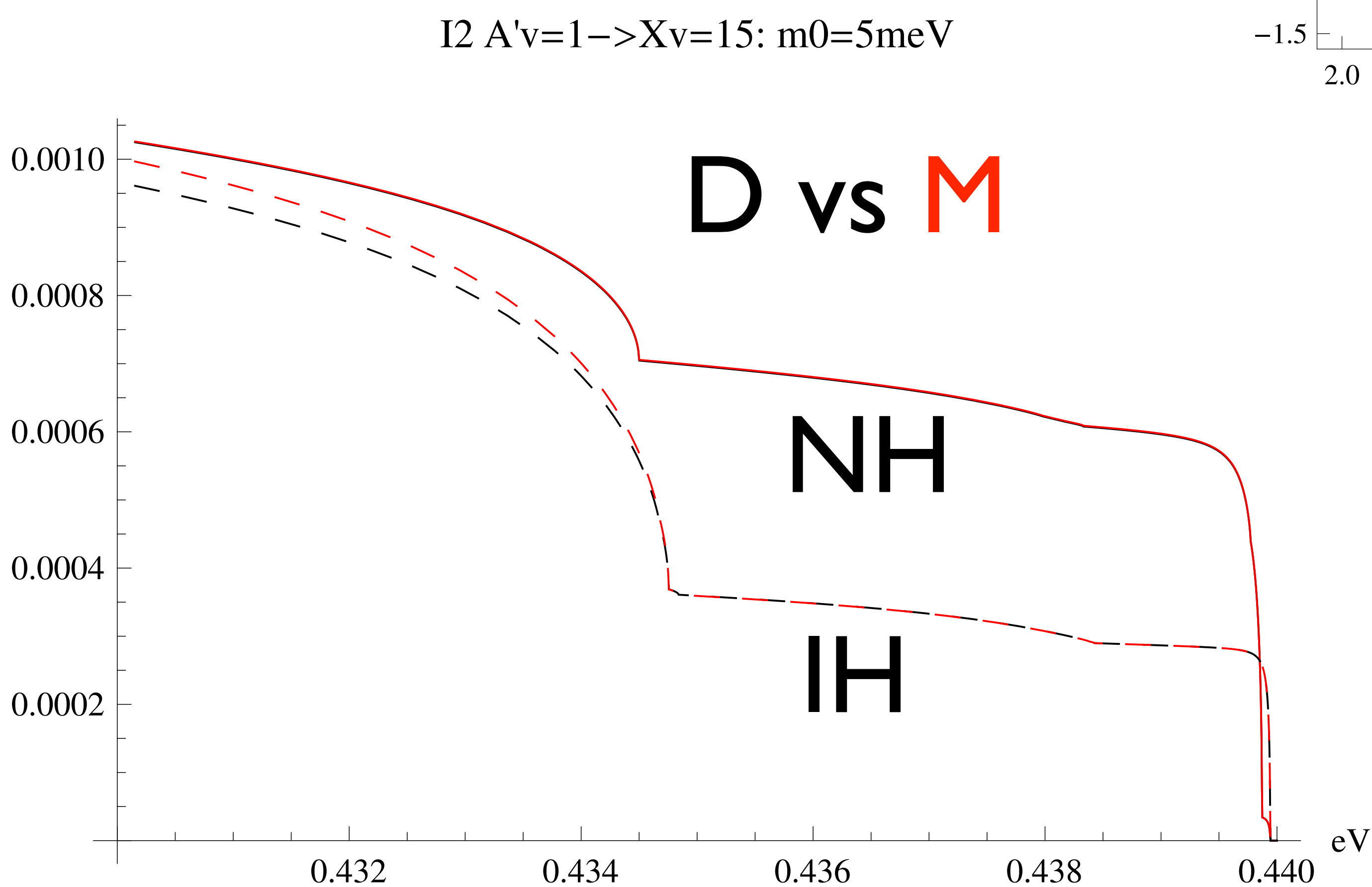


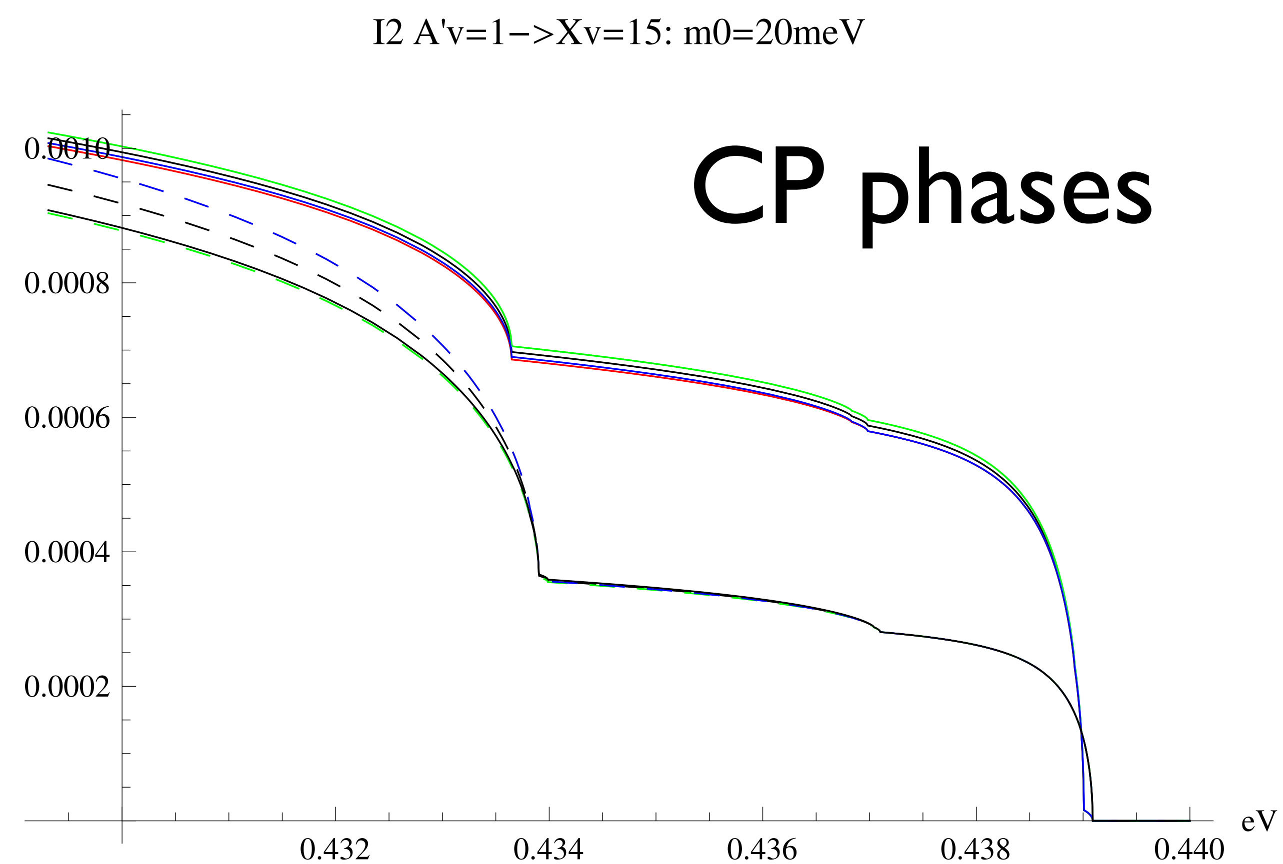
I2 molecule

potential curves

$\epsilon_{eg} \sim 1\,\mathrm{eV}$







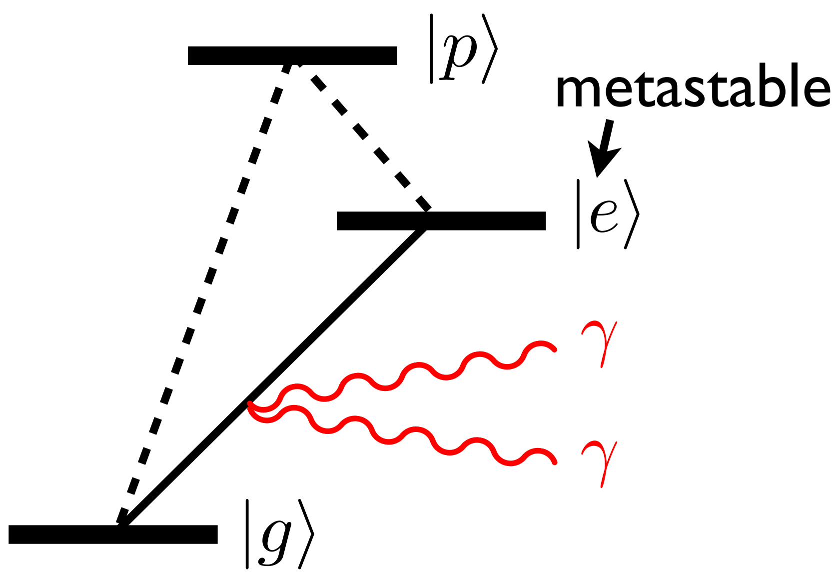
D-M diff. < 10%

PSR

Paired Super-Radiance (PSR)

M. Yoshimura, N. Sasao, MT, PRA86, 013812 (2012)

$$|e\rangle \to |g\rangle + \gamma + \gamma$$



Prototype for RENP

proof-of-concept for the macrocoherence

Preparation of initial state for RENP

coherence generation ρ_{eg}

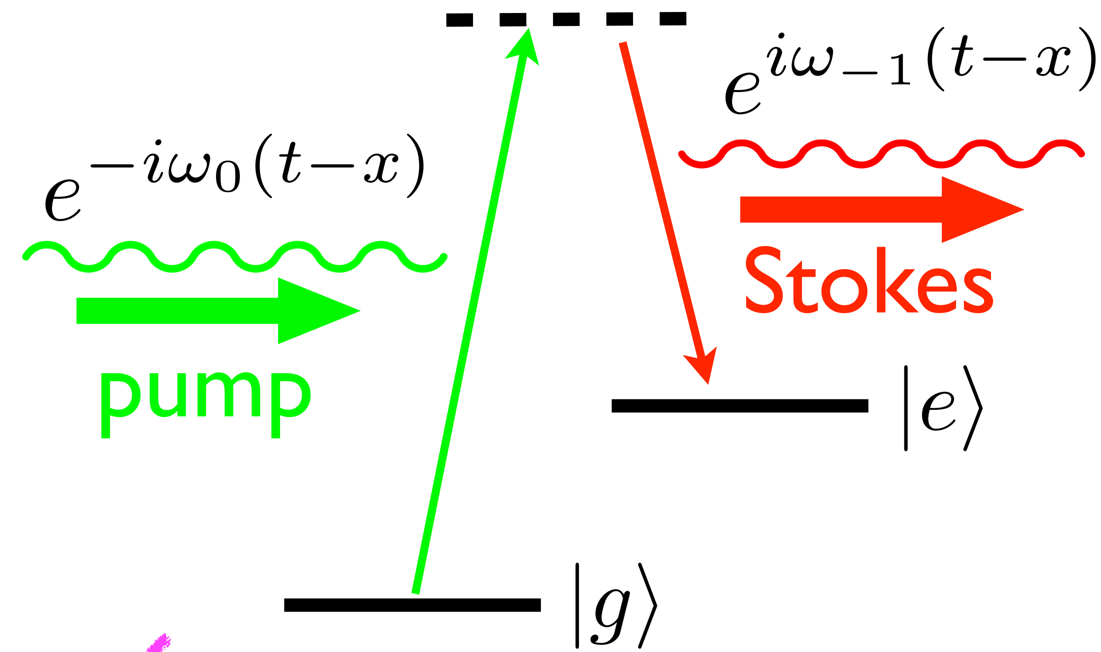
dynamical factor $\eta_\omega(t)$

Theoretical description to be tested

Maxwell-Bloch equation

PSR with spatial gratings

How to populate $|e\rangle$



Raman scattering

$$\omega_0 - \omega_{-1} = \epsilon_{eg}$$

Generated coherence

density matrix

spatial grating

$$\rho_{eg} = \rho_{eg}^{(0)} + \boxed{\rho_{eg}^{(+)} e^{i\epsilon_{eg} x}} + \rho_{eg}^{(-)} e^{-i\epsilon_{eg} x}$$

$$e^{i\omega_p(t-x)} e^{i\omega_{\bar{p}}(t-x)} = e^{i\epsilon_{eg}(t-x)}$$

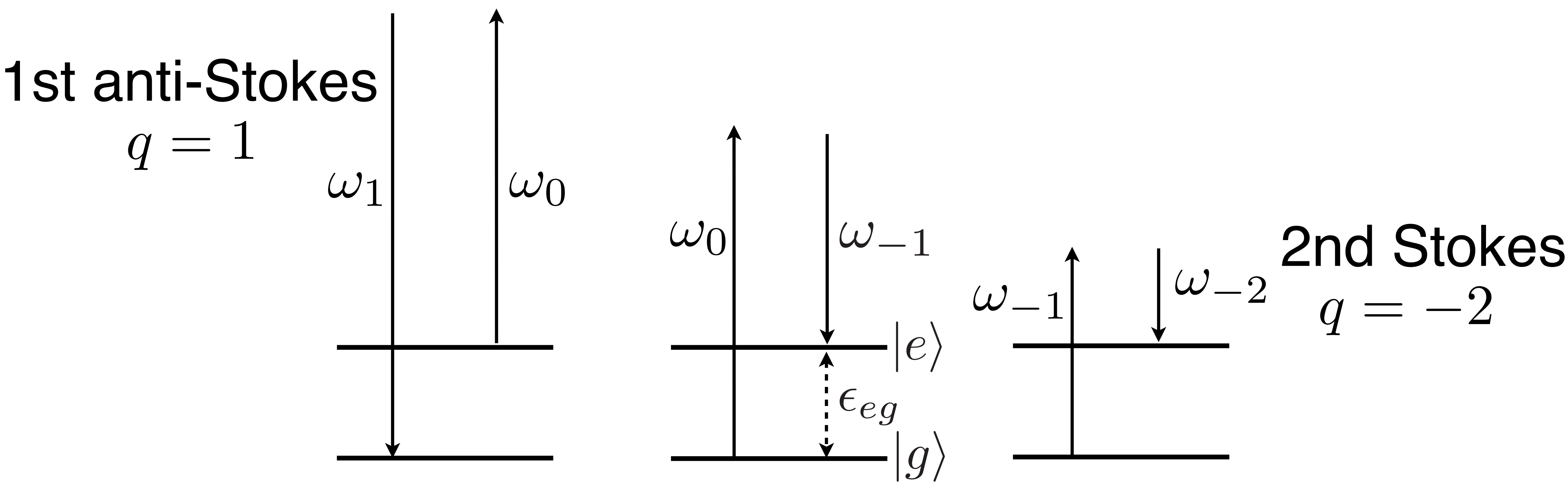
$$\omega_p + \omega_{\bar{p}} = \epsilon_{eg}$$

Macrocoherence $\longrightarrow$ Unidirectional PSR

Raman sidebands

Harris, Sokolov, Phys. Rev. A55, R4019(1997)

Kien, Liang, Katsuragawa, Ohtsuki, Hakuta, Sokolov, Phys. Rev. A60, 1562(1999)

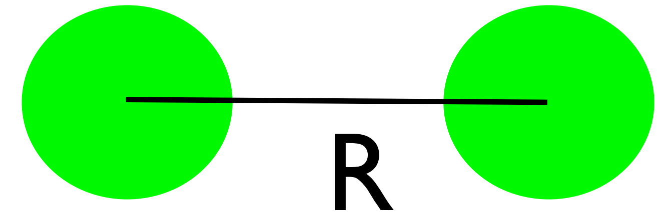


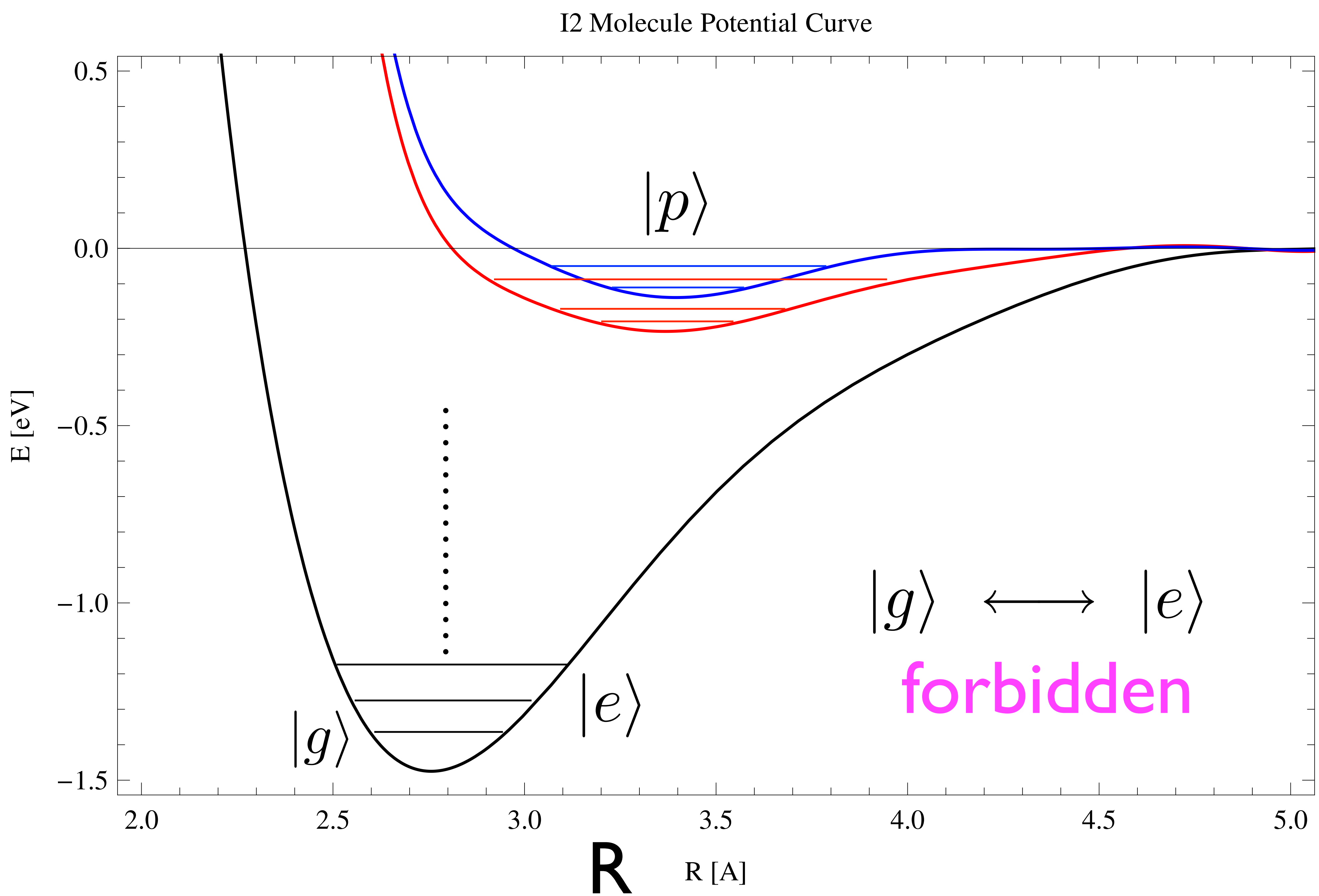
$$\omega_q = \omega_0 + q\epsilon_{eg}$$

$q \geq q_{\min}$ the lowest Stokes

Homonuclear diatomic molecule

Potential curves





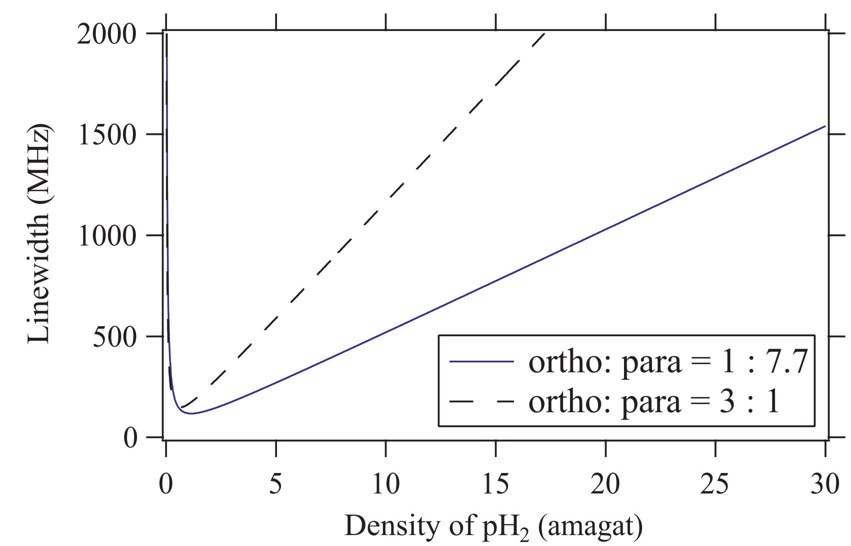
Para-hydrogen gas PSR experiment @ Okayama U

Y. Miyamoto et al., PTEP 113C01(2014), arXiv:1406.2198.

Vibrational transition of p-H2

$$|e\rangle = |Xv=1\rangle \longrightarrow |g\rangle = |Xv=0\rangle$$

two-photon decay: $\tau_{2\gamma} \sim 10^{12}$ s



p-H2: nuclear spin=singlet

smaller decoherence

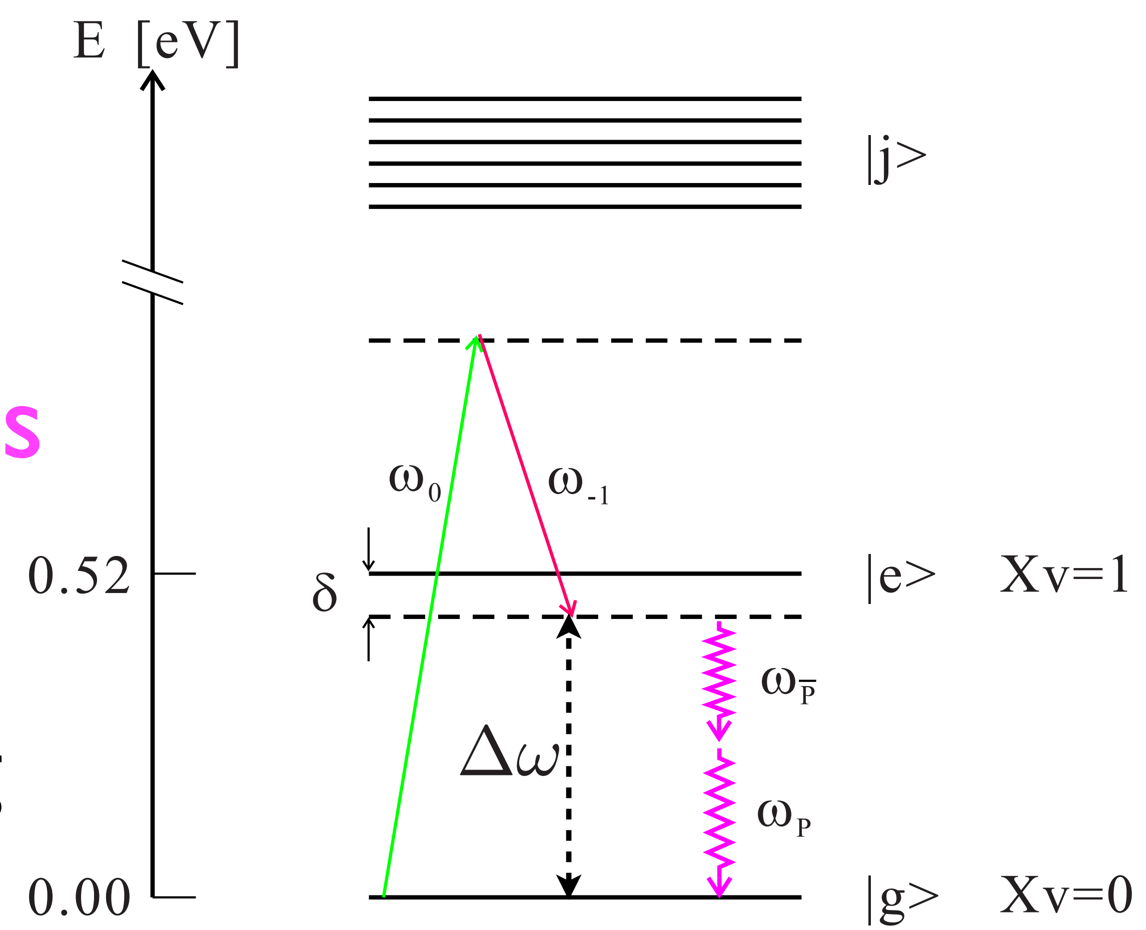
$1/T_2 \sim 130$ MHz

Coherence production

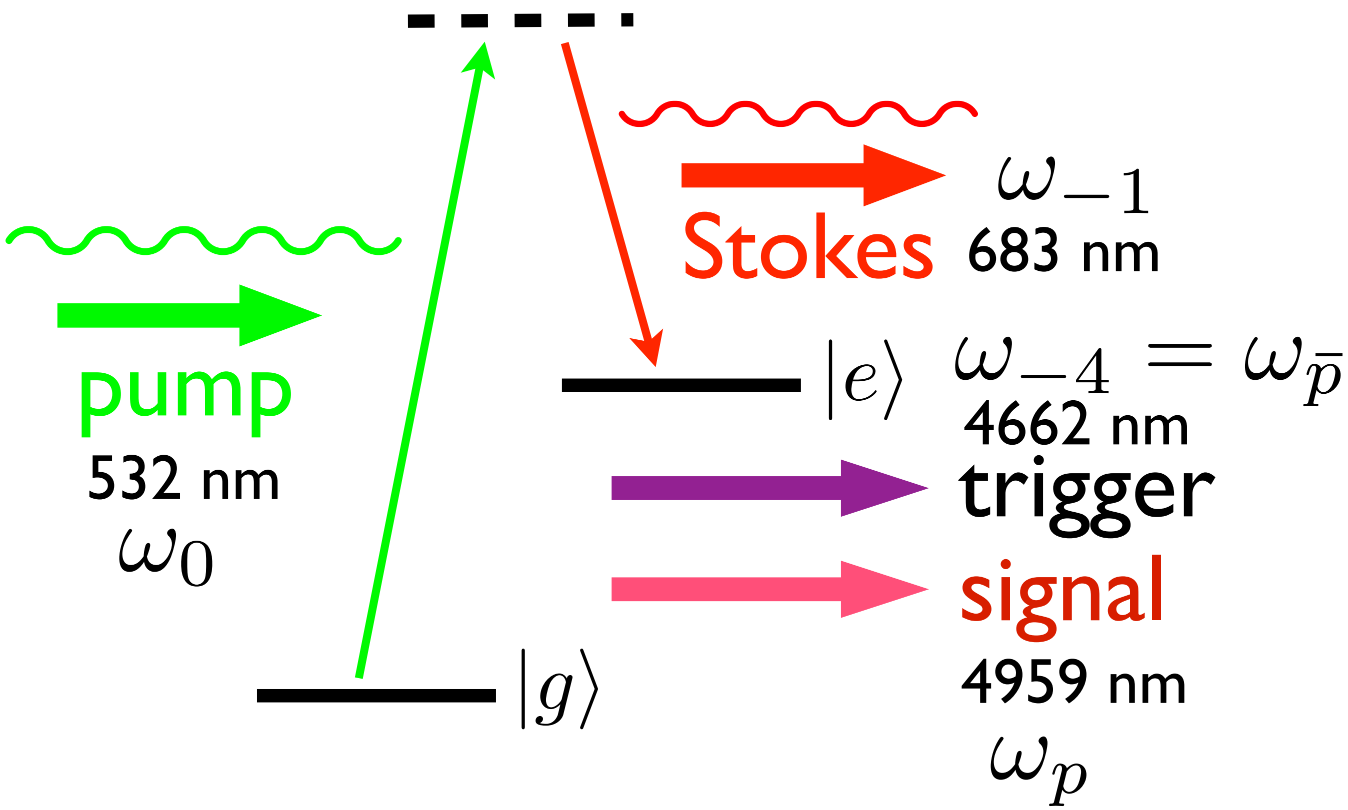
adiabatic Raman process

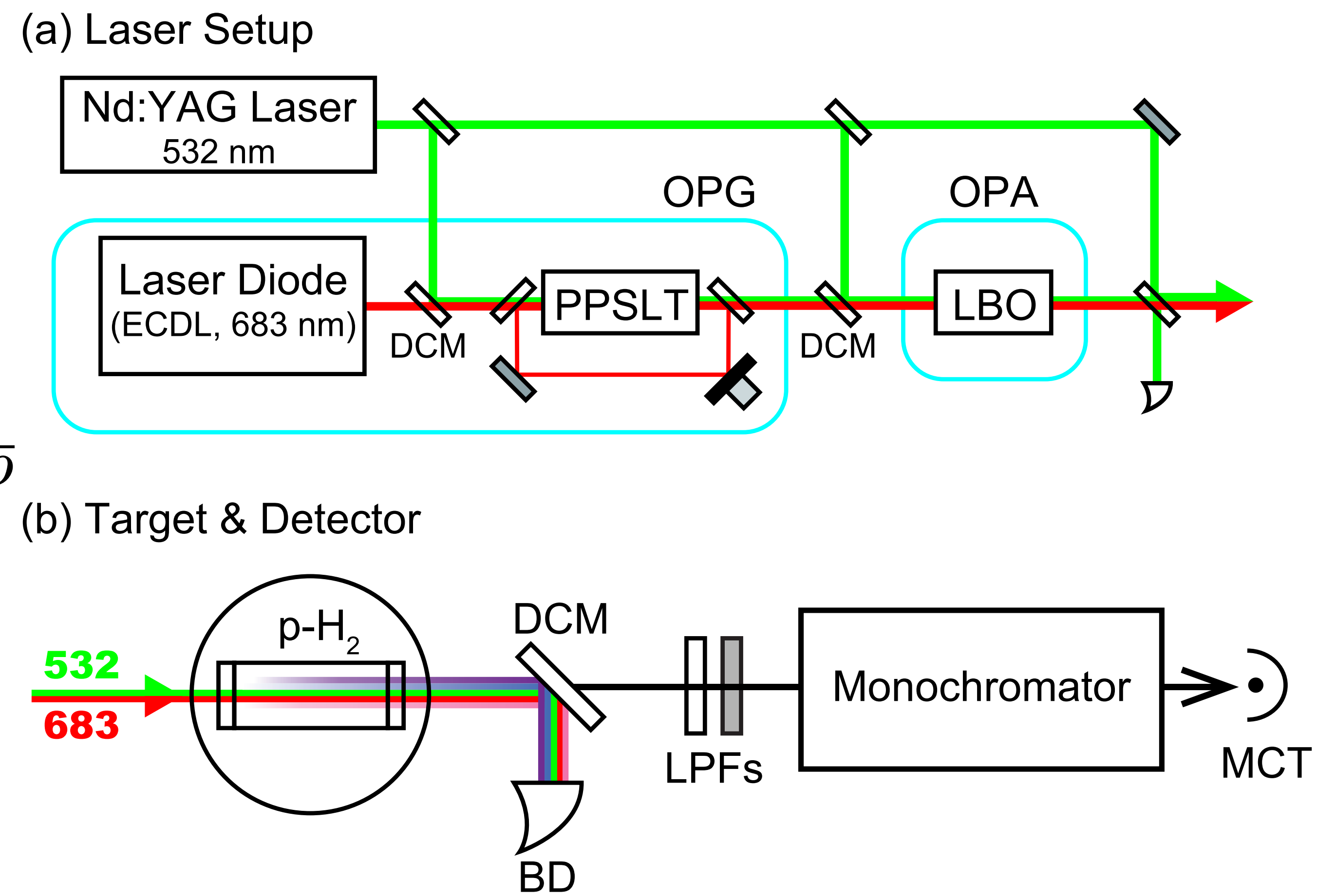
$$\begin{aligned}\Delta\omega &= \omega_0 - \omega_{-1} \\ &= \epsilon_{eg} - \delta \\ &= \omega_p + \omega_{\bar{p}}\end{aligned}$$

detuning



Experimental setup





4th Stokes (q=-4) as trigger (internal trigger)

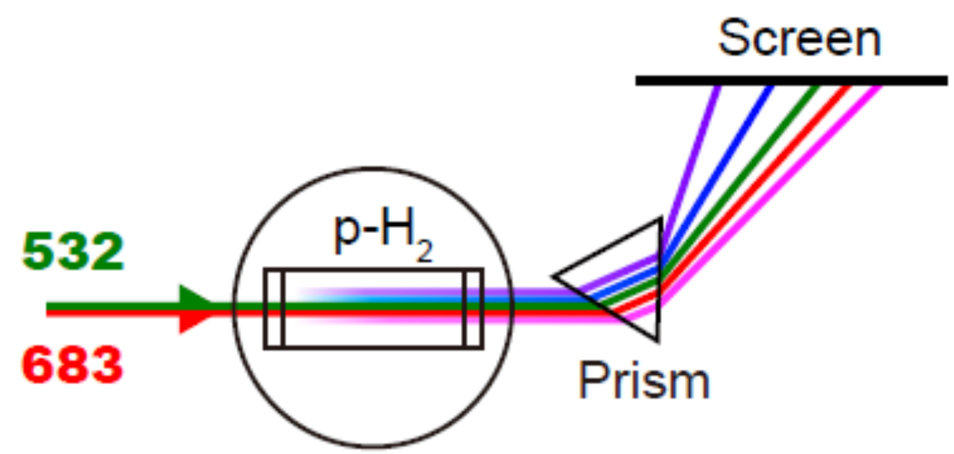
Target cell: length 15cm, diameter 2cm, 78K, 60kPa

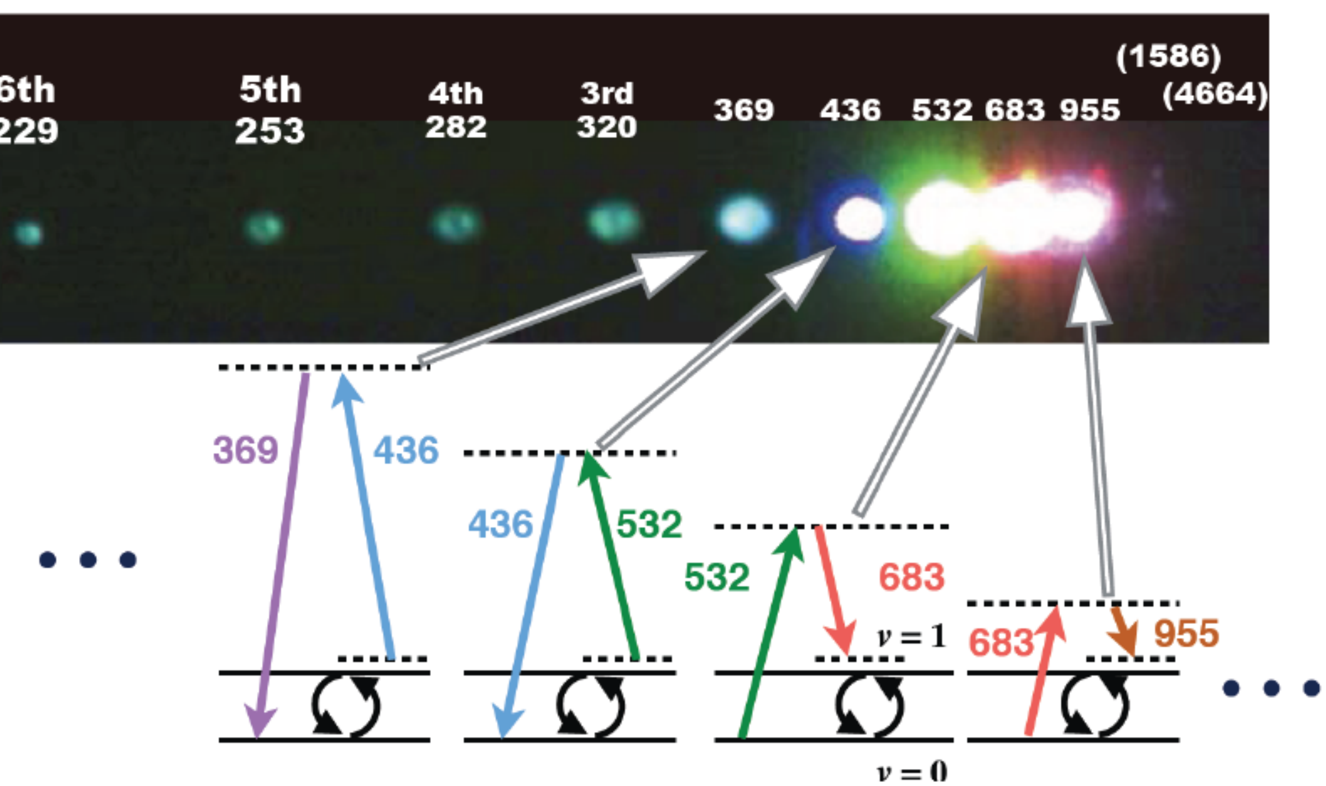
$$n = 5.6 \times 10^{19}\ \mathrm{cm}^{-3} \qquad 1/T_2 \sim 130\ \mathrm{MHz}$$

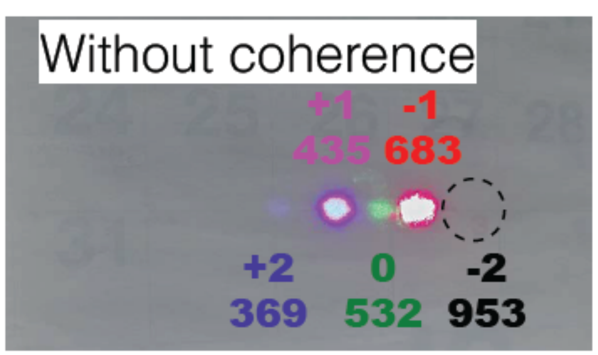
Driving lasers: $5\ \mathrm{mJ},\ 6\ \mathrm{ns},\ w_0 = 100\ \mu\mathrm{m}\ (5\ \mathrm{GW/cm^2})$

Ultra-broadband Raman sidebands

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





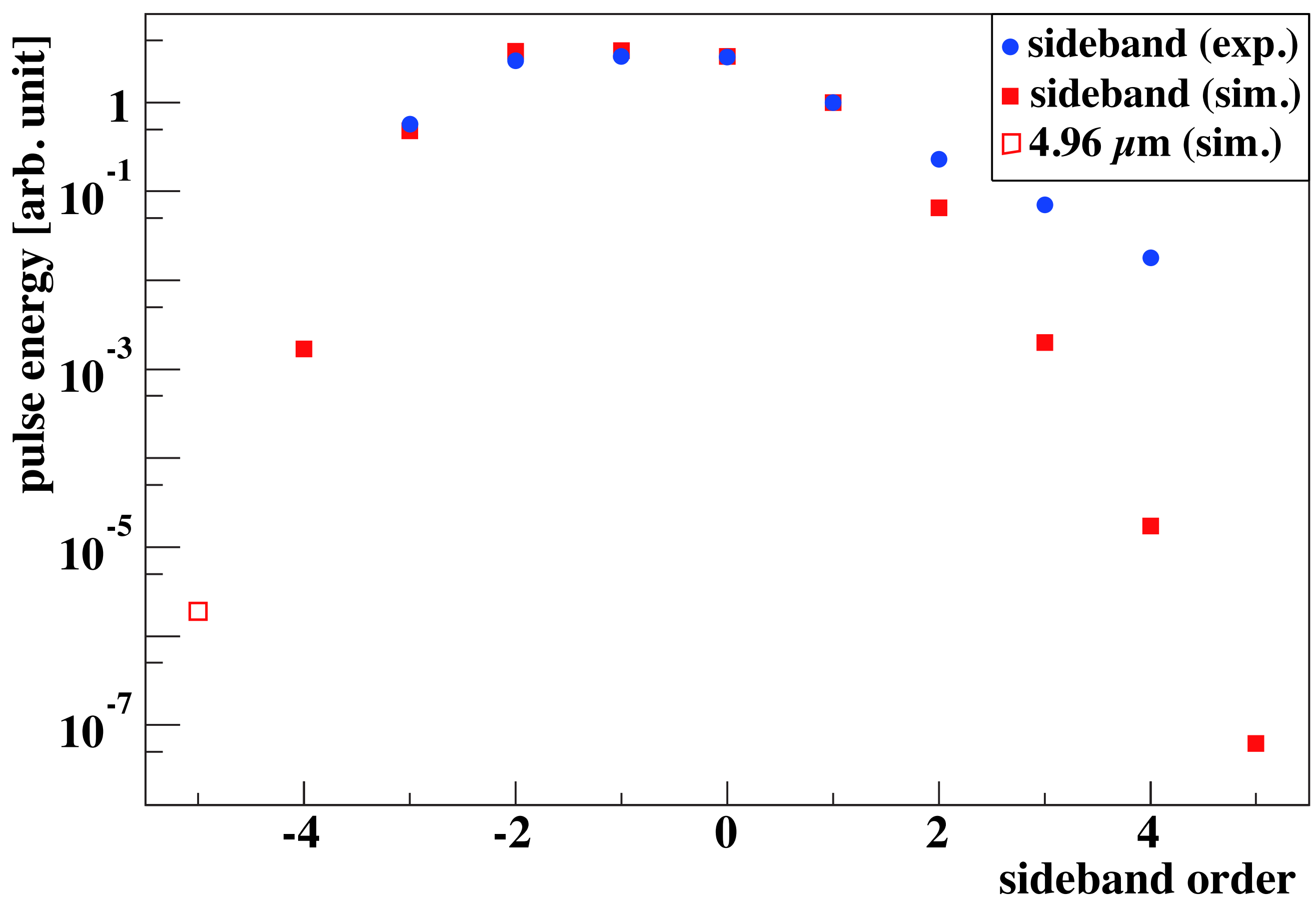


N. Sasao

Generated coherence

Maxwell-Bloch eq.

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

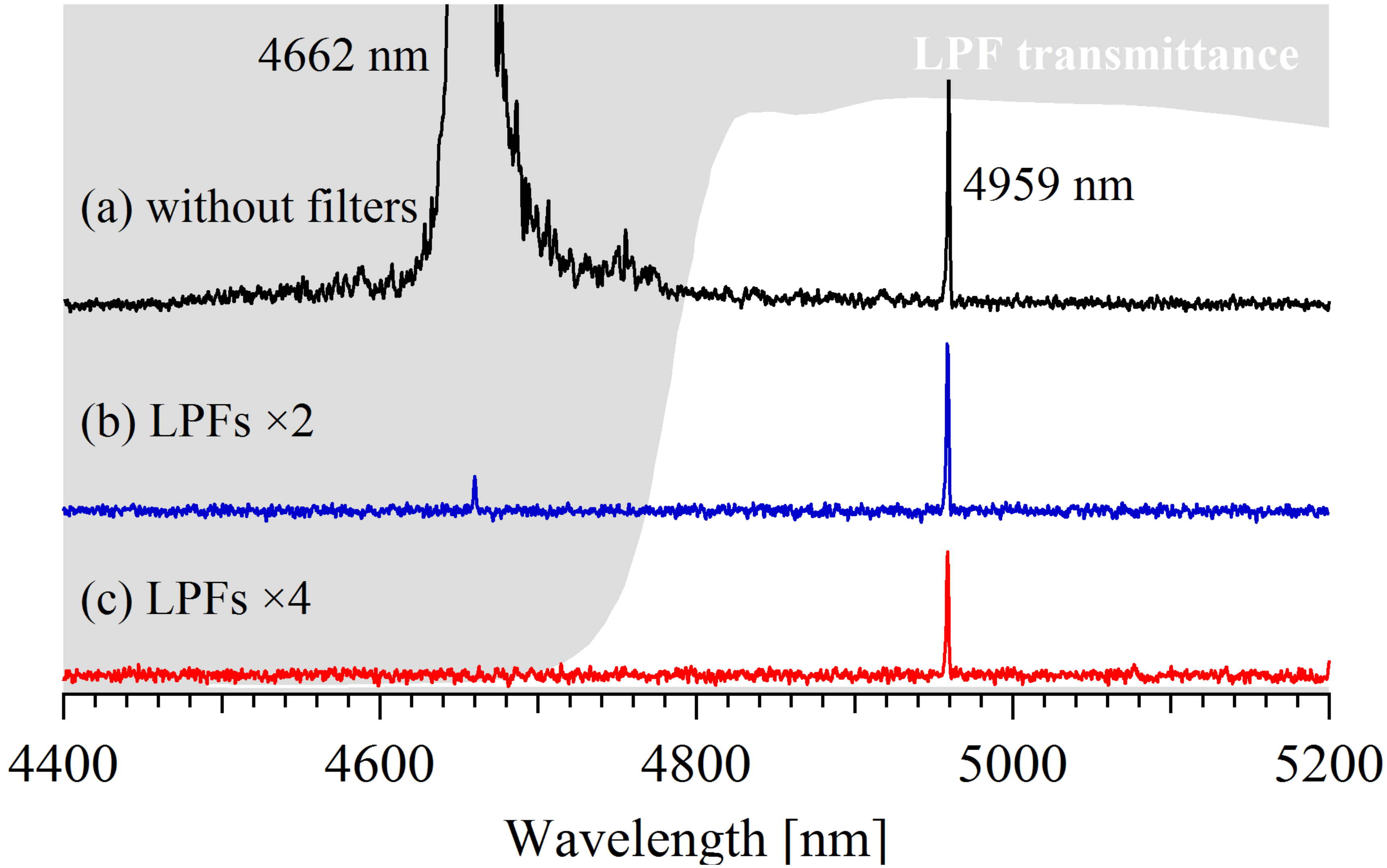


coherence estimation

$$|\rho_{eg}| \simeq 0.032$$

(6% of max.)

Observed two-photon spectrum



# of observed photons

$$4.4 \times 10^7/\mathrm{pulse}$$

Estimated spontaneous rate

$$1.6 \times 10^{-8}$$

$O(10^{15})$ (or more) enhancement!

SUMMARY

Neutrino Physics with Atoms/Molecules

- ✶ RENP spectra are sensitive to unknown neutrino parameters.

  Absolute mass, Dirac or Majorana,
  NH or IH, CP

- ✶ Macrocoherent rate amplification is essential.

  demonstrated by a QED process, PSR.

A new approach to neutrino physics