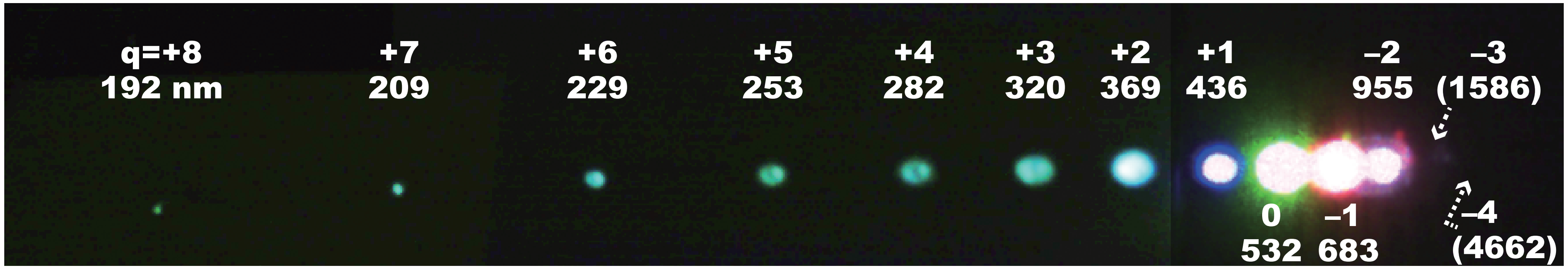
原子・分子過程による
ニュートリノ物理

田中　実

大阪大学



2015/3/12, 新物理の実証策を考える会@OIST

SPAN project

SPectroscopy with Atomic Neutrino

Okayama U.

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A. Yoshimi, K. Yoshimura, M. Yoshimura

Other institute

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C. Ohae (ECU), K. Nakajima (KEK), H. Nanjo (Kyoto)

INTRODUCTION

What we know about neutrino mass and mixing

Masses:

$$\Delta m^2_{21} \simeq (8.66\ \mathrm{meV})^2\,,\ \ |\Delta m^2_{31(2)}| \simeq (49.6(5)\ \mathrm{meV})^2$$

NuFIT (2014)

$$\sum m_\nu \leq 0.23\ \mathrm{eV}$$ PLANCK 2013

Mixing: $U = V_{\mathrm{PMNS}}\, P$

$$V_{\mathrm{PMNS}} =$$

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$P = \mathrm{diag.}(1, e^{i\alpha}, e^{i\beta})$$ Majorana phases

Bilenky, Hosek, Petcov; Doi, Kotani, Nishiura, Okuda, Takasugi; Schechter, Valle

$$\sin^2\theta_{12} \simeq 0.30\,,\ \ \sin^2\theta_{23} \simeq 0.45(58)\,,\ \ \sin^2\theta_{13} \simeq 0.022$$

NuFIT (2014)

Unknown properties of neutrinos

Absolute mass

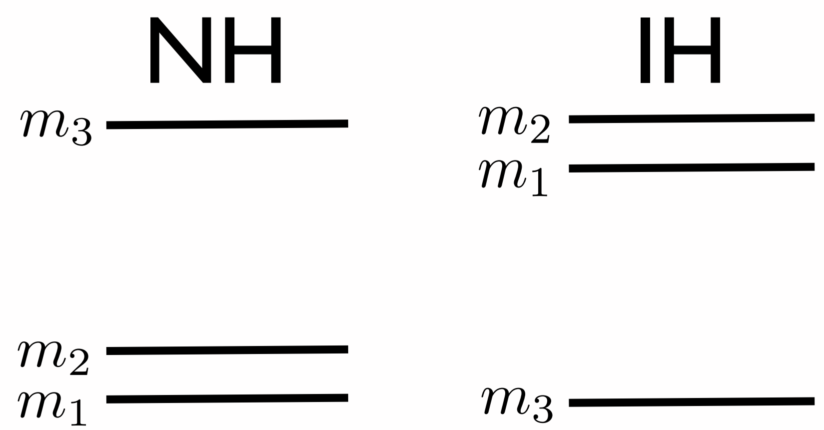
$$m_{1(3)} < 71(66)\ \mathrm{meV},\ \ 50\ \mathrm{meV} < m_{3(2)} < 87(82)\ \mathrm{meV}$$

Mass type

Dirac or Majorana

Hierarchy pattern

normal or inverted



CP violation

one Dirac phase, two Majorana phases

δ $\qquad\qquad$ $\alpha,\ \beta$

Neutrino experiments

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

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

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

Neutrinoless double beta decays

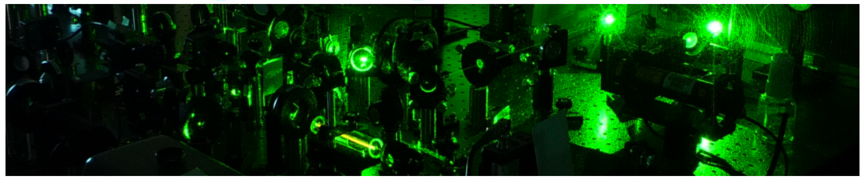
Dirac or Majorana, effective mass $\left|\sum_i m_i U_{ei}^2\right|^2$

Beta decay endpoint: KATRIN

absolute mass

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

Atomic/molecular processes

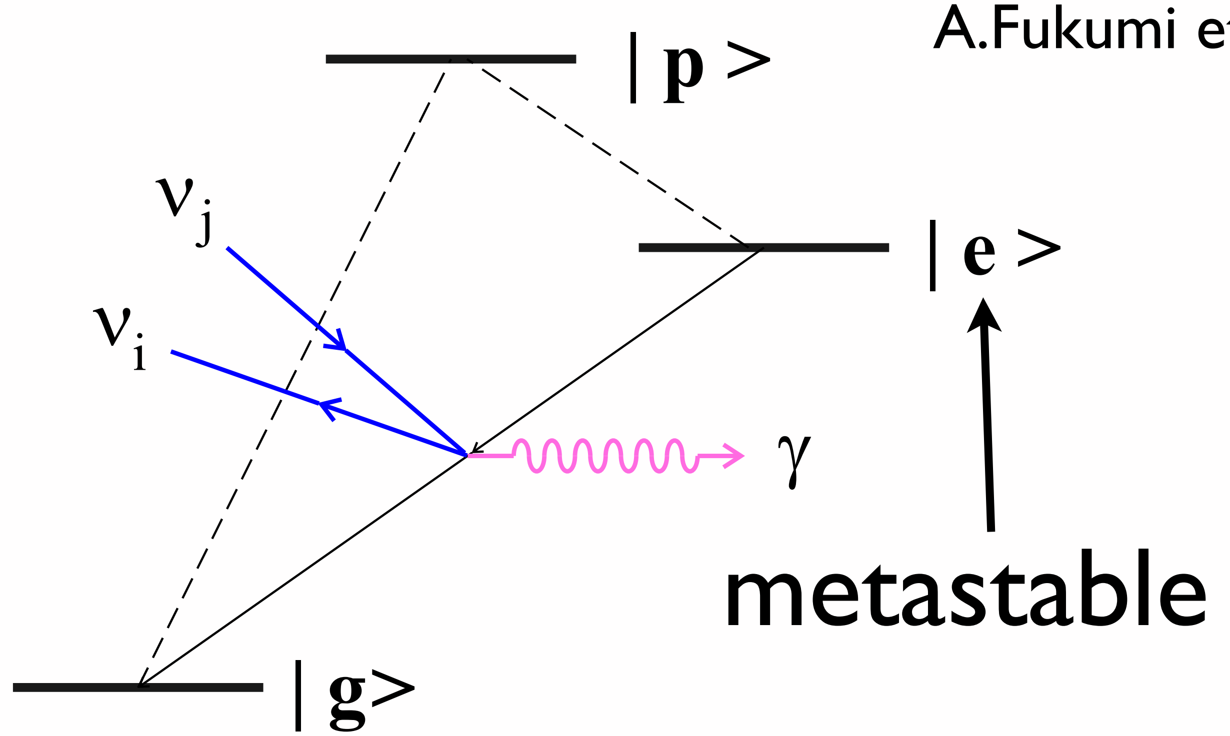


absolute mass, NH or IH, D or M, $\delta, \ \alpha, \ \beta$

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

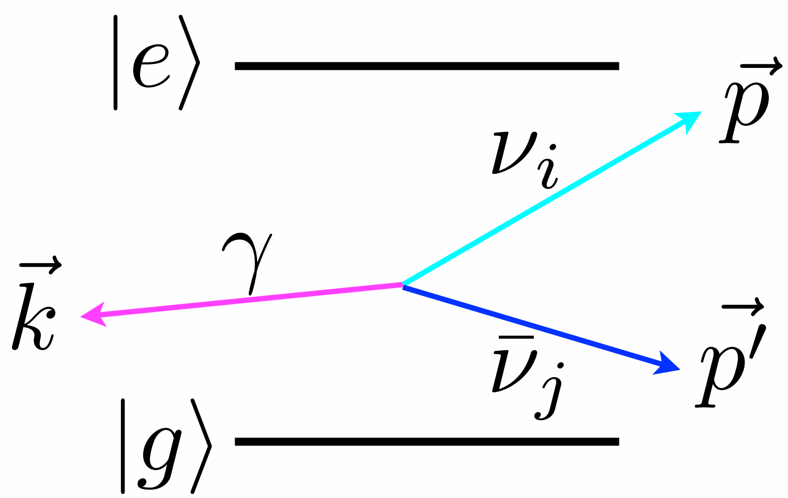
cf. nuclear processes ~ MeV

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)

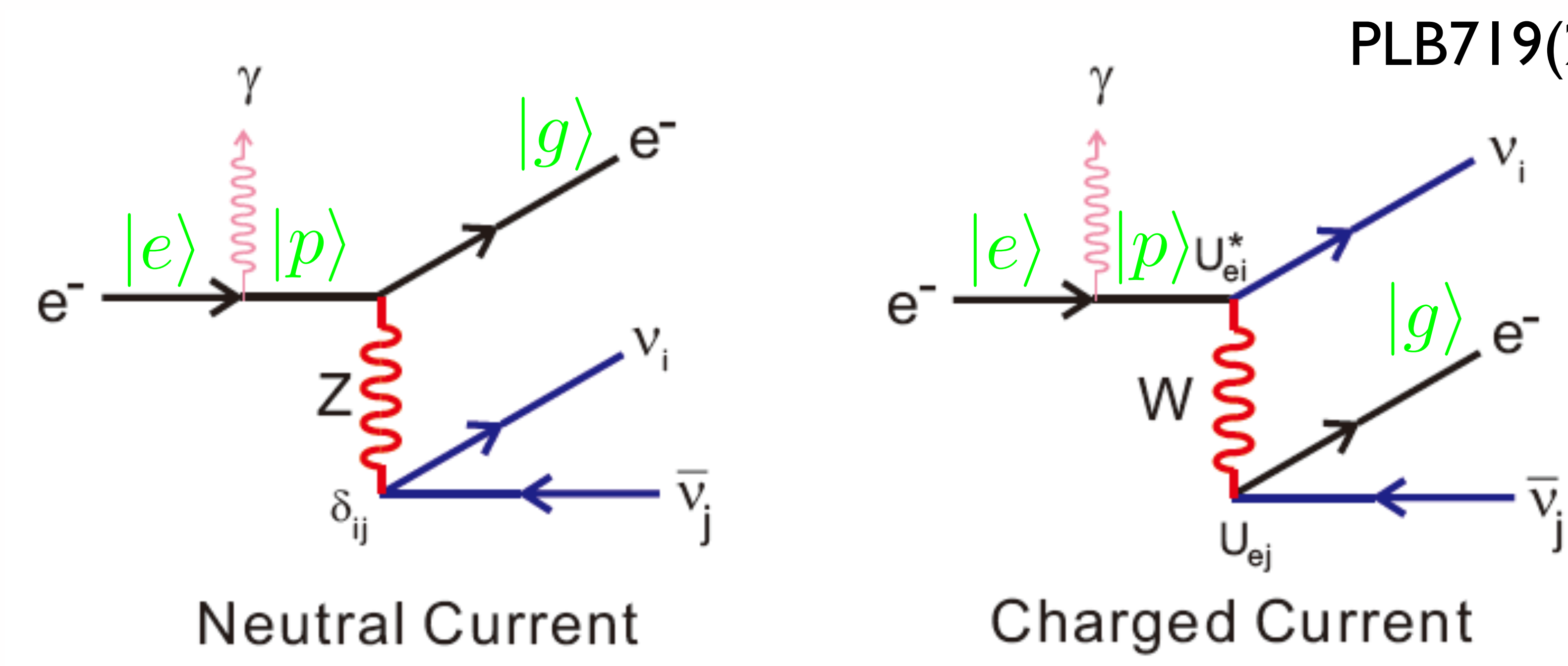
total amp. $\propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p}')$

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

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



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

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

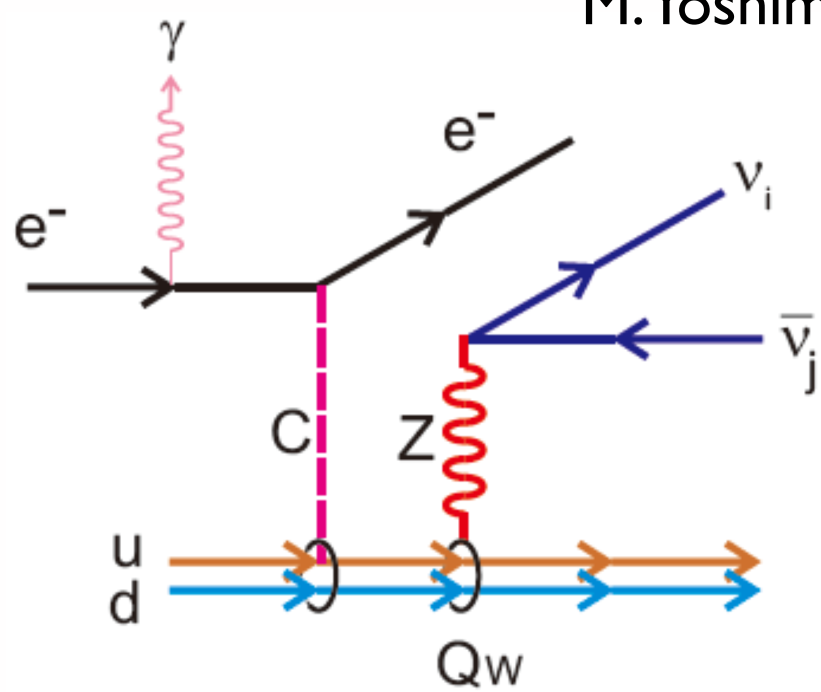
Atomic matrix element in the NR approximation

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

$$\langle g|\bar{e}\gamma^\mu \gamma_5 e|p\rangle \simeq (0, 2\langle g|\boldsymbol{s}|p\rangle)$$ → 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 macrocoherence
→ 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

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

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

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

Spectral function (spin current)

$$I(\omega) = F(\omega)/(\epsilon_{pg} - \omega)^2$$

$$\boxed{F(\omega) = \sum_{ij} \Delta_{ij}(B_{ij} I_{ij}(\omega) - \delta_M B_{ij}^M m_i m_j)\theta(\omega_{ij} - \omega)}$$

$$\Delta_{ij}^2 = 1 - 2\frac{m_i^2 + m_j^2}{q^2} + \frac{(m_i^2 - m_j^2)^2}{q^4} \qquad q^2 = (p_i + p_j)^2$$

$$I_{ij}(\omega) = \frac{q^2}{6}\left[2 - \frac{m_i^2 + m_j^2}{q^2} - \frac{(m_i^2 - m_j^2)^2}{q^4}\right] + \frac{\omega^2}{9}\left[1 + \frac{m_i^2 + m_j^2}{q^2} - 2\frac{(m_i^2 - m_j^2)^2}{q^4}\right]$$

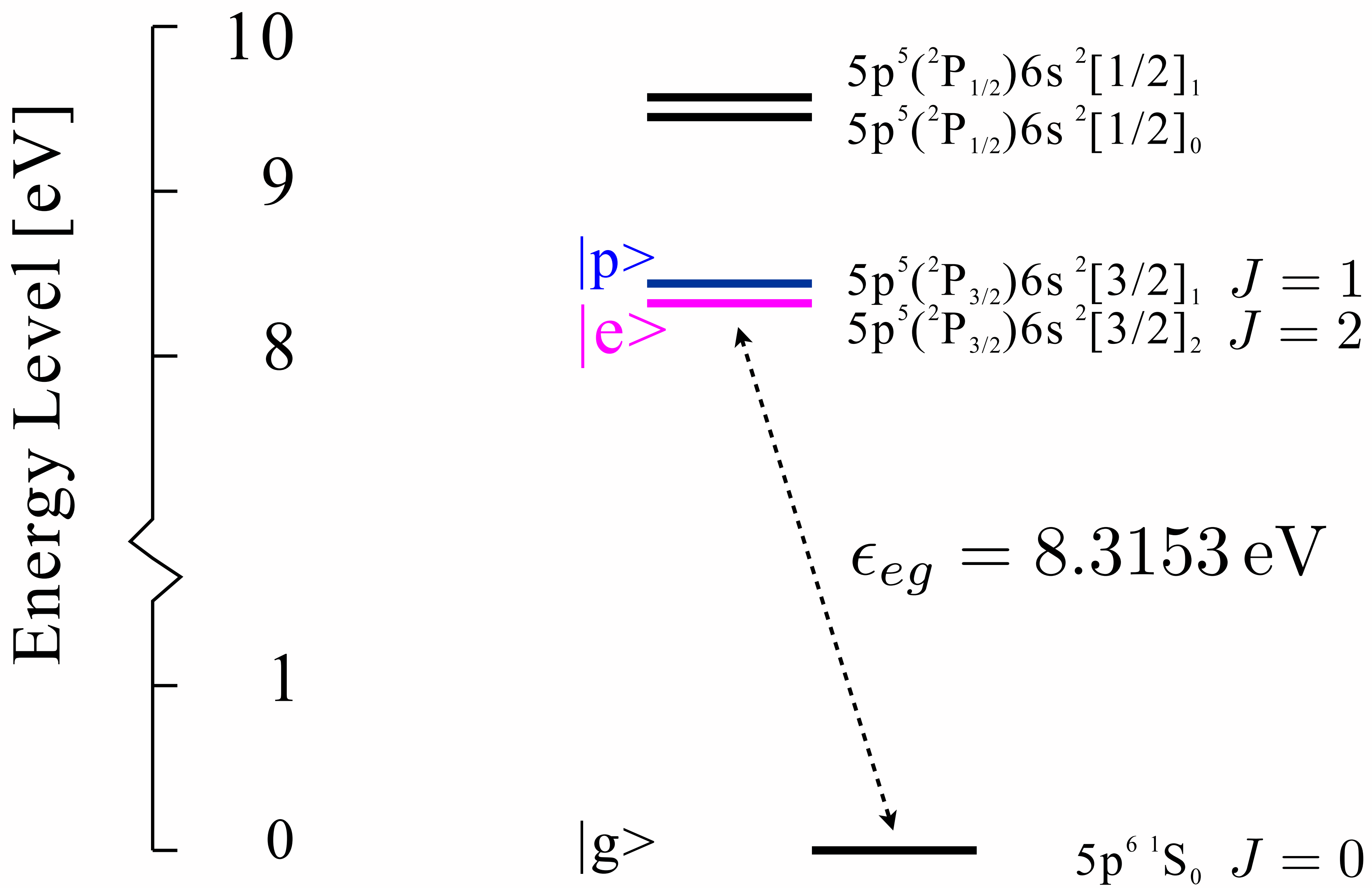
$\delta_M = 0(1)$ for Dirac(Majorana)

$$B_{ij} = |U_{ei}^* U_{ej} - \delta_{ij}/2|^2, B_{ij}^M = \Re[(U_{ei}^* U_{ej} - \delta_{ij}/2)^2]$$

Dynamical factor

$$\sim |\text{coherence} \times \text{field}|^2$$

Xe (gas target)

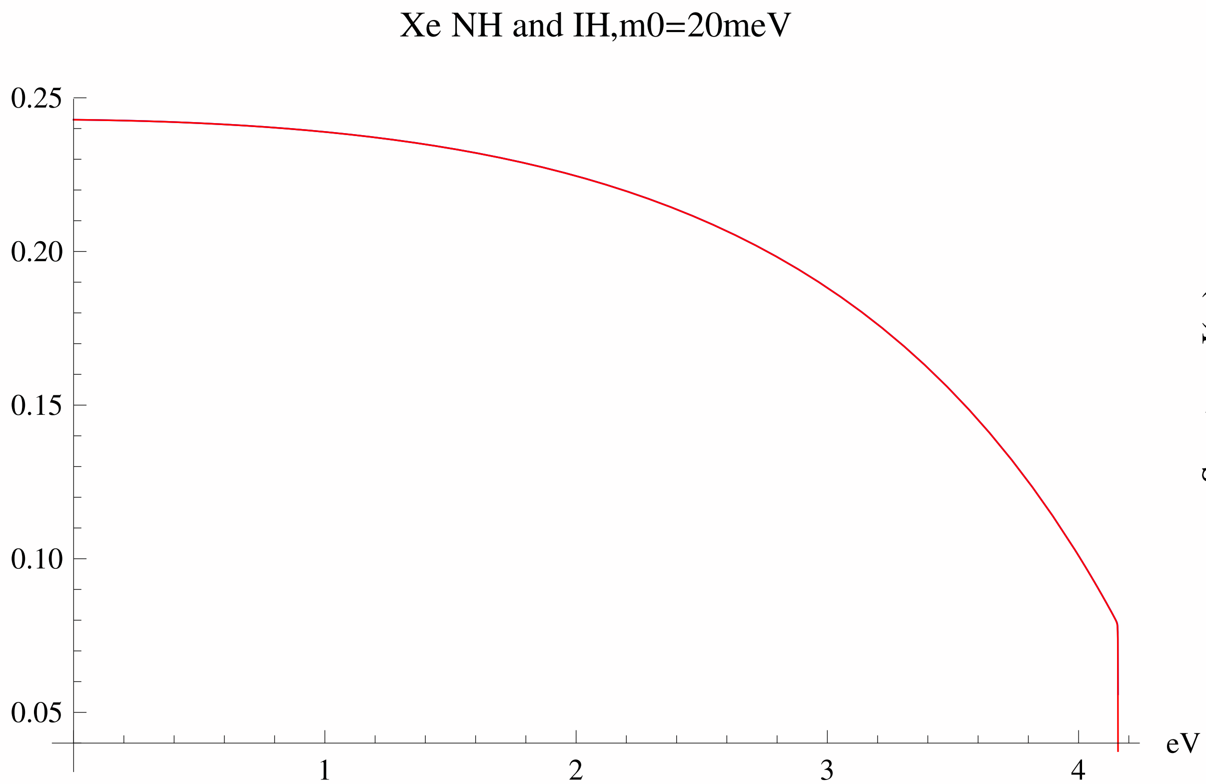


$$|e\rangle \leftrightarrow |p\rangle \quad \mathrm{M1}$$

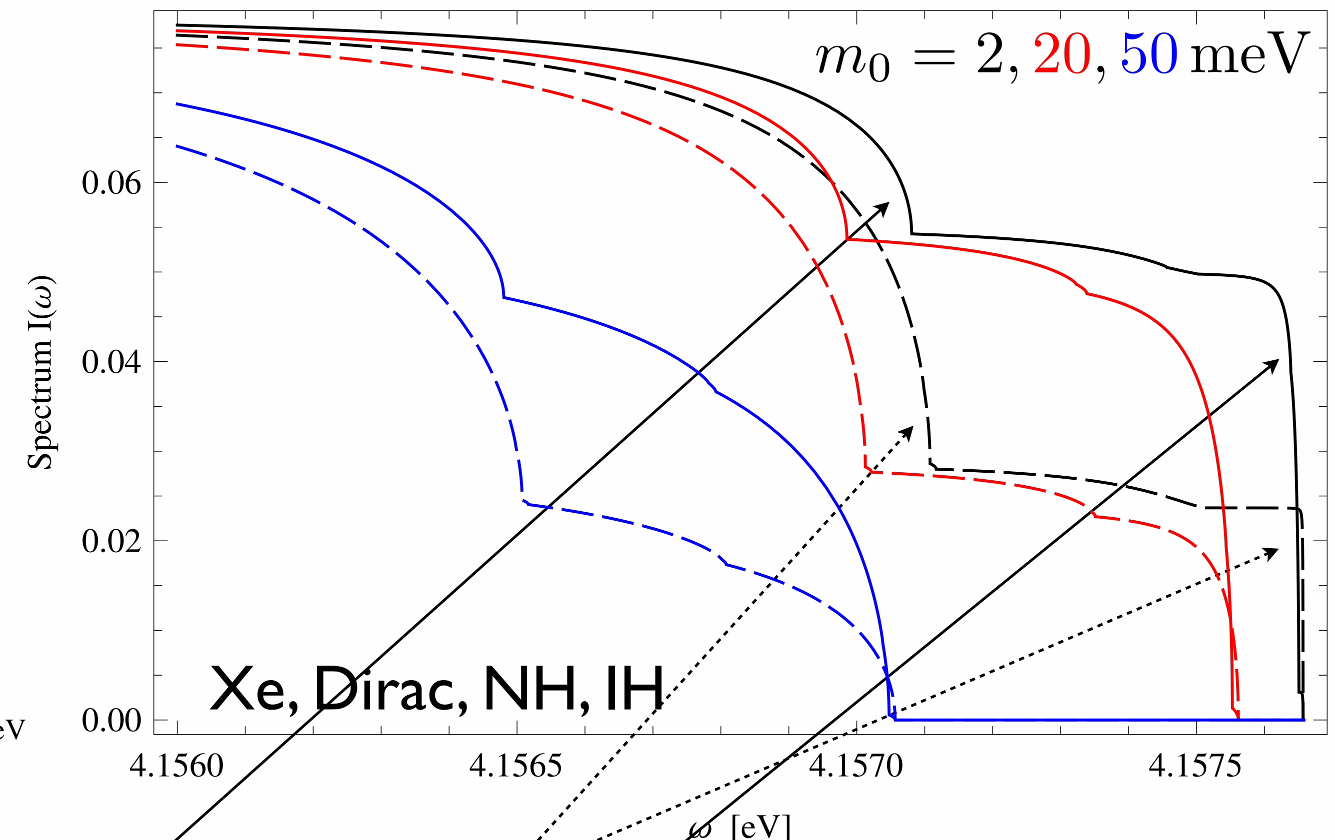
$$|p\rangle \leftrightarrow |g\rangle \quad \mathrm{E1}$$

Photon spectrum (spin current)

Global shape



Threshold region



The threshold weight factors

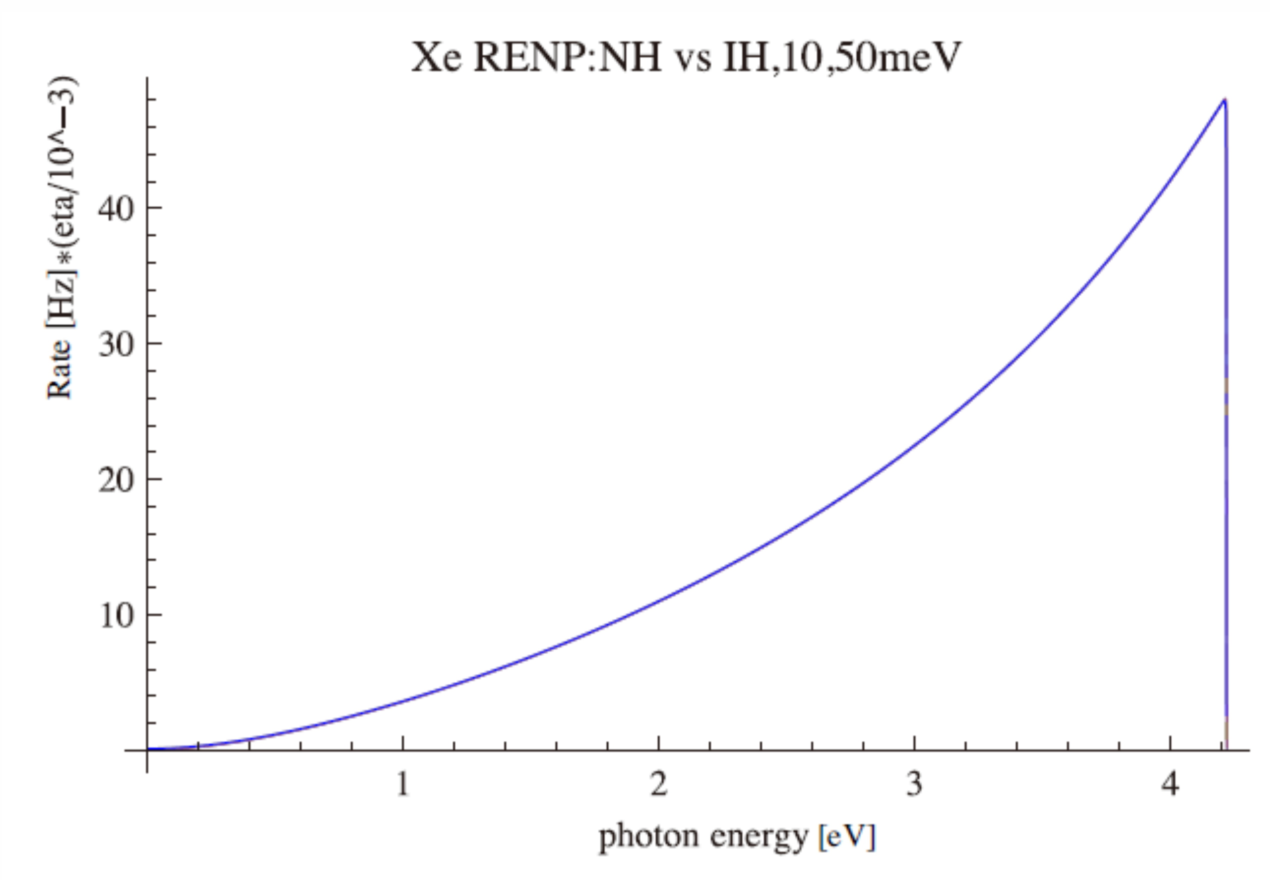
B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2c_{13}^2-1/2)^2$	$(s_{12}^2c_{13}^2-1/2)^2$	$(s_{13}^2-1/2)^2$	$2c_{12}^2s_{12}^2c_{13}^4$	$2s_{12}^2c_{13}^2s_{13}^2$	$2c_{12}^2c_{13}^2s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

Photon spectrum (nuclear monopole)

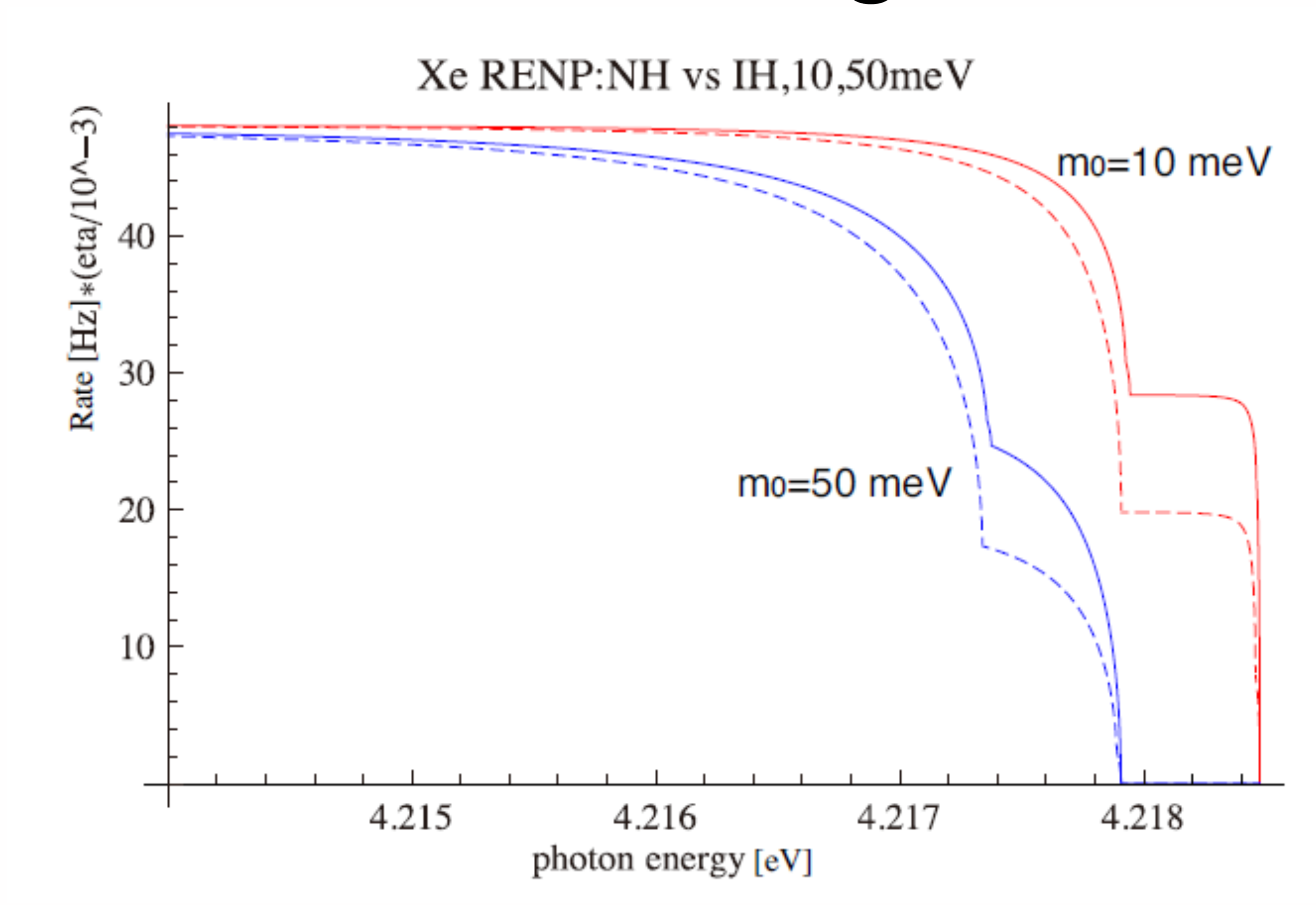
Xe $^3\mathrm{P}_1$ 8.4365 eV

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

Global shape



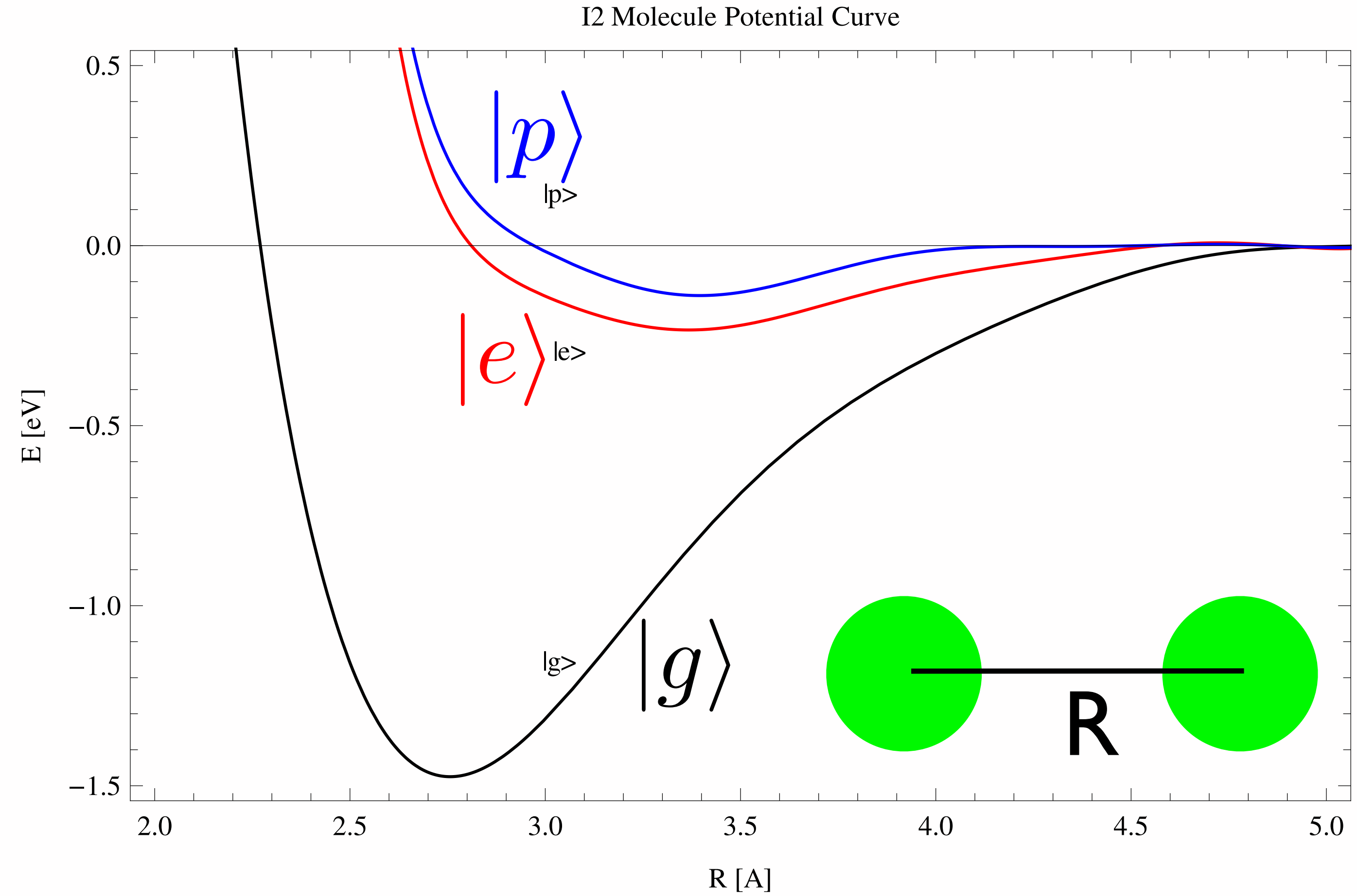
Threshold region

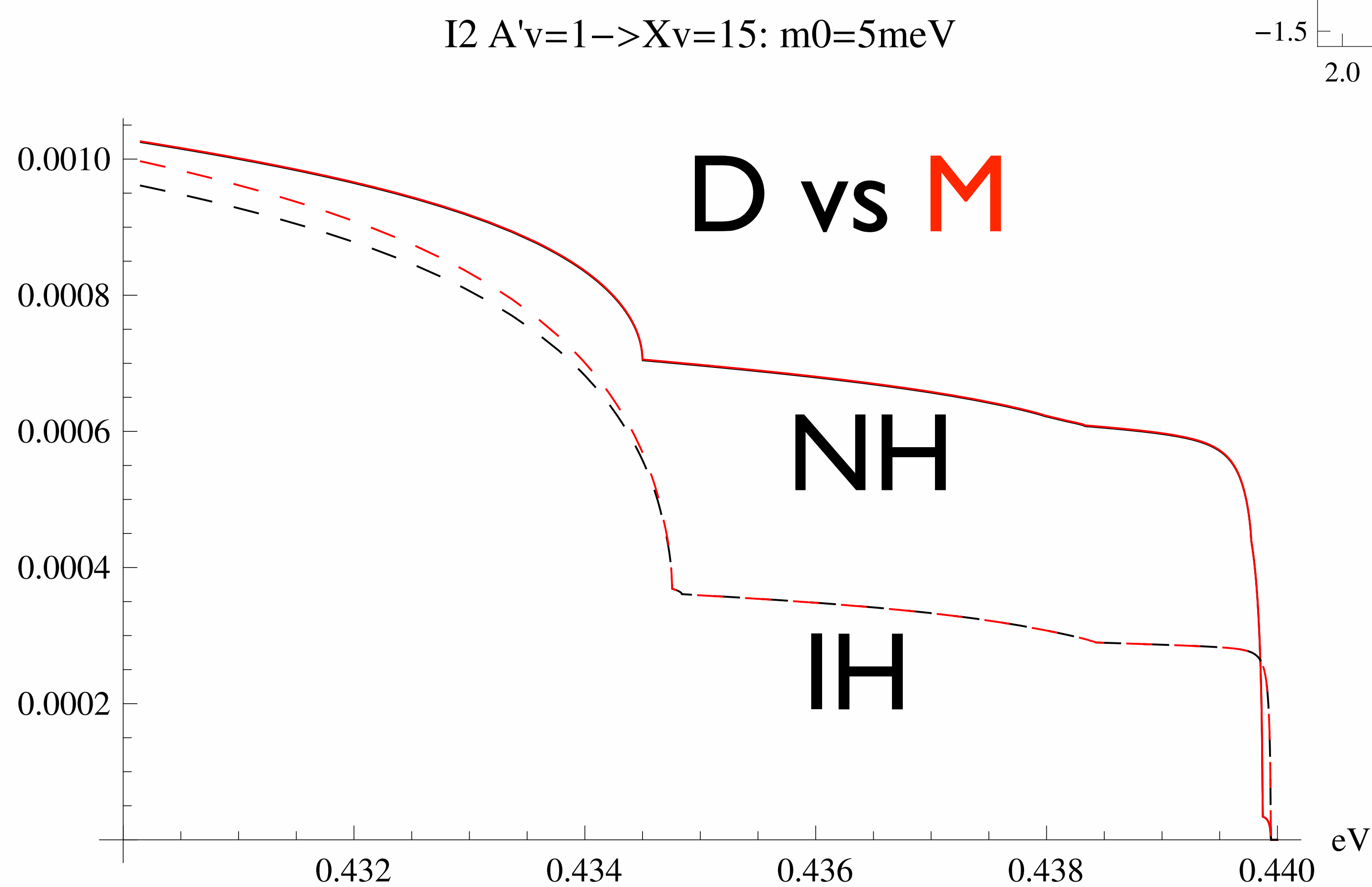


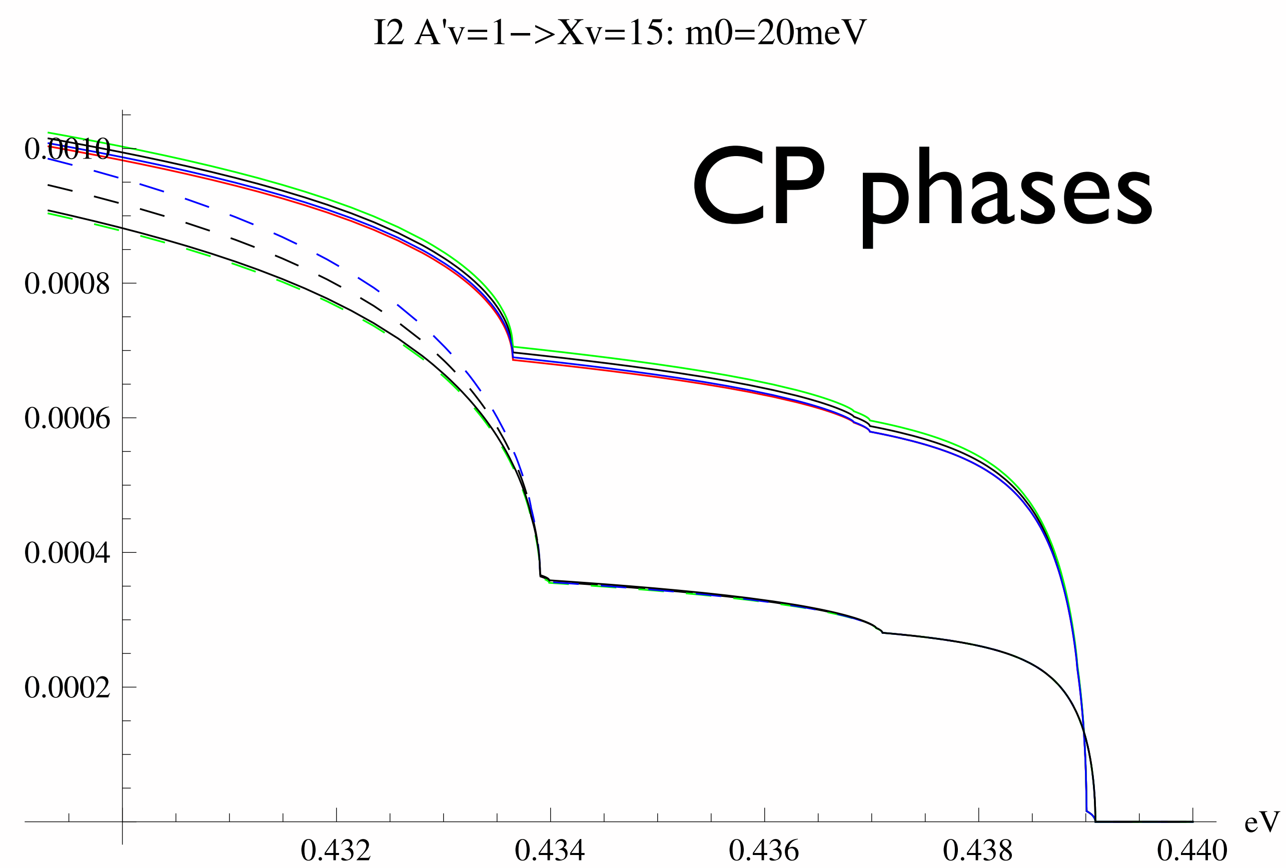
I2 molecule

potential curves

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







D-M diff. < 10%

CNB

Cosmic Neutrino Background (CNB)

Big bang cosmology

Standard model of particle physics

CNB

CNB at present: $f(\boldsymbol{p}) = [\exp(|\boldsymbol{p}|/T_\nu - \xi) + 1]^{-1}$

(not) Fermi-Dirac dist. $|\boldsymbol{p}| = \sqrt{E^2 - m_\nu^2}$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945 \text{ K} \simeq 0.17 \text{ meV}$$

$$n_\nu \simeq 6 \times 56 \text{ cm}^{-3}$$

Detection?

RENP in CNB

M. Yoshimura, N. Sasao, MT,
PRD91, 063516 (2015); arXiv:1409.3648

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

Pauli exclusion

$$d\Gamma \propto |\mathcal{M}|^2 \boxed{[1 - f_i(p)]\,[1 - \bar{f}_j(p')]}$$

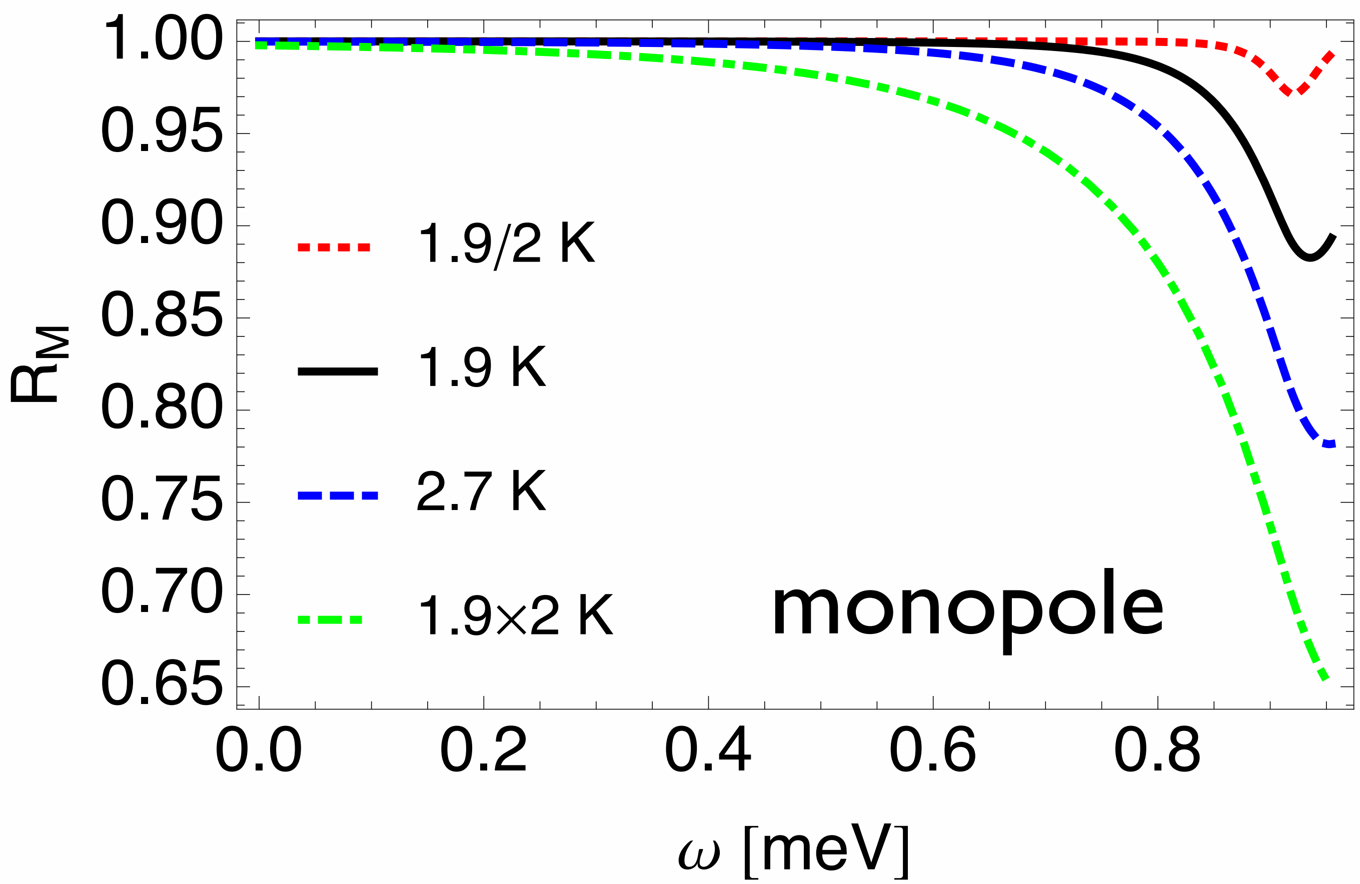
→ spectral distortion

Distortion factor

$$R_X(\omega) \equiv \frac{\Gamma_X(\omega, T_\nu)}{\Gamma_X(\omega, 0)}$$

$$X = \begin{cases} M & \text{nuclear monopole} \\ S & \text{valence } e \text{ spin current} \end{cases}$$

larger rate $i = j$



level splitting

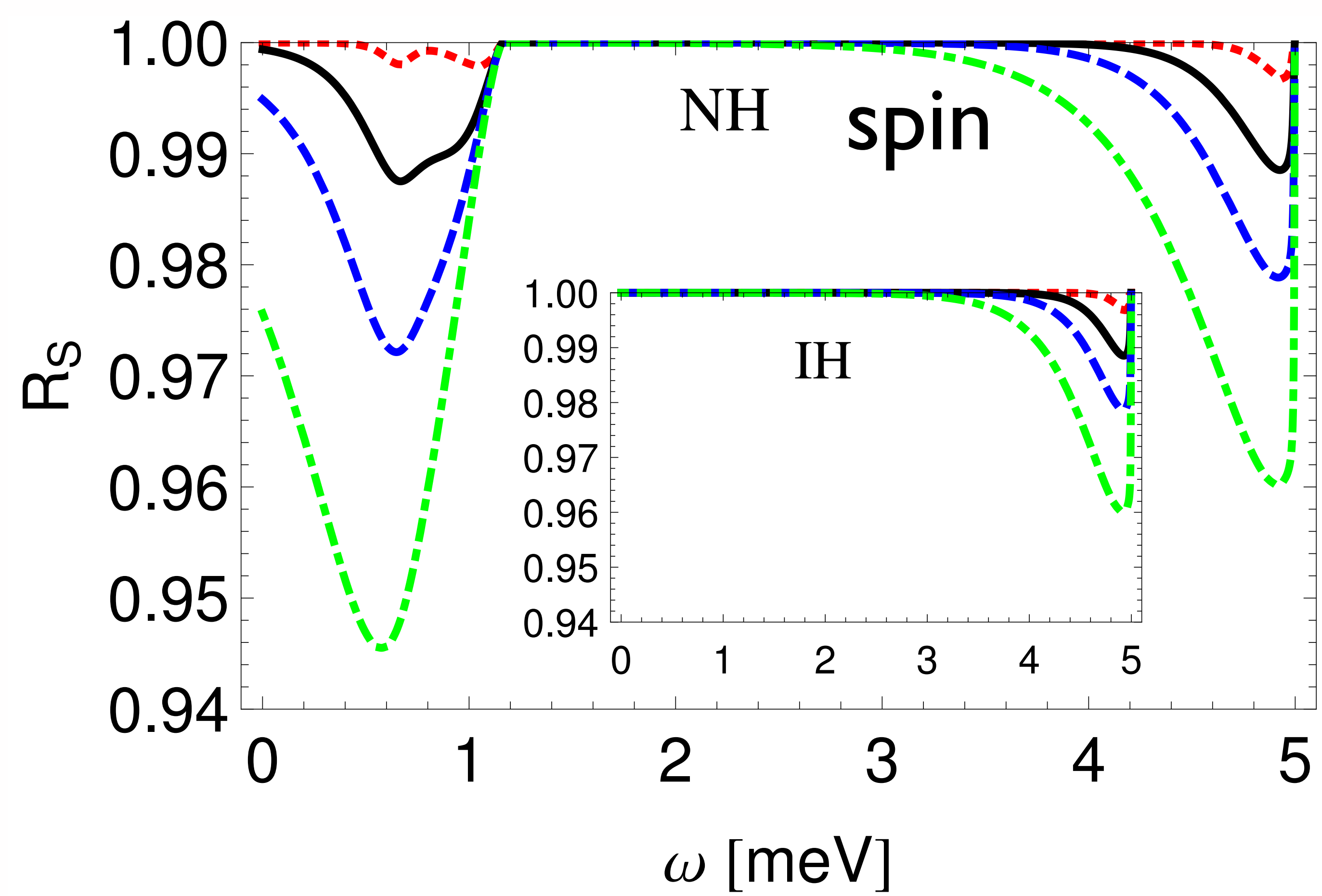
$$\epsilon_{eg} = 11 \text{ meV}$$

smallest neutrino mass

$$m_0 = 5 \text{ meV}$$

chemical potential

$$\xi_i \equiv \mu_i / T_\nu = 0$$

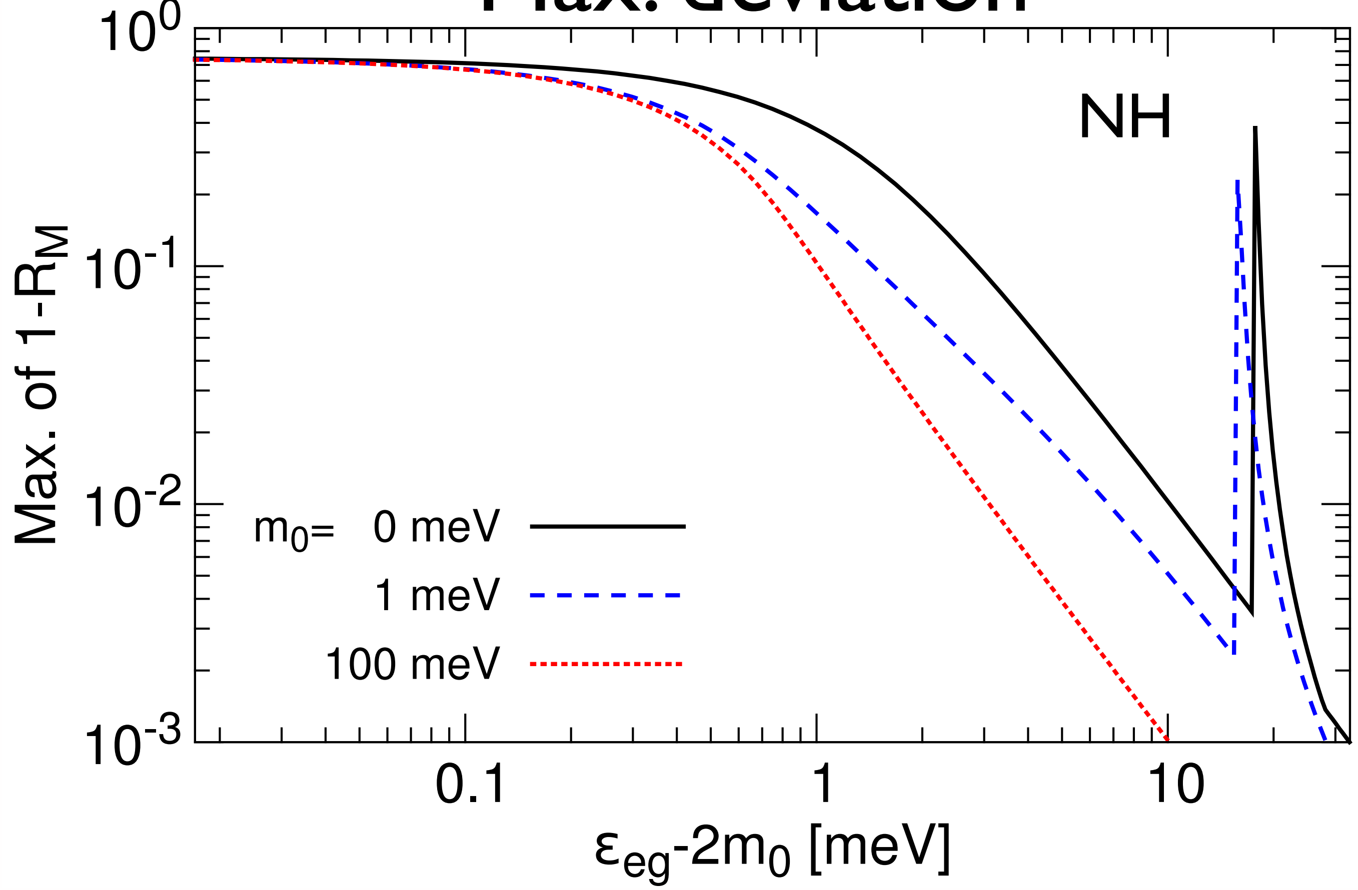


$$\epsilon_{eg} = 10 \text{ meV}$$

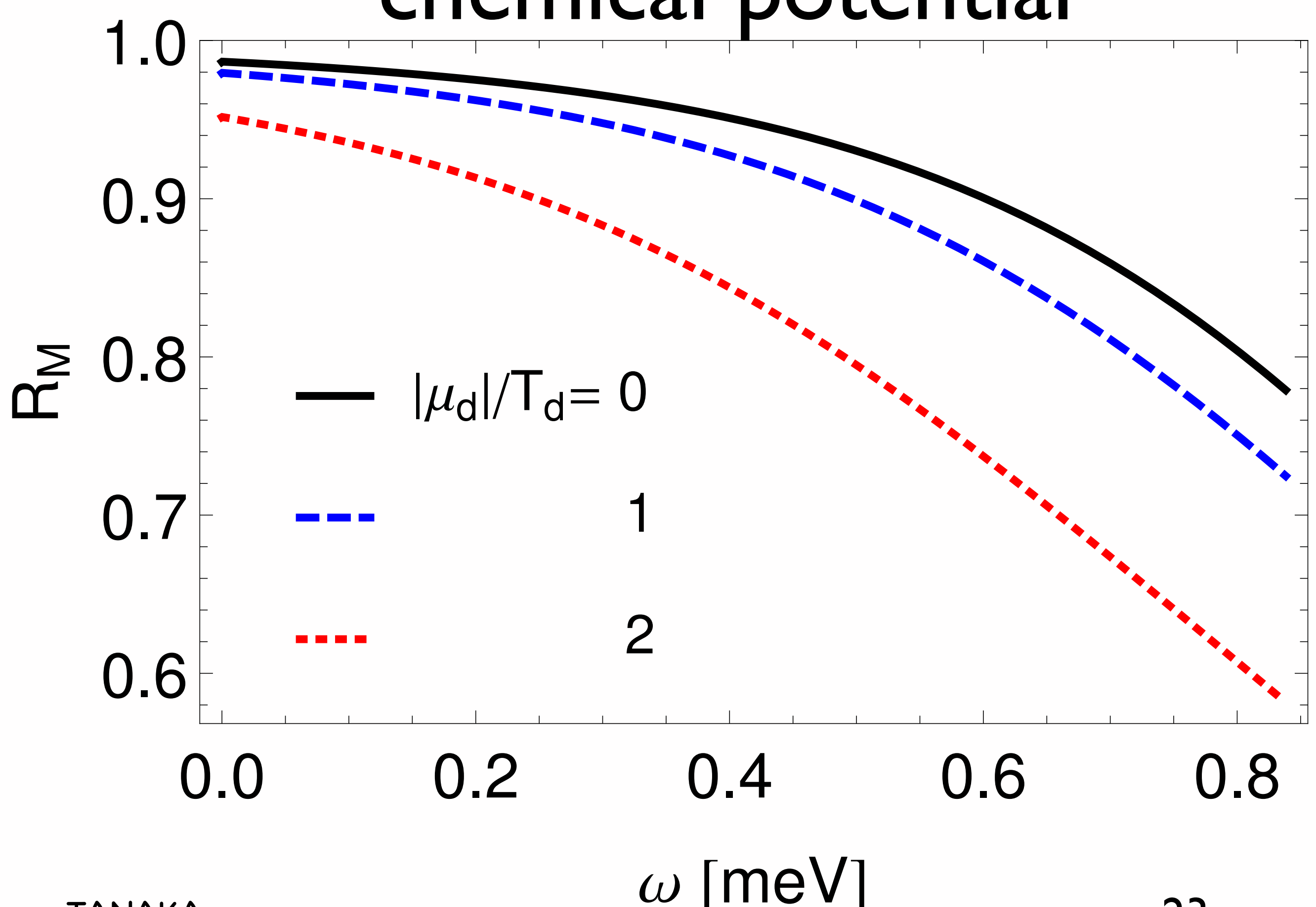
$$m_0 = 0.1 \text{ meV}$$

$$\xi_i = 0$$

Max. deviation



chemical potential



$$\epsilon_{eg} = 10T_\nu \simeq 1.7 \text{ meV}$$

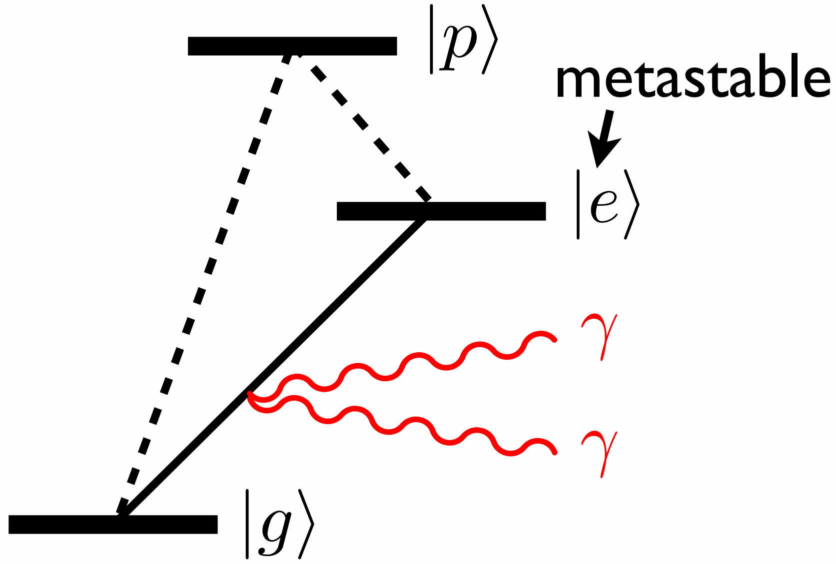
$$m_0 = 0$$

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 equation

Effective two-level interaction Hamiltonian

$$|g\rangle,\ |e\rangle,\ \cancel{|p\rangle} \qquad \mathcal{H}_I = \begin{pmatrix} \alpha_{ee} & \alpha_{ge} e^{i\varepsilon_{eg} t} \\ * & \alpha_{gg} \end{pmatrix} E^2$$

$$\alpha_{ge} = \frac{2 d_{pe} d_{pg}}{\epsilon_{pg} + \epsilon_{pe}}\,, \qquad \alpha_{aa} = \frac{2 d_{pa}^2 \epsilon_{pa}}{\epsilon_{pa}^2 - \omega^2}\,, \qquad (a = g\,, e)$$

d_{pa} : dipole matrix element

Field (1+1 dim.)

$$\omega = \epsilon_{eg}/2$$

$$E = E_R\, e^{-i(\omega t - kx)} + E_L\, e^{-i(\omega t + kx)} + \text{c.c.}$$

$$k = \omega$$

$|e\rangle$

L-mover $\qquad\qquad$ R-mover

$e^{i\omega(t+x)}$ $\qquad\qquad$ $e^{i\omega(t-x)}$

$$\sim e^{2i\omega t} = e^{i\epsilon_{eg} t}$$

macrocoherence

$|g\rangle$

Bloch equation $\partial_t \rho = i[\rho, \mathcal{H}_I] + \text{relaxation terms}$

density matrix

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

coherence (of an atom) $|\rho_{eg}| \le 1/2$

Maxwell equation $(\partial_t^2 - \partial_x^2)E = -\partial_t^2 P$

macroscopic polarization $P = -\dfrac{\delta}{\delta E}\mathrm{tr}(\rho \mathcal{H}_I)$

Rotating wave approximation (RWA)

omitting fast oscillation terms

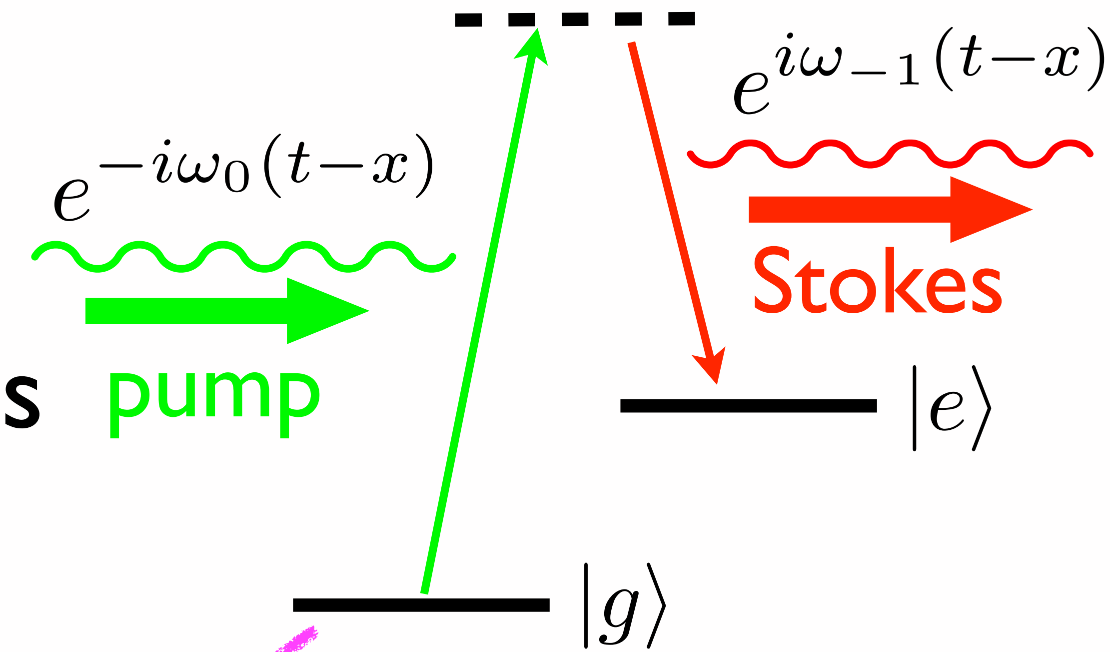
Slowly varying envelope approximation (SVEA)

$|\partial_{x,t} E_{R,L}| \ll \omega |E_{R,L}|$, $|\partial_{x,t} R_i^{(0,\pm)}| \ll \omega |R_i^{(0,\pm)}|$

PSR with spatial gratings

How to populate $|e\rangle$

Stimulated Raman process



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

Generated coherence

spatial grating

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

Stokes

pump

x

ω_p PSR

$\omega_{\bar{p}}$

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

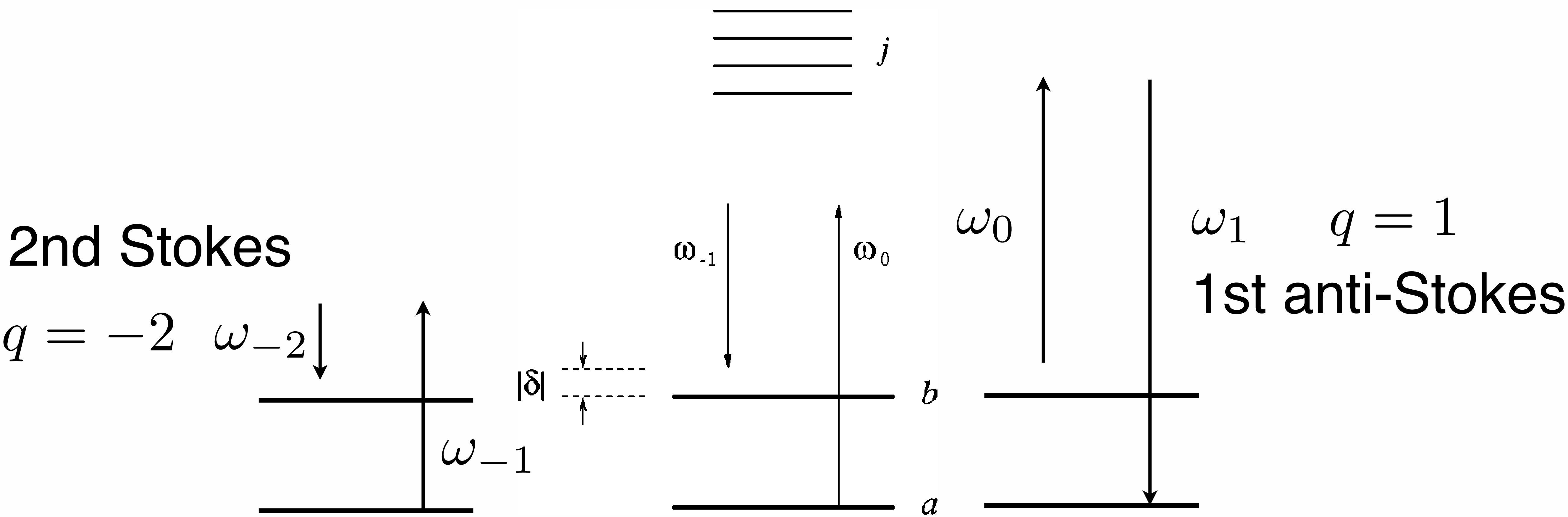
$$\omega_p + \omega_{\bar{p}} = \epsilon_{eg}$$

momentum conservation in the macrocoherence $\rightarrow$ Unidirectional PSR

Raman sideband generation

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

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



$$\omega_q = \omega_0 + q(\omega_b - \omega_a - \delta) = \omega_0 + q\,\omega_m$$

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

Hamiltonian

$$H_{\text{int}} = -\sum_j E(\mu_{ja}\sigma_{ja} + \mu_{aj}\sigma_{aj} + \mu_{jb}\sigma_{jb} + \mu_{bj}\sigma_{bj})$$

$$\mu_{\alpha\beta} = \langle\alpha|d|\beta\rangle \quad \sigma_{\alpha\beta} = |\alpha\rangle\langle\beta|$$

$$E = \frac{1}{2}\sum_q (E_q e^{-i\omega_q\tau} + E_q^* e^{i\omega_q\tau})$$

Effective Hamiltonian

$|j\rangle$ far off-resonance → two-level system

$$H_{\text{eff}} = -\hbar\begin{bmatrix}\Omega_{aa} & \Omega_{ab} \\ \Omega_{ba} & \Omega_{bb} - \delta\end{bmatrix}$$

Stark shifts

$$\Omega_{aa} = \frac{1}{2}\sum_q a_q |E_q|^2 \qquad a_q = \frac{1}{2\hbar^2}\sum_j \left(\frac{|\mu_{ja}|^2}{\omega_j - \omega_a - \omega_q} + \frac{|\mu_{ja}|^2}{\omega_j - \omega_a + \omega_q} \right)$$

$$\Omega_{bb} = \frac{1}{2}\sum_q b_q |E_q|^2 \qquad b_q = \frac{1}{2\hbar^2}\sum_j \left(\frac{|\mu_{jb}|^2}{\omega_j - \omega_b - \omega_q} + \frac{|\mu_{jb}|^2}{\omega_j - \omega_b + \omega_q} \right)$$

Two-photon Rabi freq.

$$\Omega_{ab} = \Omega_{ba}^* = \frac{1}{2}\sum_q d_q E_q E_{q+1}^* \qquad d_q = \frac{1}{2\hbar^2}\sum_j \left(\frac{\mu_{aj}\mu_{jb}}{\omega_j - \omega_b - \omega_q} + \frac{\mu_{aj}\mu_{jb}}{\omega_j - \omega_a + \omega_q} \right)$$

Adiabatic eigenstate

$$|+\rangle = \cos\frac{\theta}{2} e^{i\varphi/2}|a\rangle + \sin\frac{\theta}{2} e^{-i\varphi/2}|b\rangle \xrightarrow{E \to 0} |a\rangle$$

$$\tan\theta = \frac{2|\Omega_{ab}|}{\Omega_{aa} - \Omega_{bb} + \delta} \qquad \Omega_{ab} = |\Omega_{ab}| e^{i\varphi}$$

Wave propagation

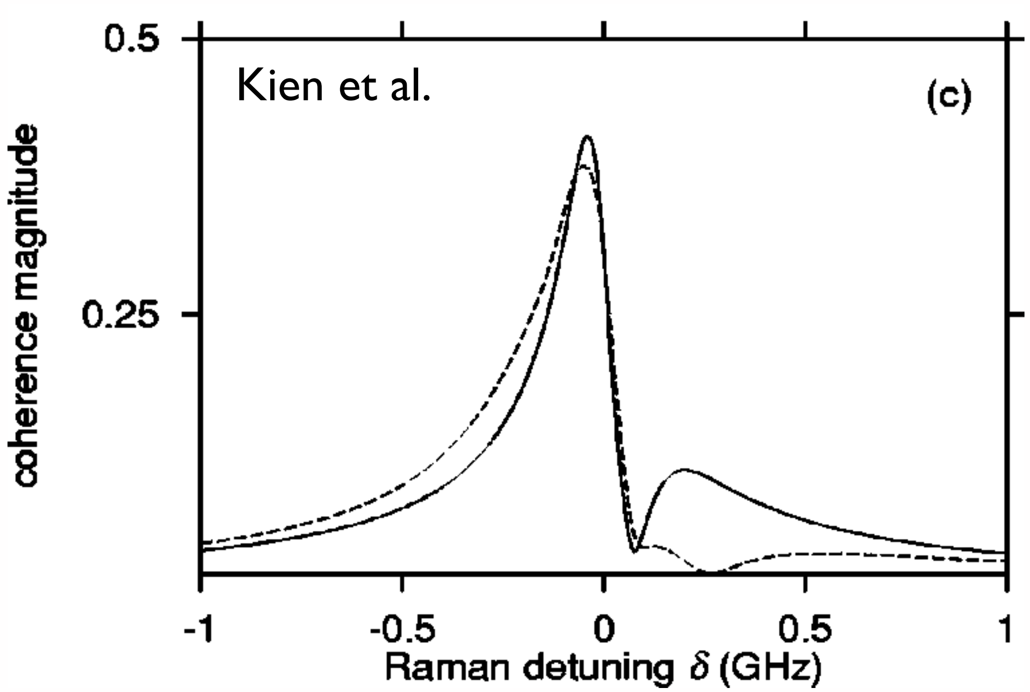
$$(\partial_t + \partial_z)E_q = in\hbar\omega_q \left(a_q\rho_{aa}E_q + b_q\rho_{bb}E_q + d_{q-1}\rho_{ba}E_{q-1} + d_q^*\rho_{ab}E_{q+1}\right)$$

Coherence $\rho_{ab} = \frac{1}{2}\sin\theta e^{i\varphi}$

molecular system of far off-resonance

$\Omega_{aa} \simeq \Omega_{bb}$ $\tan\theta \simeq 2|\Omega_{ab}|/\delta$ → $|\rho_{ab}| \simeq 1/2$

$|\rho_{ab}|$



δ

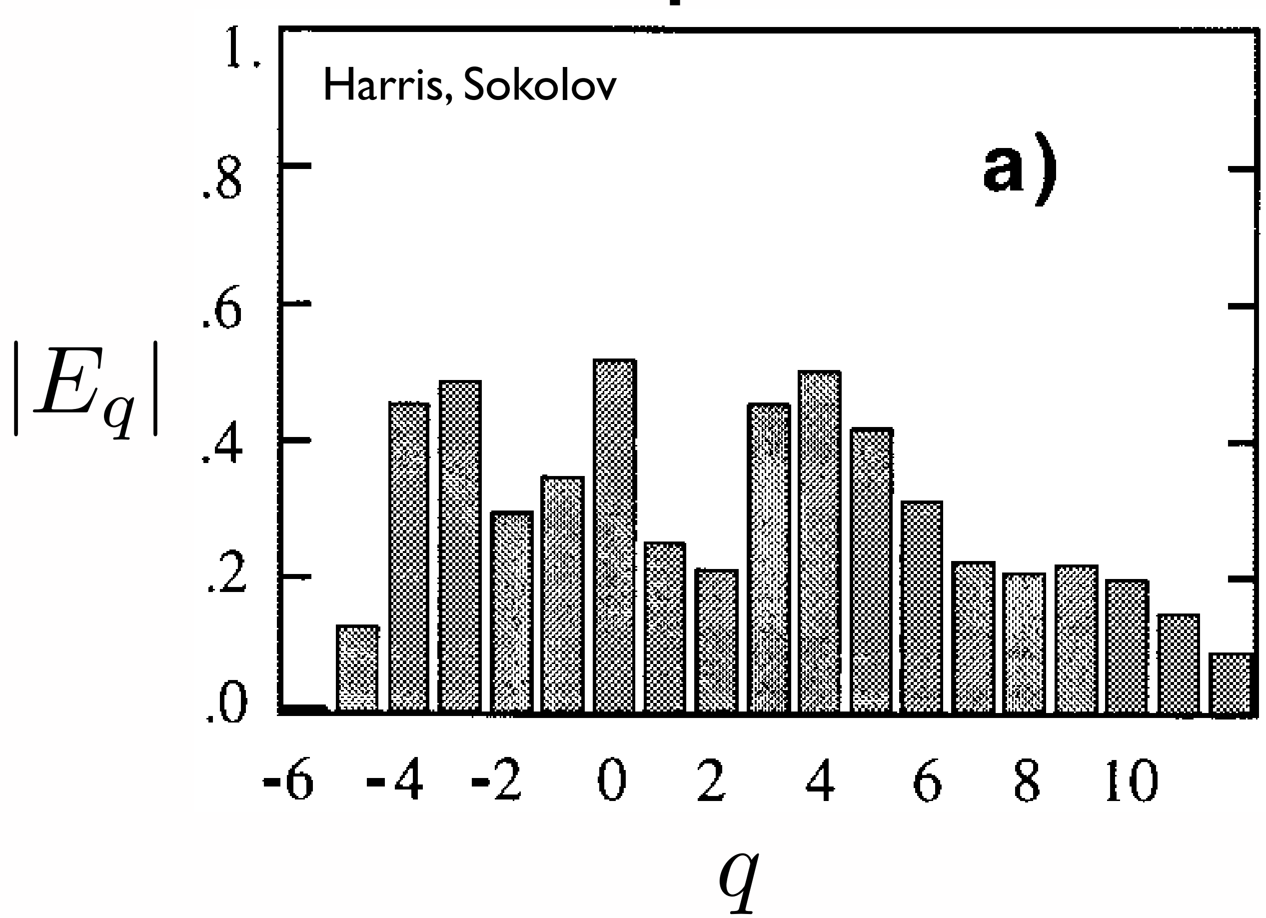
$\delta > 0\,,\ \sin\theta > 0$

phased state

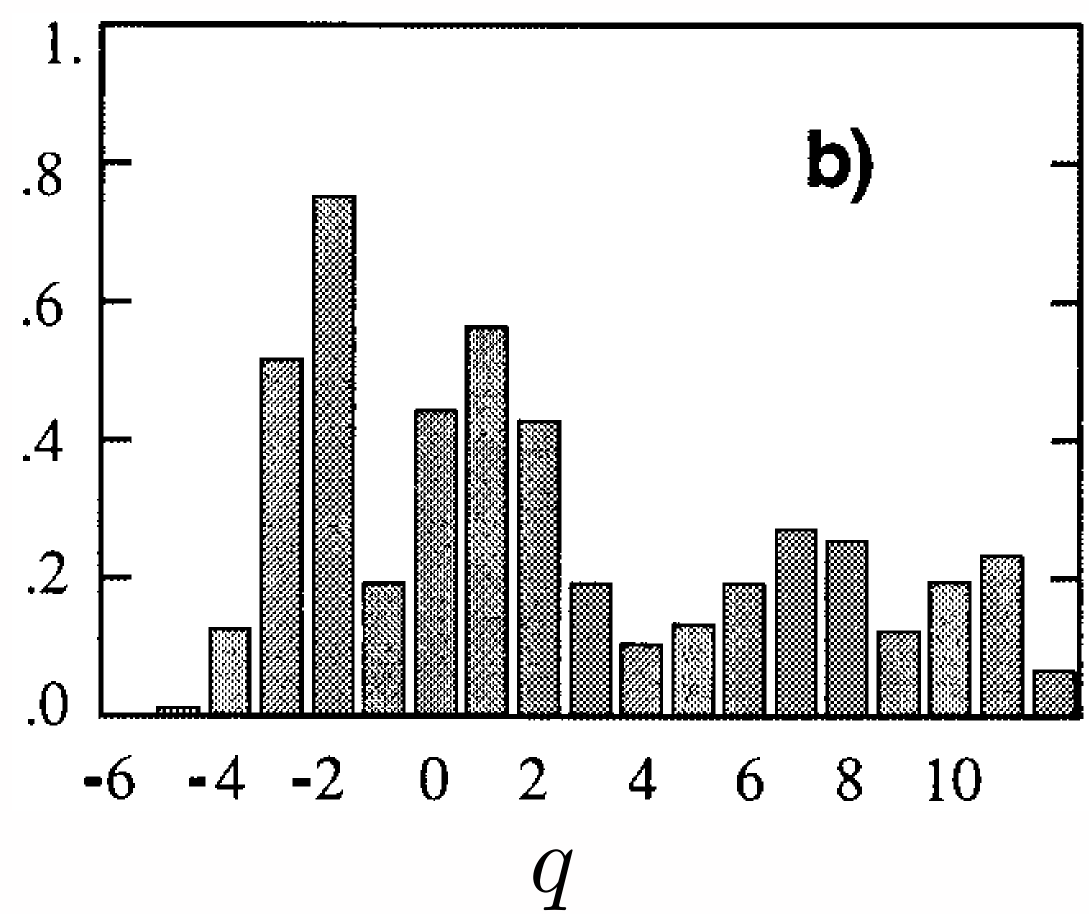
$\delta < 0\,,\ \sin\theta < 0$

antiphased state

antiphased

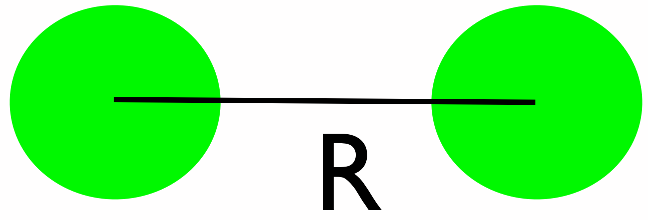


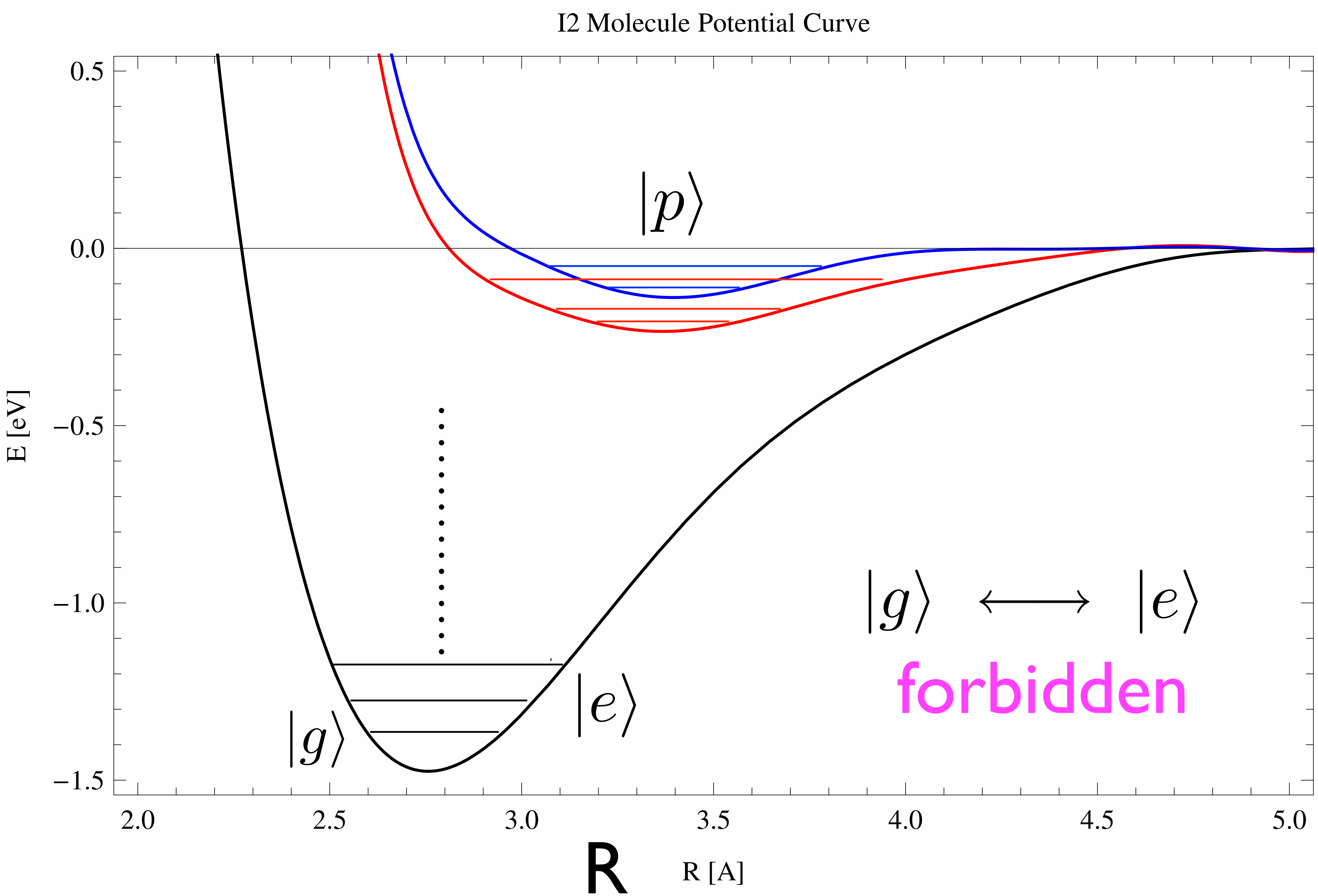
phased



Homonuclear diatomic molecule

Potential curves





Para-hydrogen gas PSR experiment

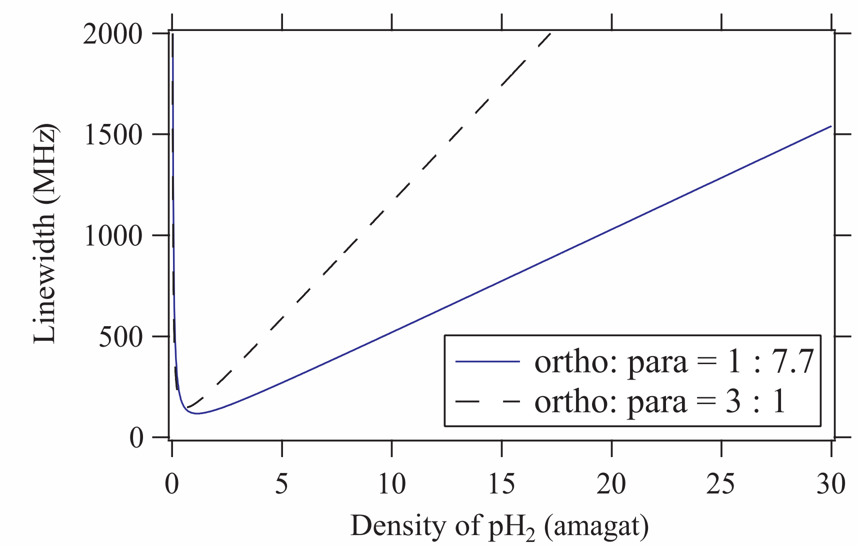
@ Okayama U

Y. Miyamoto et al. PTEP113C01(2014)
arXiv1406.2198

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

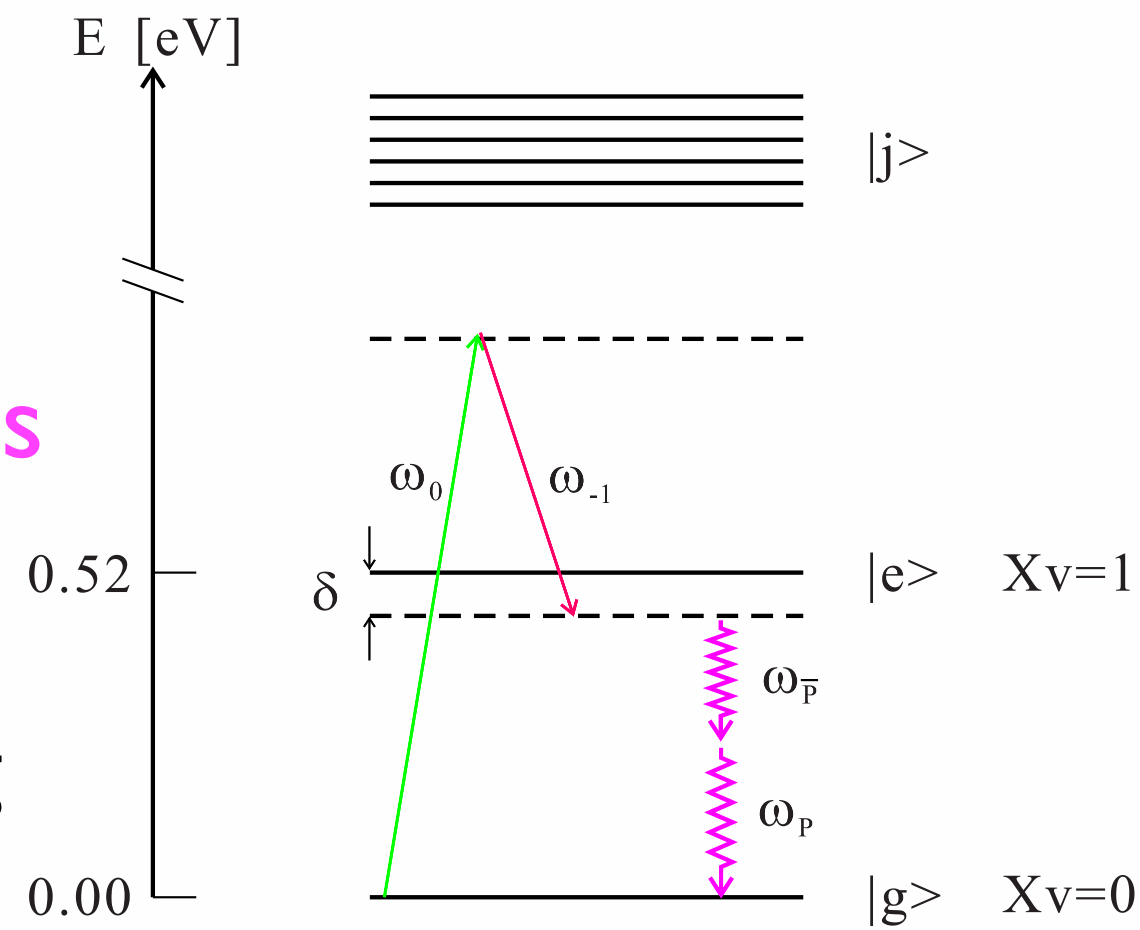
$$1/T_2 \sim 130 \text{ MHz}$$

coherence production

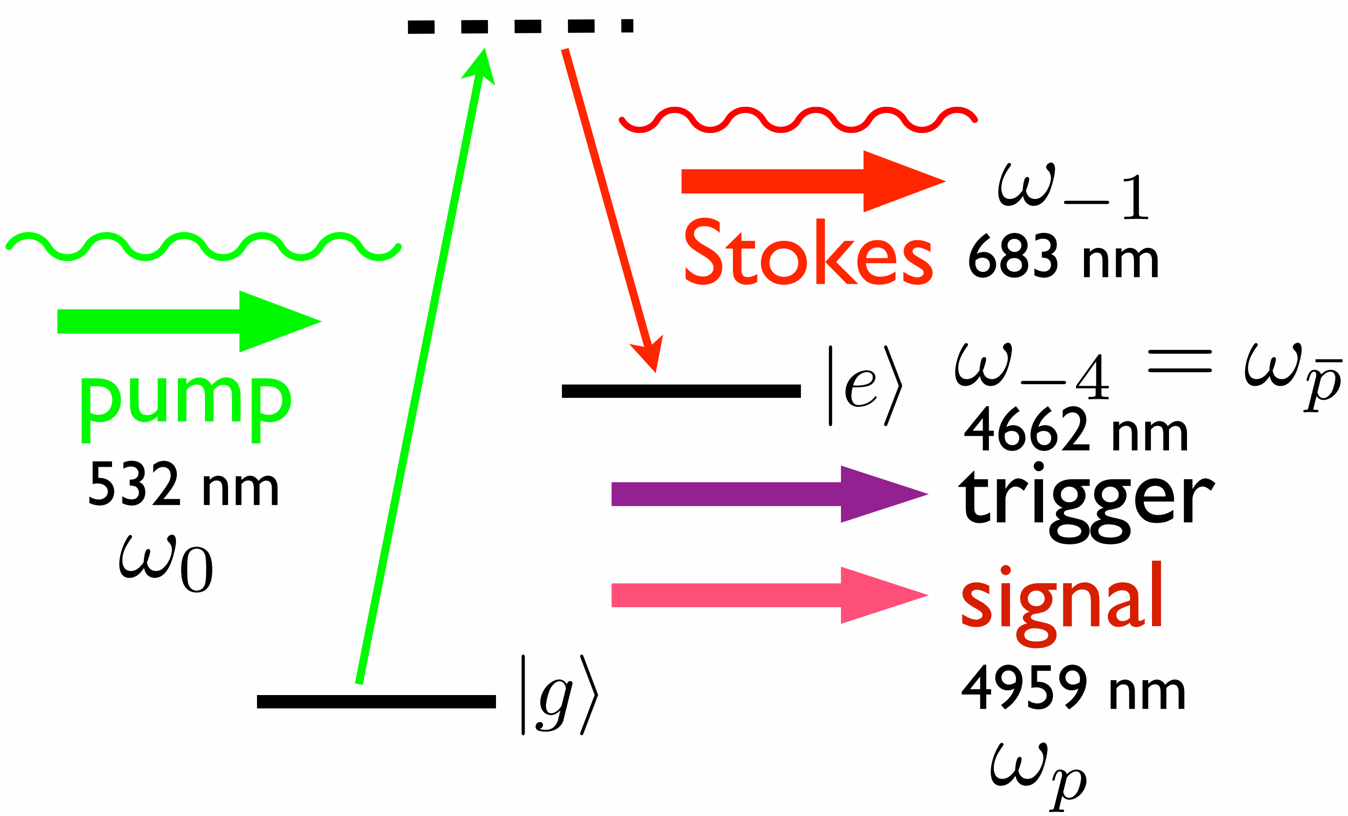
adiabatic Raman process

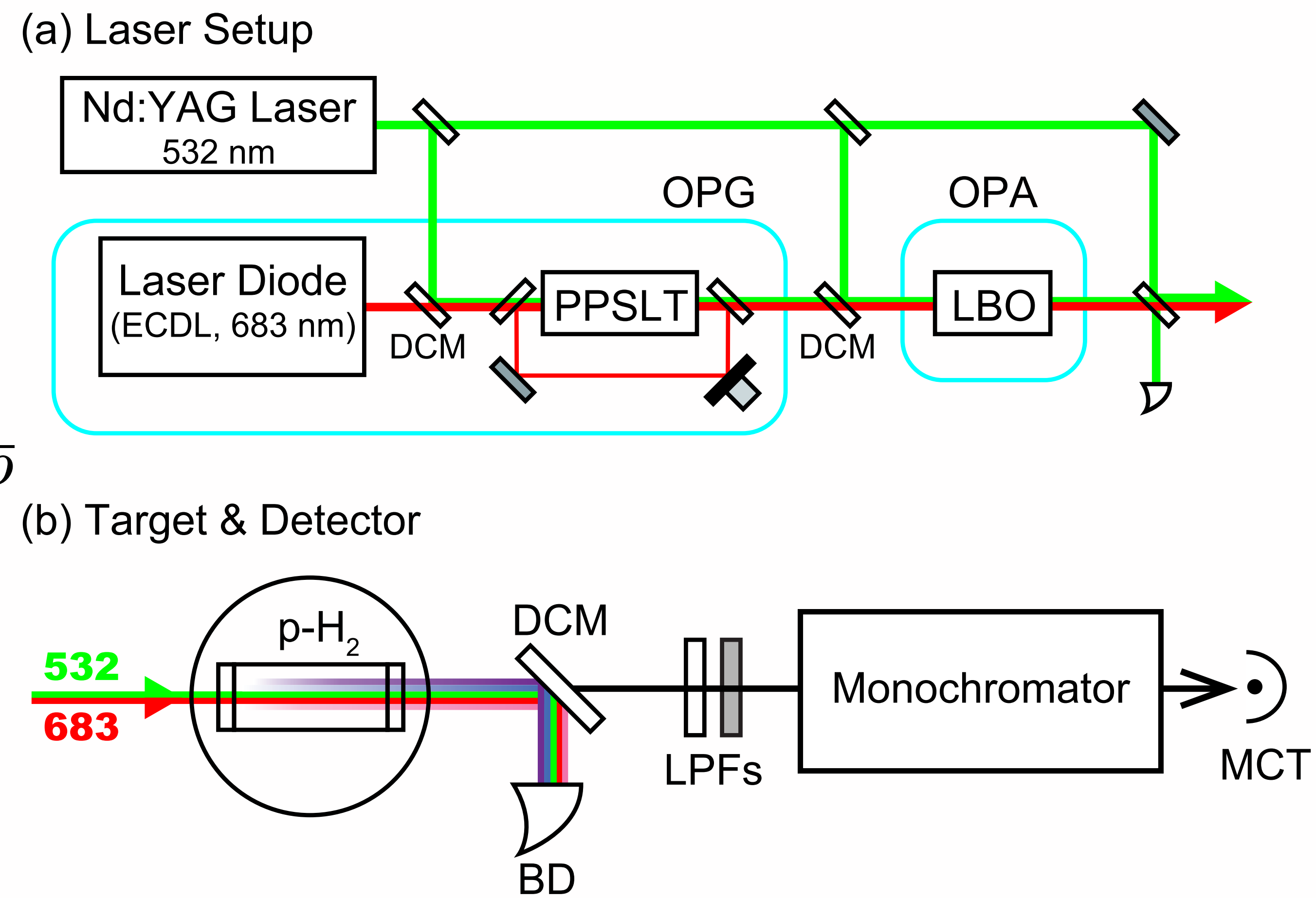
$$\Delta\omega = \omega_0 - \omega_{-1}$$
$$= \epsilon_{eg} - \delta$$
$$= \omega_p + \omega_{\bar{p}}$$

detuning



Experimental setup





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

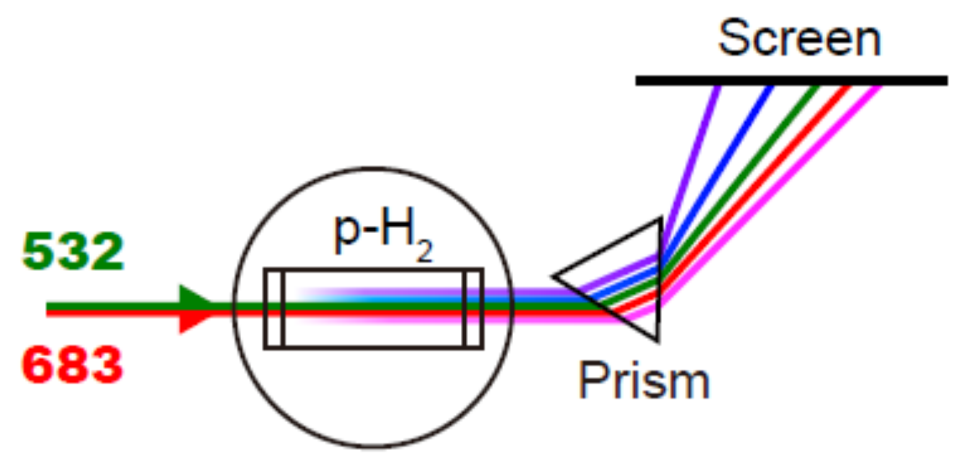
Target cell: length 15cm, diameter 2cm, 78K, 60kPa

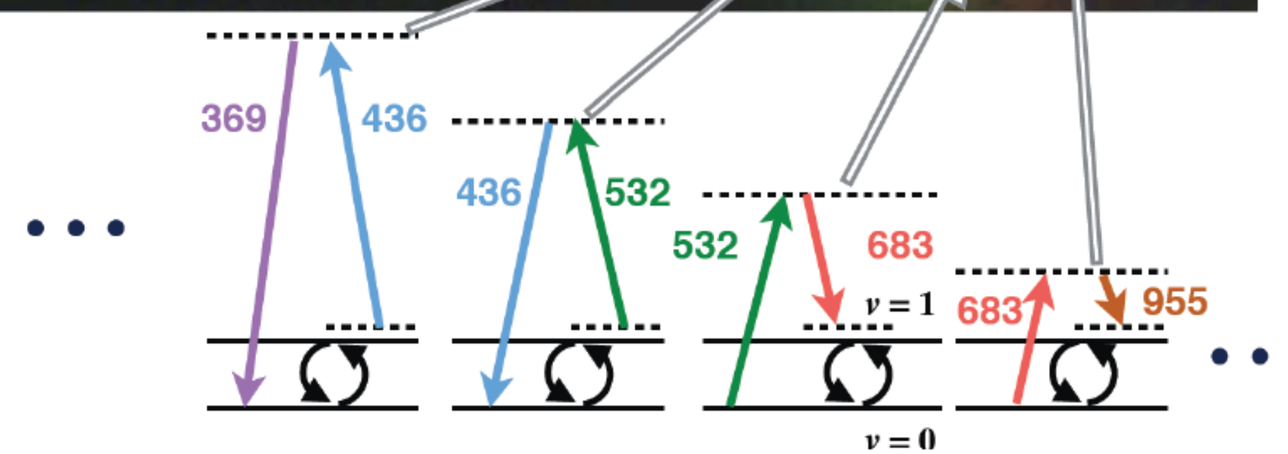
$$n = 5.6 \times 10^{19}\ \mathrm{cm}^{-3} \qquad 1/T_2 \sim 130\ \mathrm{MHz}$$

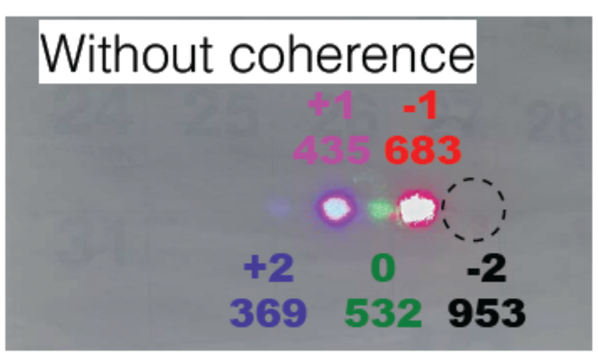
Driving lasers: $5\ \mathrm{mJ},\ 6\ \mathrm{ns},\ w_0 = 100\ \mu\mathrm{m}\ (5\ \mathrm{GW/cm}^2)$

Ultra-broadband Raman sidebands

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







2014/10/29 Kyoto 34

N. Sasao

Generated coherence

Maxwell-Bloch eq.

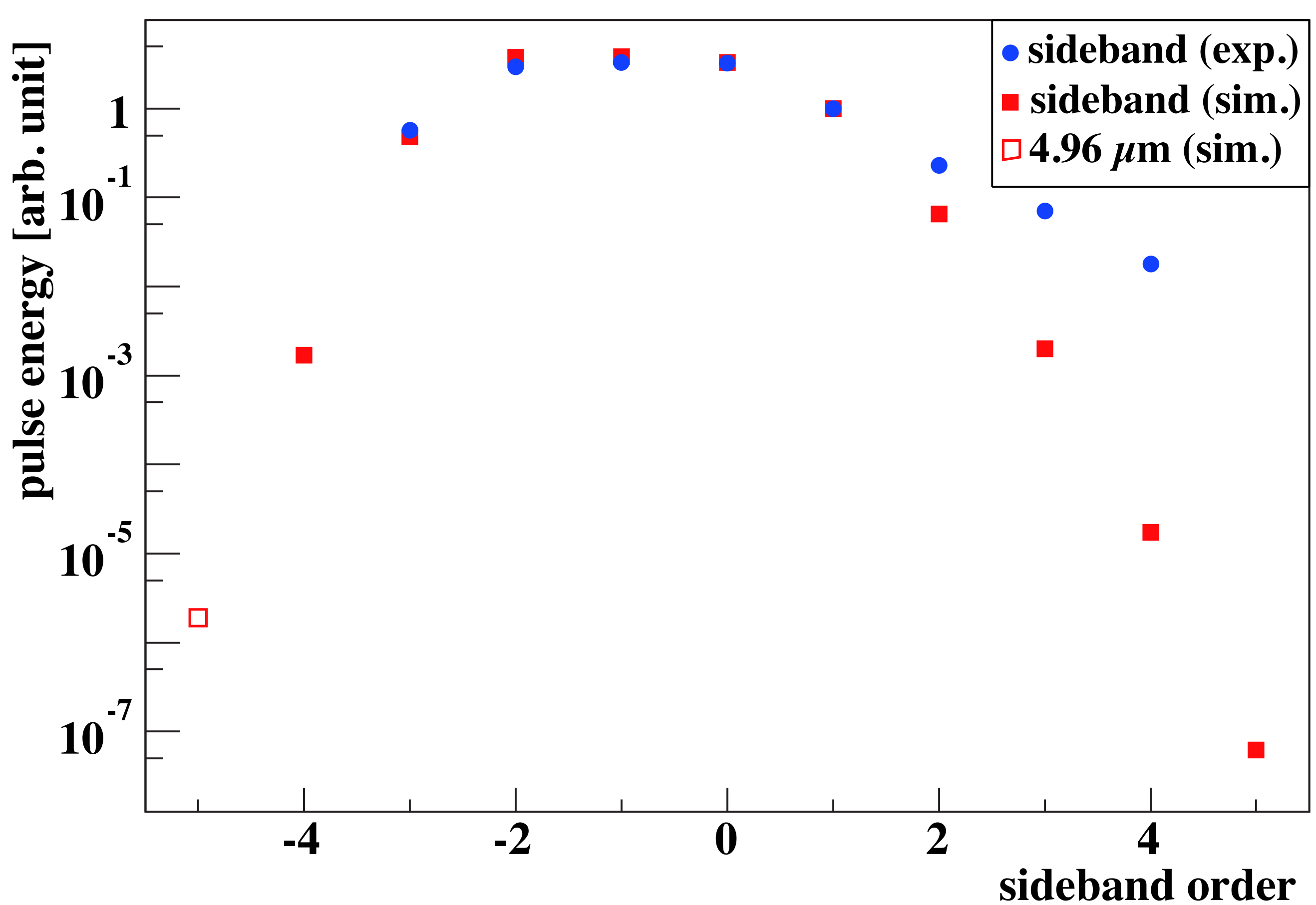
$$\frac{\partial \rho_{gg}}{\partial \tau} = i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{ee},$$

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

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

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

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

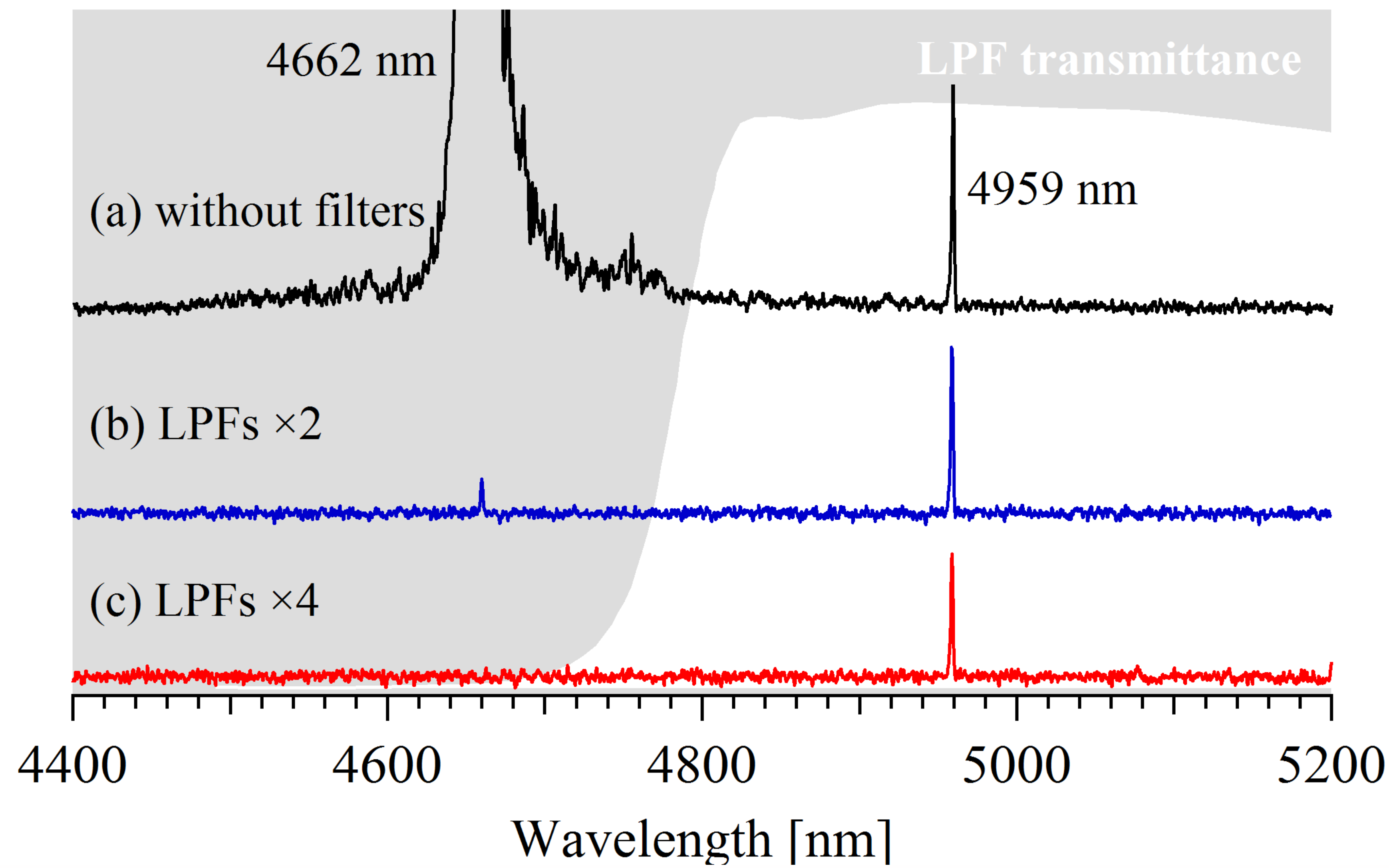


coherence estimation

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

(6% of max.)

Observed two-photon spectrum



# of observed photons

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

Estimated spontaneous rate

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

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

BG-free RENP

Ref. M. Yoshimura, N. Sasao, M.T. arXiv:15010571

QED backgrounds

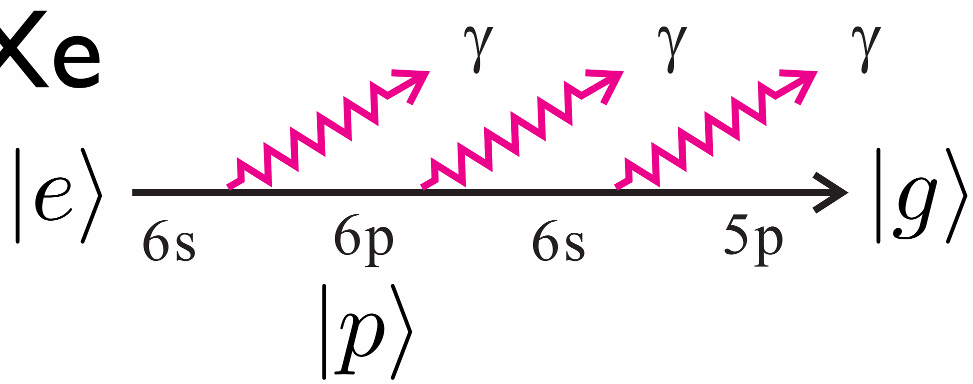
Macrocoherent amplification of RENP

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

Macrocoherent amplification of QED processes

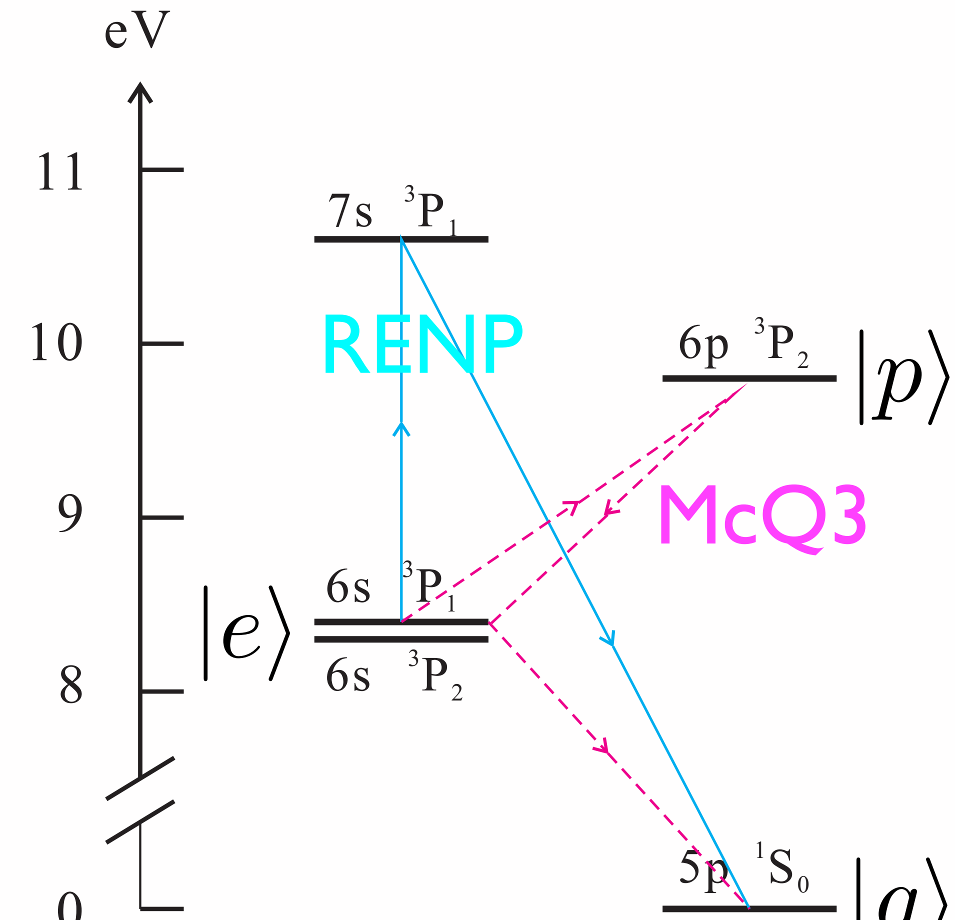
$$|e\rangle \to |g\rangle + \gamma_0 + \gamma_1 \gamma_2$$ McQ3

Ex. Xe



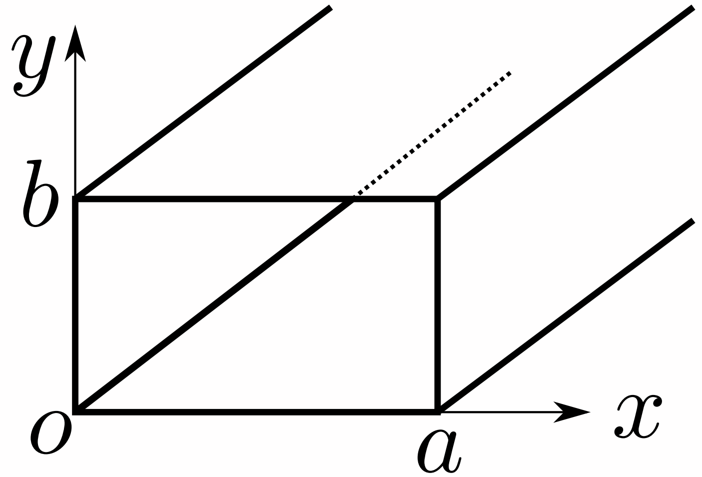
$$\frac{d\Gamma_3}{d\omega} = \frac{3\pi^2}{2} \frac{\gamma_{pe}\gamma_{pq}\gamma_{qg}}{\epsilon_{pe}^3 \epsilon_{pq}^3 \epsilon_{qg}^3} n^3 V \eta_3(t) \omega^2 (\epsilon_{eg} - \omega_0 - \omega)^2 F_3^2(\omega)$$

$$\Gamma_3 \sim 10^{20}\ \mathrm{Hz} \left(\frac{n}{10^{20}/\mathrm{cm}^3} \right)^3 \frac{V}{\mathrm{cm}^3} \frac{\eta_3(t)}{10^{-3}}$$



serious BG though reducible

McQn vs. RENP in a waveguide



TE modes

$$E_y \sim \sin\left(\frac{n_x \pi}{a} x\right) \cos\left(\frac{n_y \pi}{b} y\right) e^{i(kz-\omega t)}$$

Dispersion: $\omega^2 = k^2 + \omega_c^2$

Cutoff freq. (Mass): $\omega_c^2 = M^2 = \pi^2 \left(\frac{n_x^2}{a^2} + \frac{n_y^2}{b^2}\right)$

The lowest mode: $\mathrm{TE}_{1,0}$ $M = \pi/a$

Threshold

McQn $\omega \leq \epsilon_{eg}/2 - n(n-2)M^2/2\epsilon_{eg}$

RENP $\omega \leq \epsilon_{eg}/2 - [(m_i + m_j)^2 - M^2]/2\epsilon_{eg}$

→ $(n-1)M > m_i + m_j$ BG-free RENP

McQ3

$M > (m_i + m_j)/2 \geq m_0$ (the smallest neutrino mass)

$$M = \frac{\pi}{a} \simeq 0.6 \text{ meV} \left(\frac{1\text{mm}}{a} \right)$$

Photonic crystals may be realistic.

Ex. Xe $\epsilon_{eg} = 8.3153 \text{ eV} \quad m_0 = 1 \text{ meV}, \ a = 10 \ \mu\text{m}$

$$\omega_{\text{max}}(\text{McQ3}) = 4.1570 \text{ eV}$$
$$\omega_{\text{max}}(\text{RENP}) = 4.1579 \text{ eV}$$

SUMMARY

Neutrino Physics with Atoms/Molecules

- ✶ RENP spectra are sensitive to unknown neutrino parameters.
  Absolute mass, Dirac or Majorana,
  NH or IH, CP
- ✶ RENP spectra are sensitive to the cosmic neutrino background.
- ✶ Macrocoherent rate amplification is essential.
  Demonstrated by a QED process, PSR.
- ✶ Background-free RENP
  Waveguide (photonic crystals?)

A new approach to neutrino physics

春の学会

3/21 午後: DJ 田中 (CNB)

3/22 午前: DF 増田, 原 (PSR)

午後: DB 笹尾 (シンポ), AG 植竹 (PSR)

3/24 午前: BG 中島, 大饗 (FEL SR), CE 吉見 (Th)