Physics
OSAKA UNIVERSITY

Neutrino Physics with Atomic/Molecular Processes

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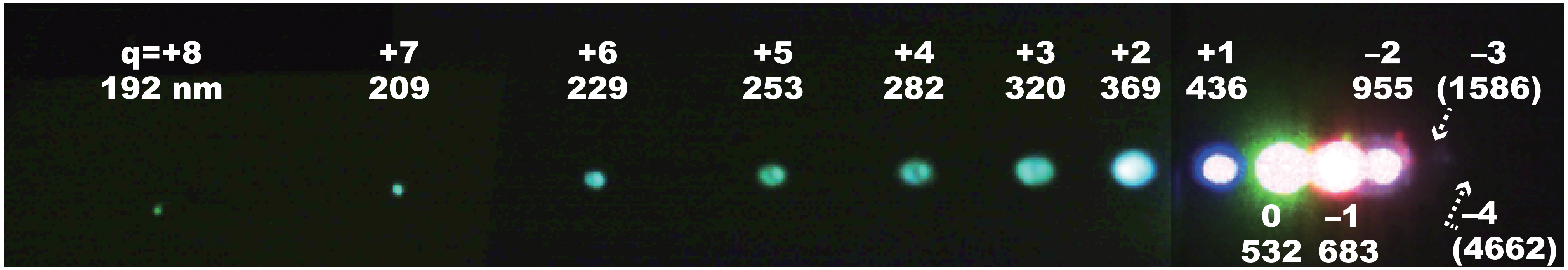


Nov. 25, 2014 @ Osaka HET seminar

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

What we know about neutrino mass and mixing

Masses:

$$\Delta m_{21}^2 = 7.54 \times 10^{-5}\ \mathrm{eV}^2\,, \quad |\Delta m_{31(32)}^2| = 2.47\ (2.46) \times 10^{-3}\ \mathrm{eV}^2$$

Fogli et al. (2012)

$$\sum m_\nu \leqslant 0.58\ \mathrm{eV}$$ Jarosik et al. (2011)

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

$$s_{12}^2 \simeq 0.31,\ s_{23}^2 \simeq 0.39,\ s_{13}^2 \simeq 0.024$$

Fogli et al. (2012)

Unknown properties of neutrinos

Absolute mass

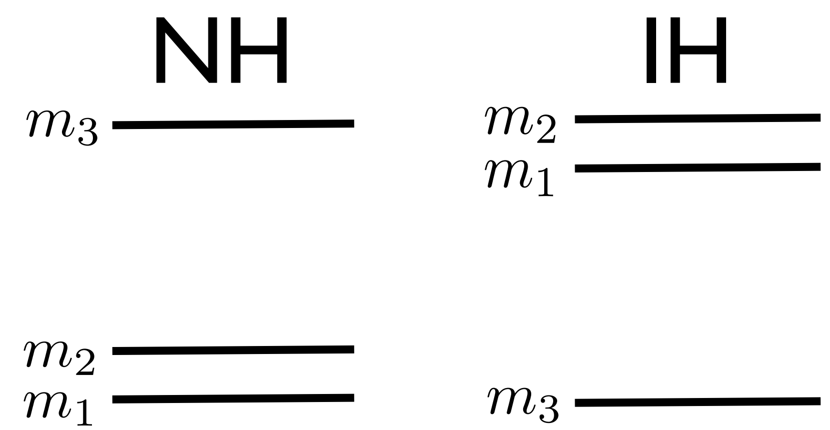
$$m_{1(3)} < 0.19\,\mathrm{eV}\,,\ \ 0.050\,\mathrm{eV} < m_{3(2)} < 0.58\,\mathrm{eV}$$

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

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

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

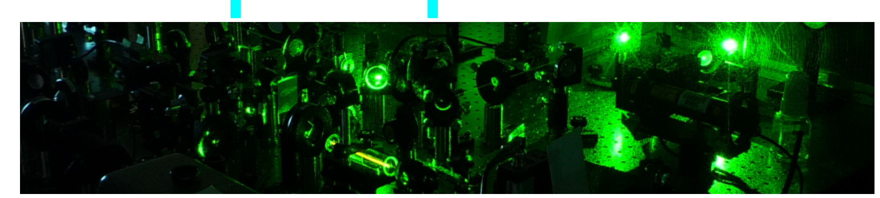
Neutrinoless double beta decays

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



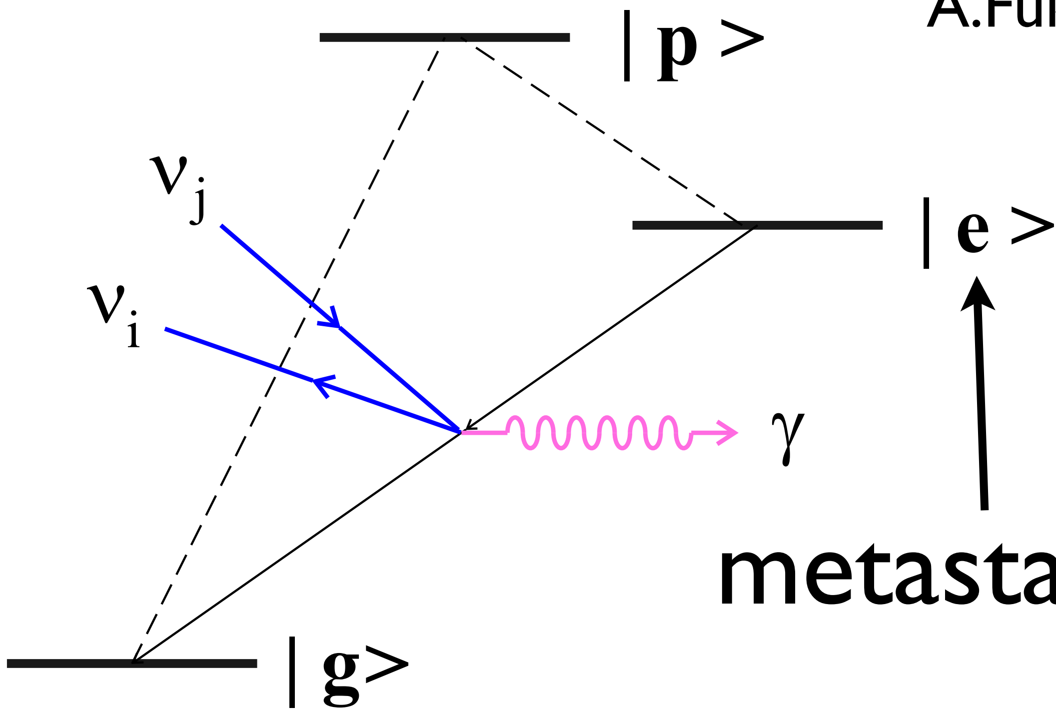
Atomic/molecular processes

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



metastable

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

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

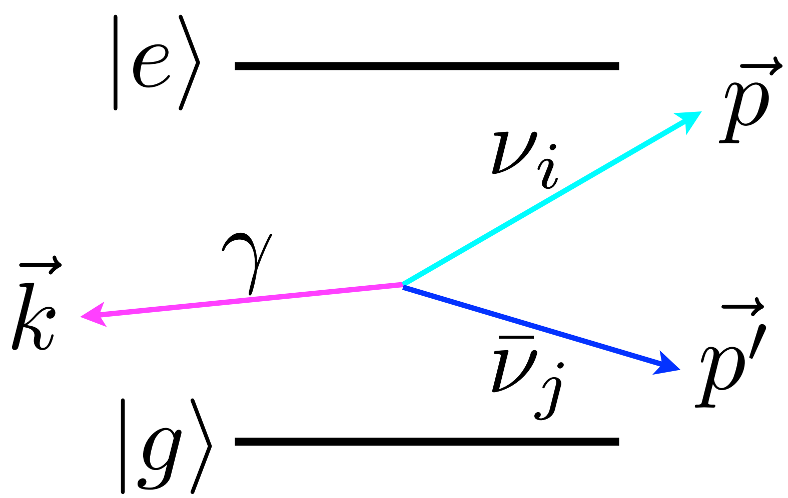
cf. nuclear processes ~ MeV

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)

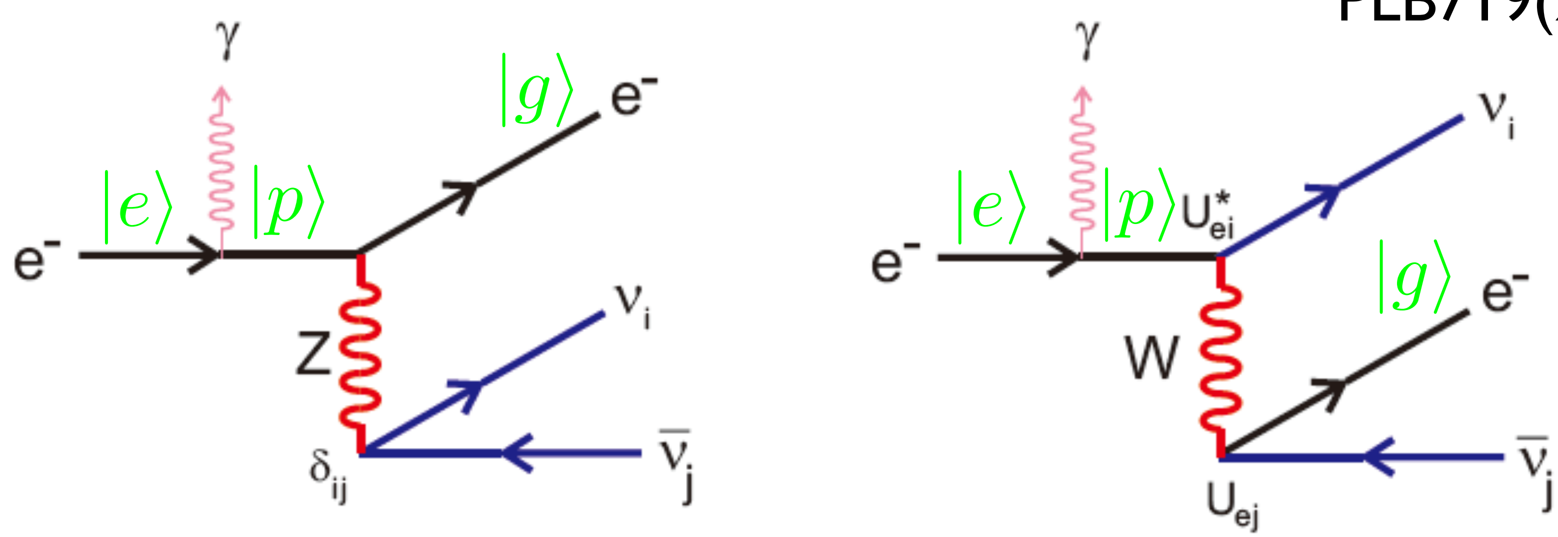
total amp. $\propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p}')$

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

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



Neutral Current   Charged Current

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

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

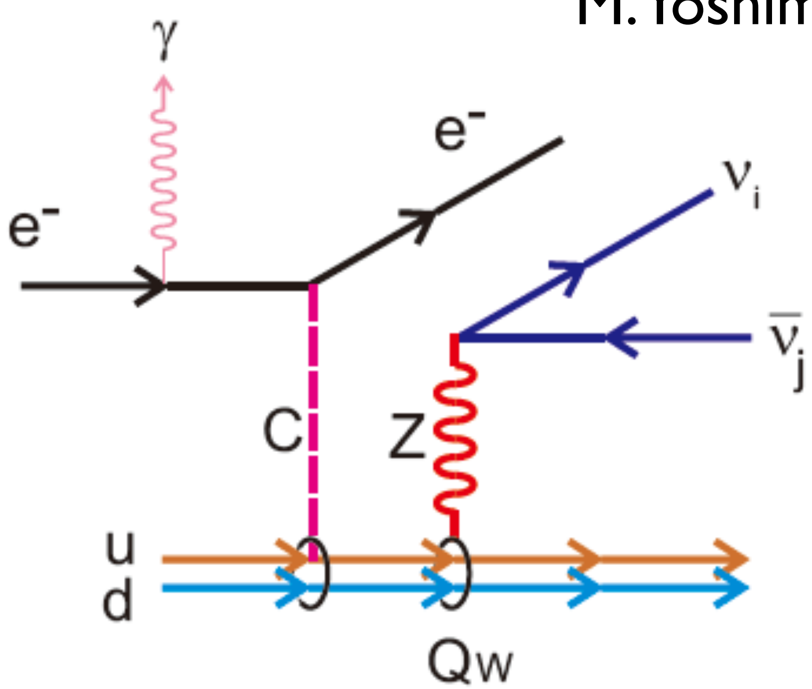
Atomic matrix element in the NR approximation

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

$$\langle g | \bar{e} \gamma^\mu \gamma_5 e | p \rangle \simeq (0, 2\langle g | \boldsymbol{s} | p \rangle)$$ → 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: $Q_W \simeq -(\#\ \mathrm{of\ neutrons})$

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

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

dynamical factor → $\eta_\omega(t)$

spectral function → $I(\omega)$

overall rate → Γ_0

Overall rate

macro-coherence → n^2V

~ field energy density → $\epsilon_{eg} n$

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

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

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

Spectral function (spin current)

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

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

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

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

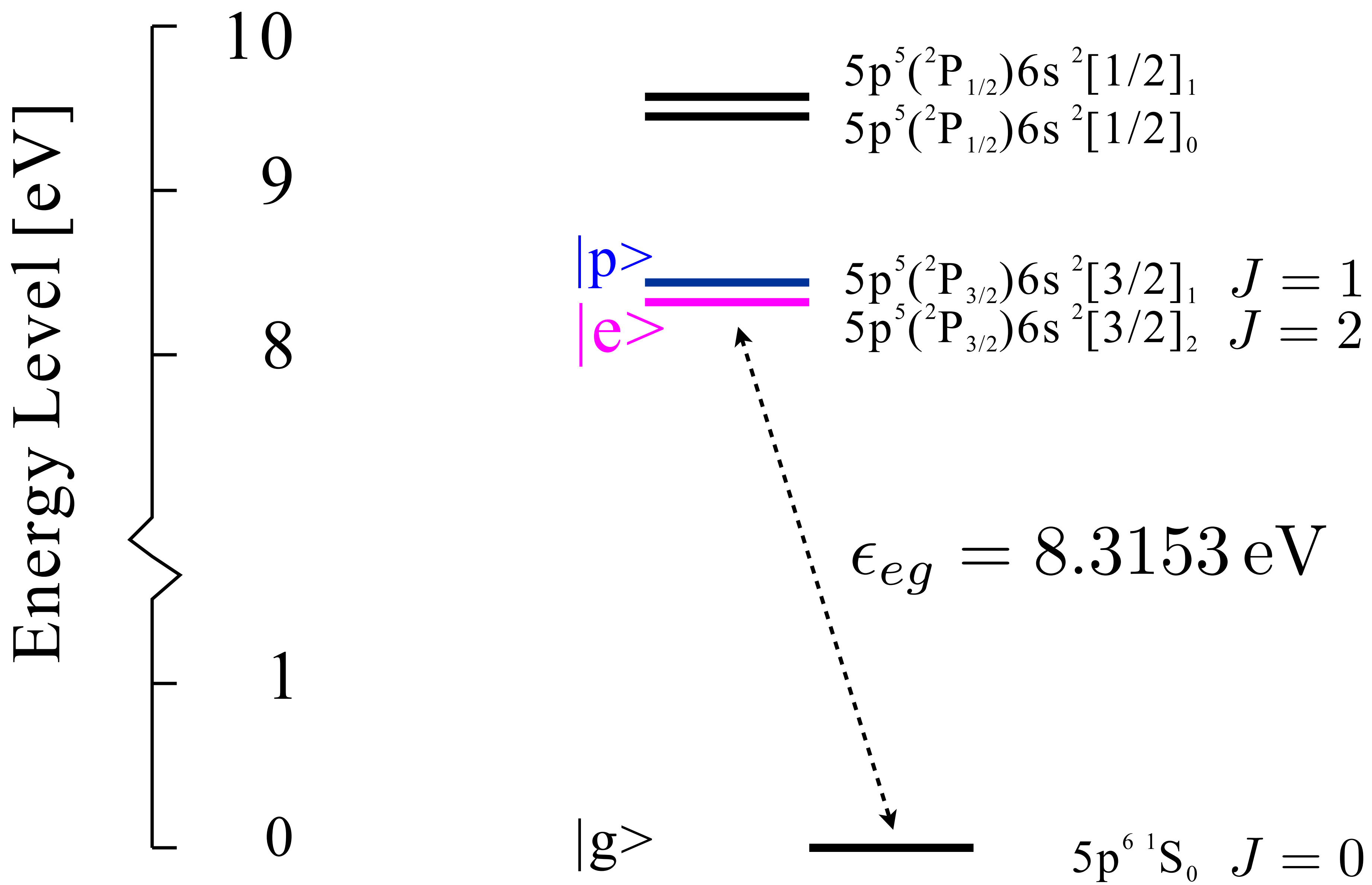
$\delta_M = 0(1)$ for Dirac(Majorana)

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

Dynamical factor

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

Xe (gas target)

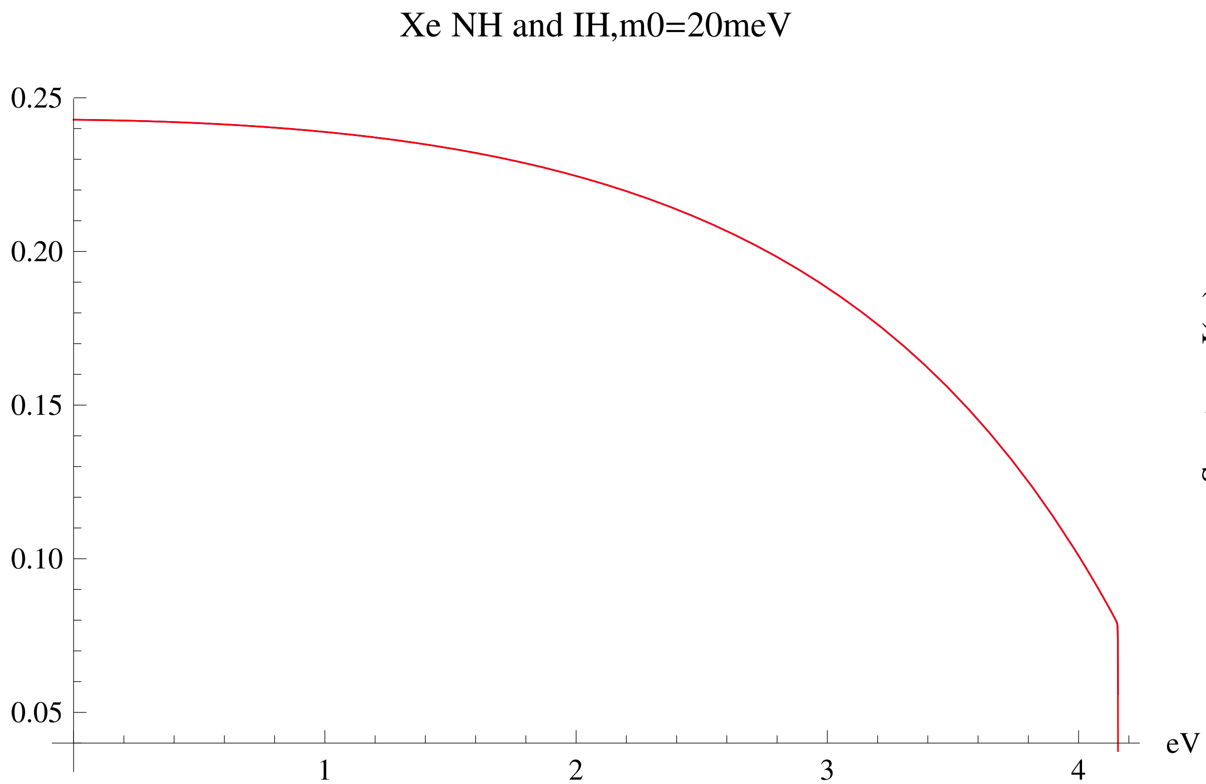


$$|e\rangle \leftrightarrow |p\rangle \quad \mathrm{M1}$$

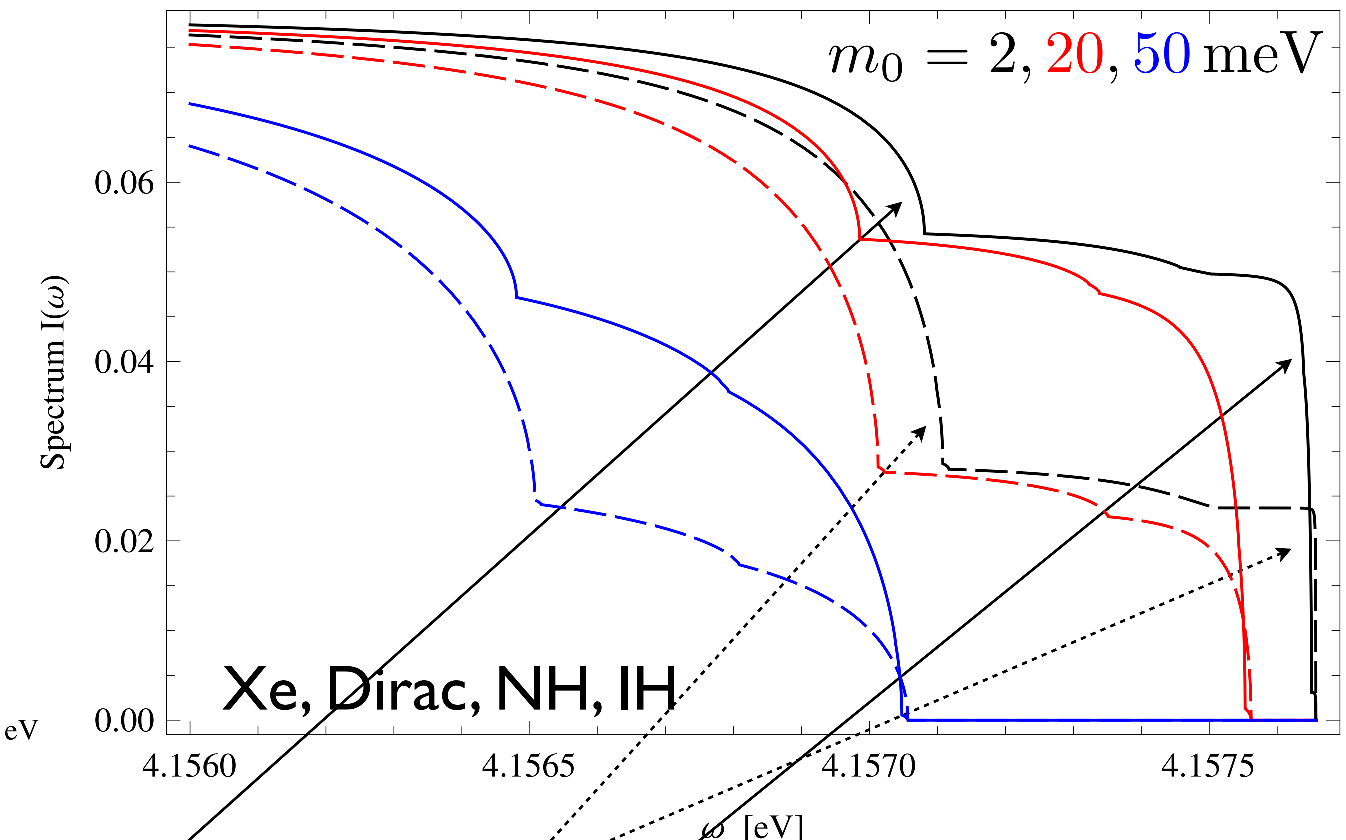
$$|p\rangle \leftrightarrow |g\rangle \quad \mathrm{E1}$$

Photon spectrum (spin current)

Global shape



Threshold region



The threshold weight factors

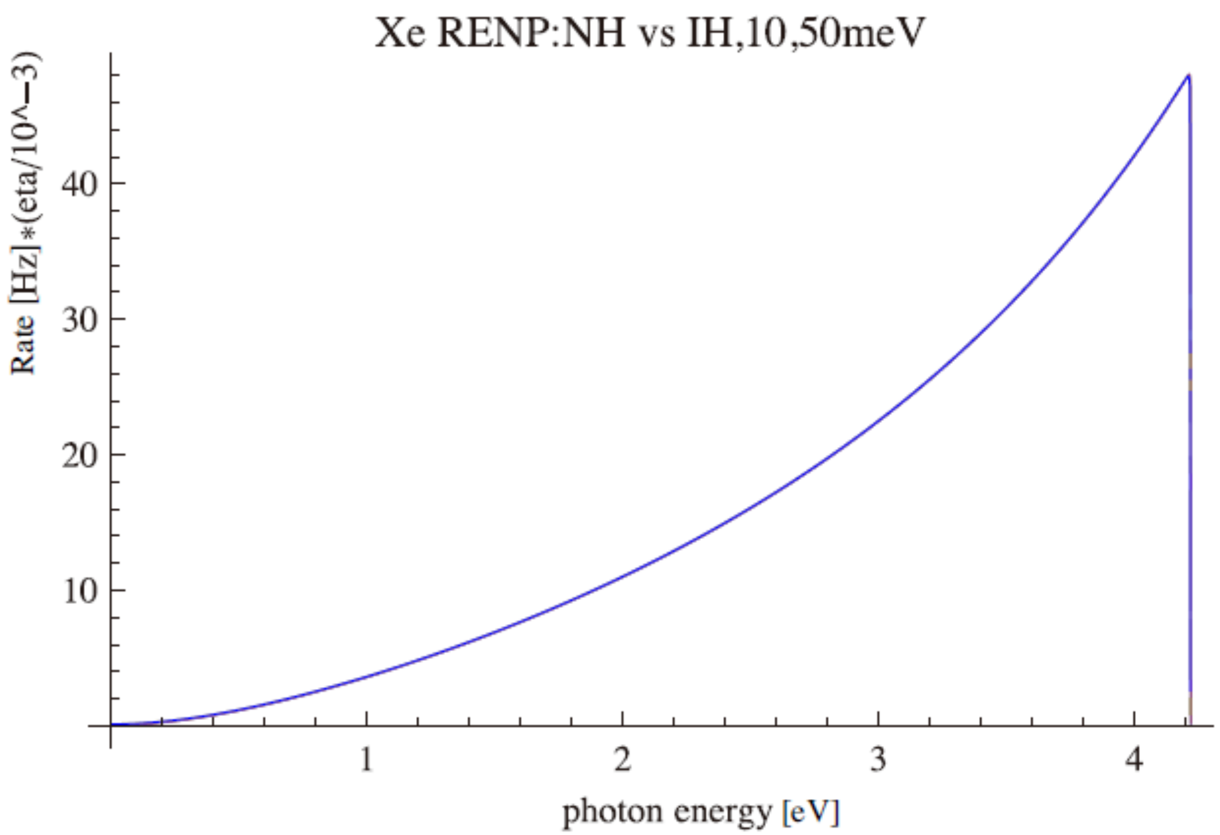
B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{13}^2 - 1/2)^2$	$2c_{12}^2 s_{12}^2 c_{13}^4$	$2s_{12}^2 c_{13}^2 s_{13}^2$	$2c_{12}^2 c_{13}^2 s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

Photon spectrum (nuclear monopole)

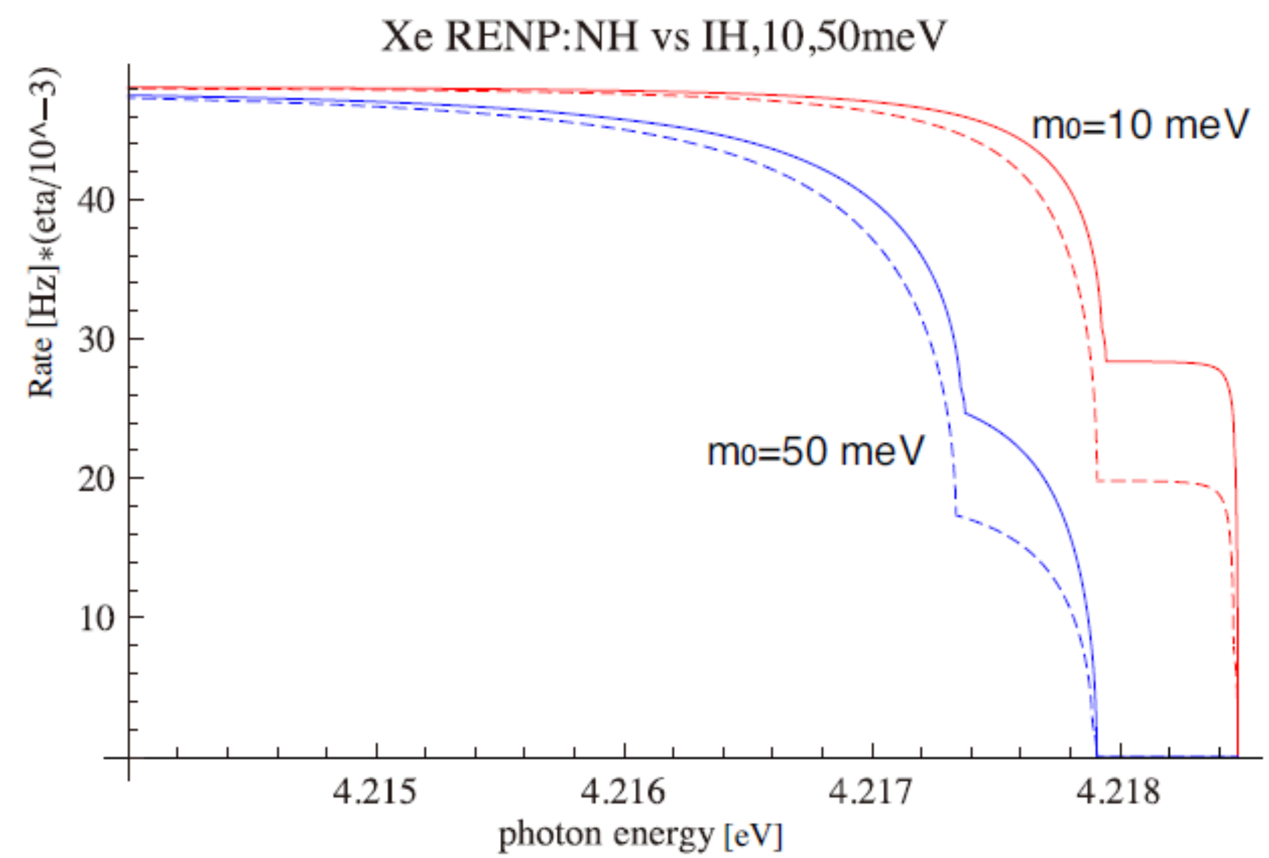
Xe $^3\mathrm{P}_1$ 8.4365 eV

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

Global shape



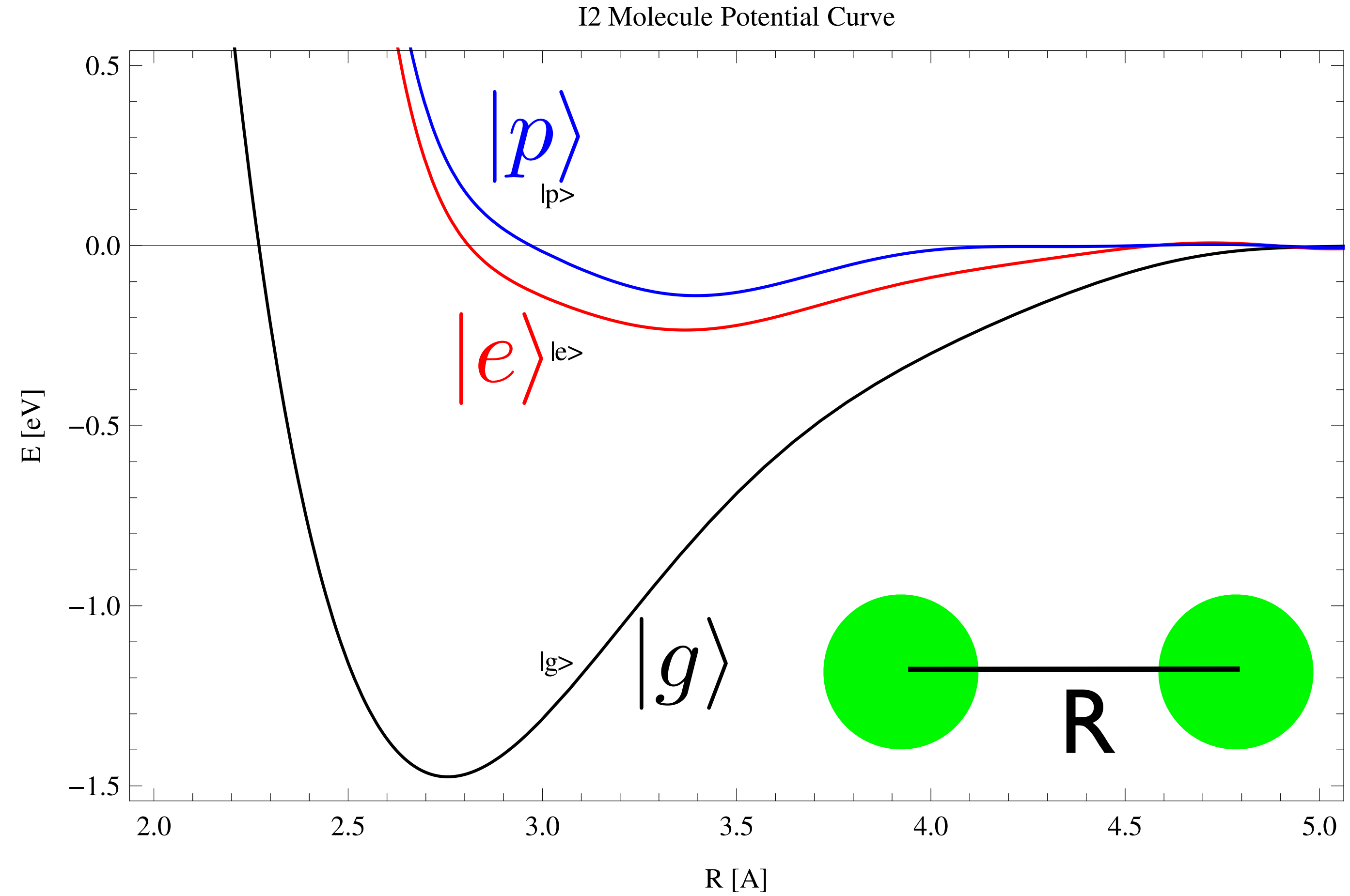
Threshold region

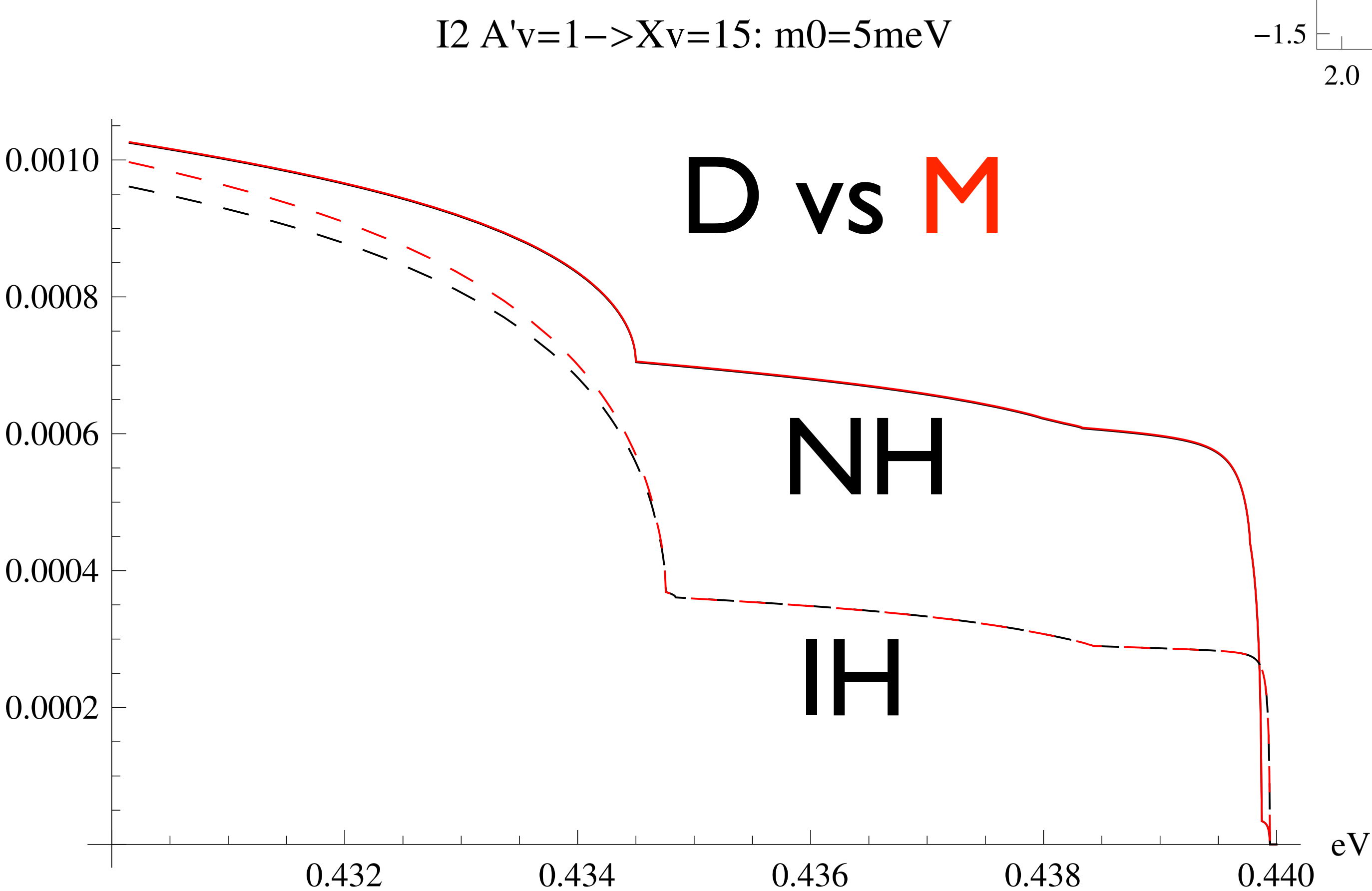


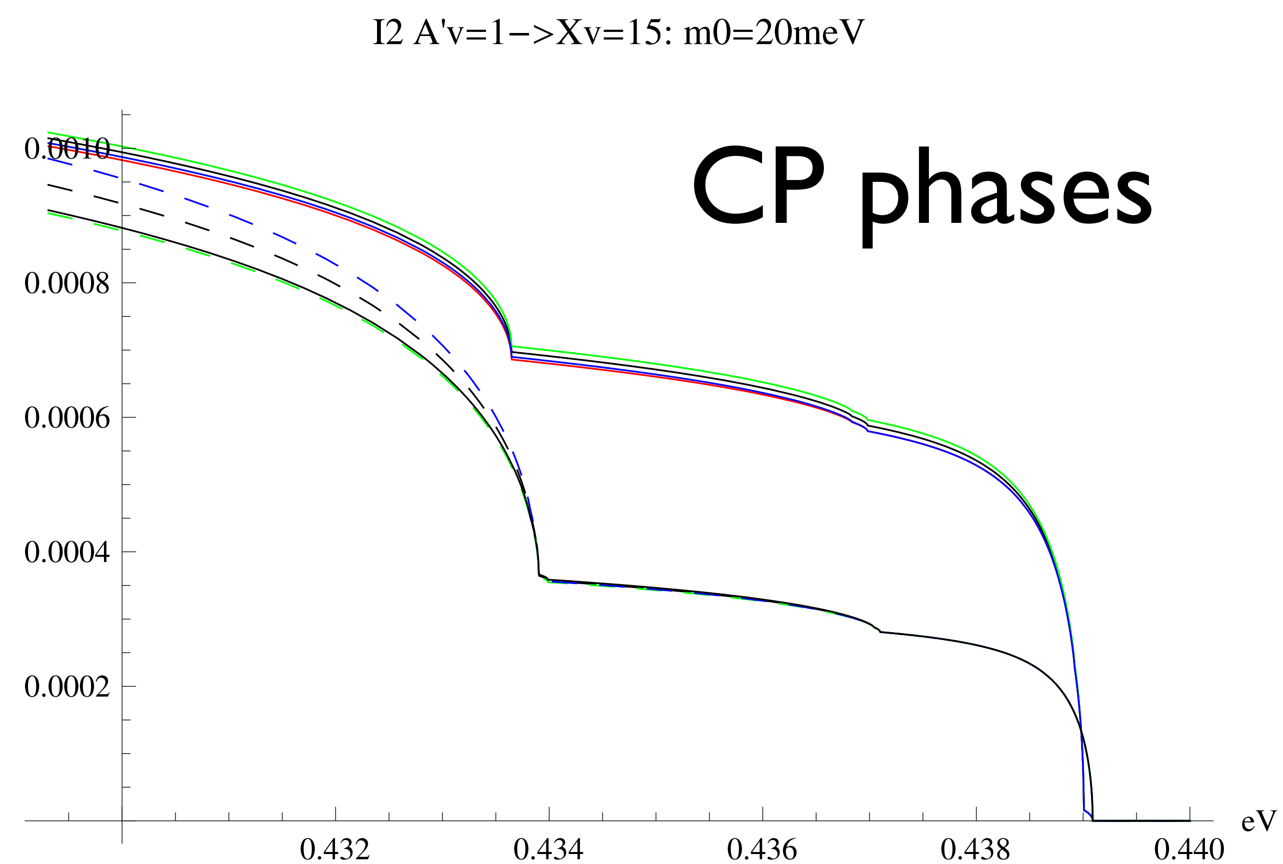
I_2 molecule

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

(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, arXiv:1409.3648

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

Pauli exclusion

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

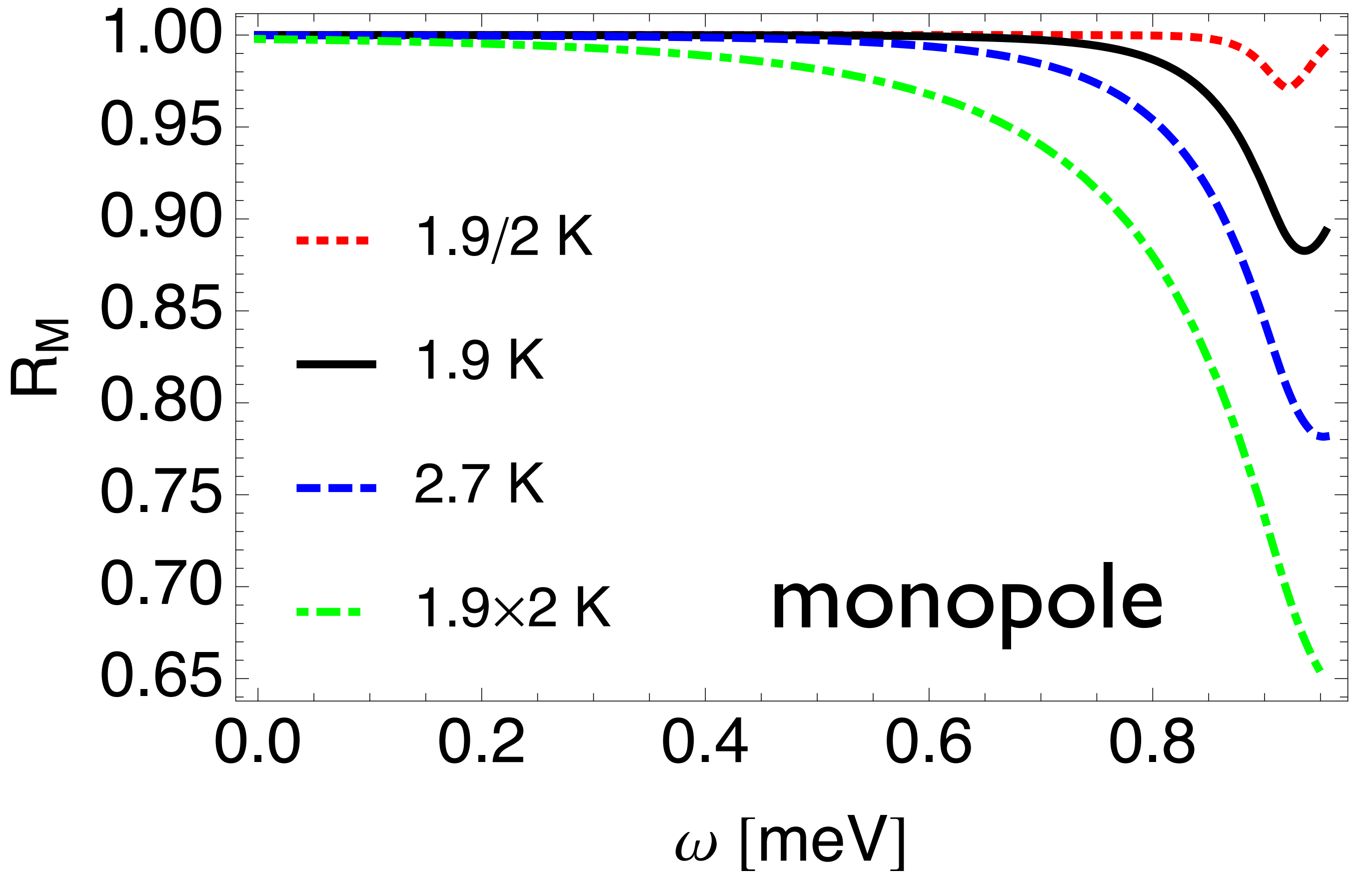
→ spectral distortion

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

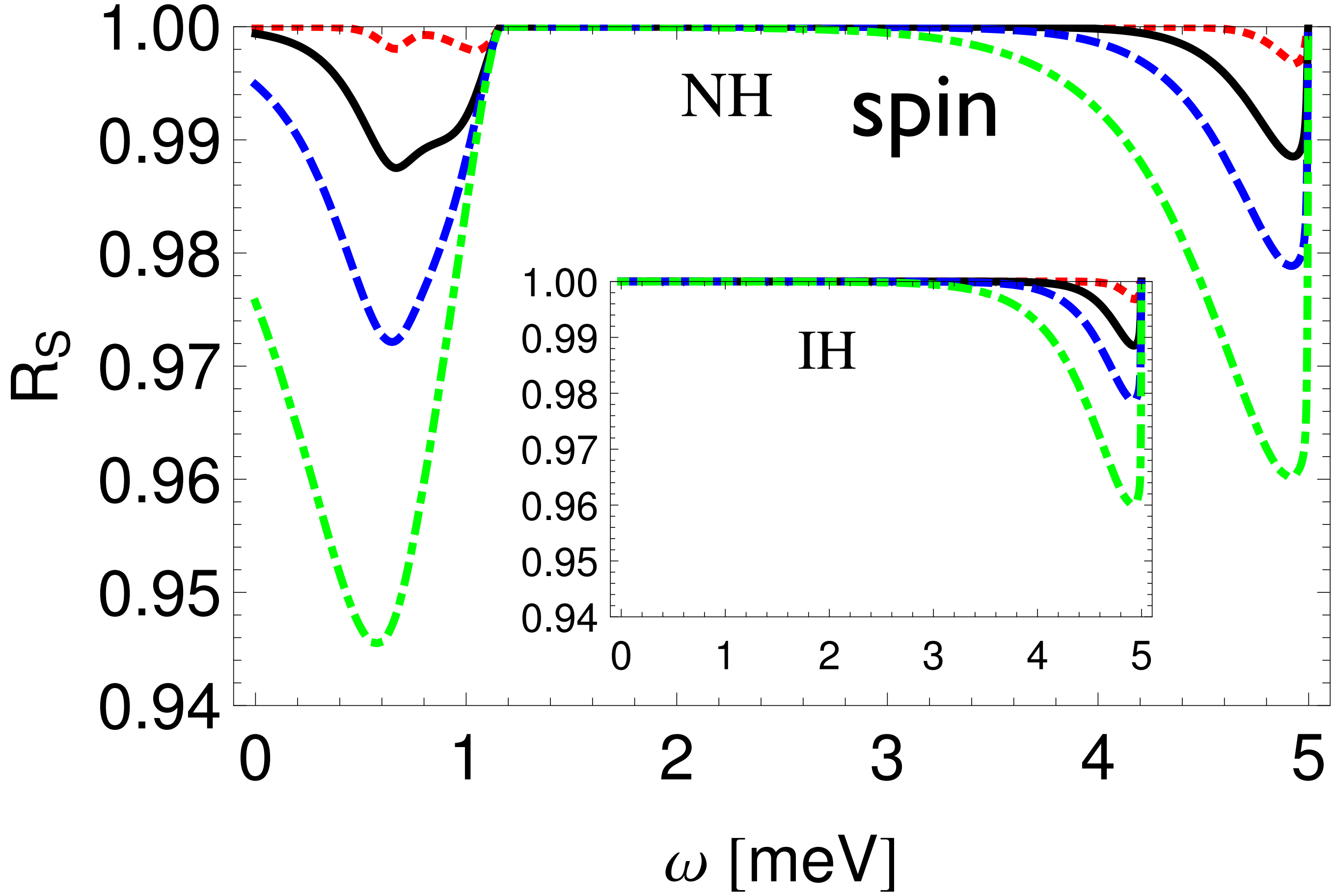
$\epsilon_{eg} = 11 \text{ meV}$

smallest neutrino mass

$m_0 = 5 \text{ meV}$

chemical potential

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

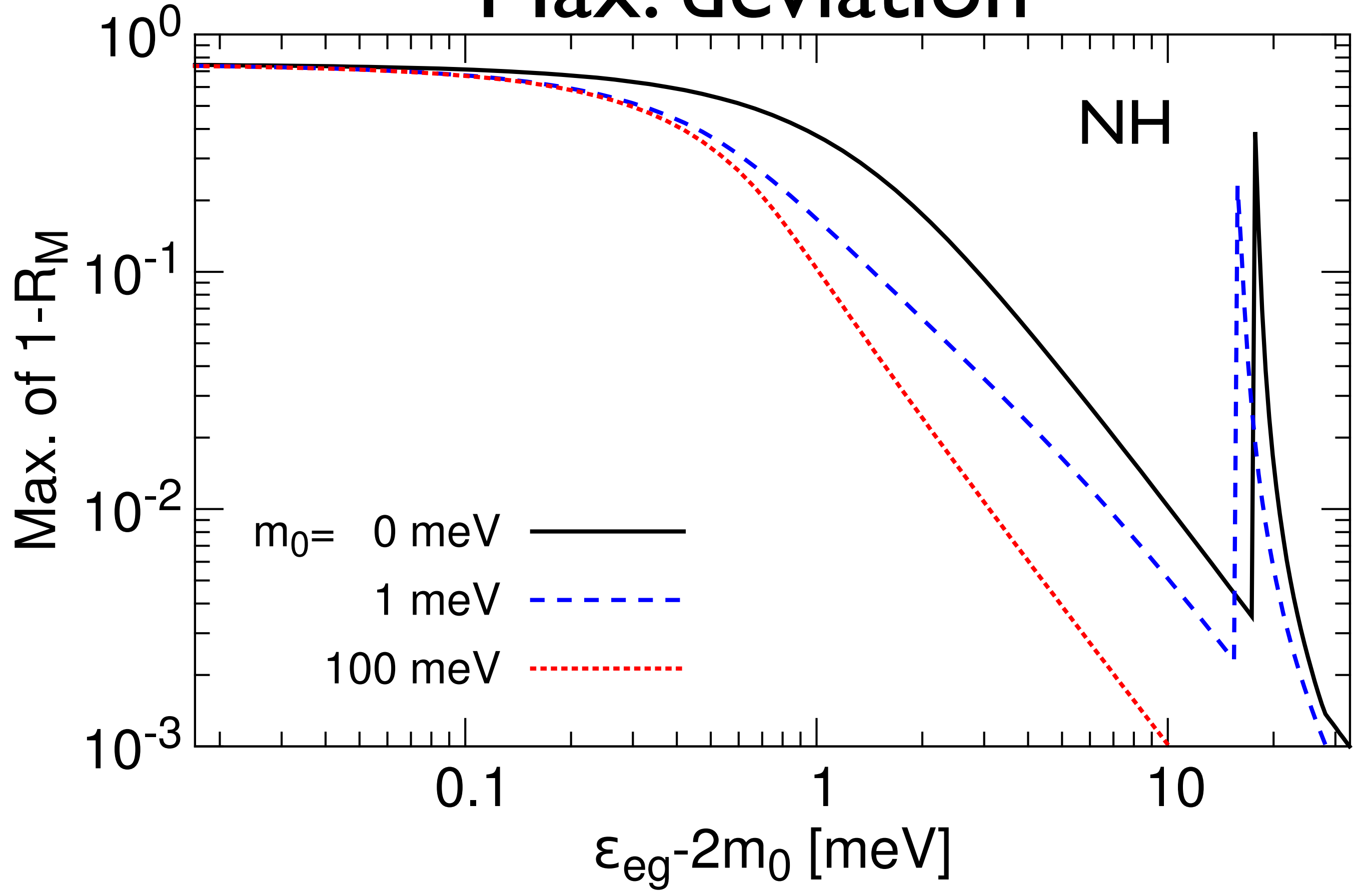


$\epsilon_{eg} = 1 \text{ meV}$

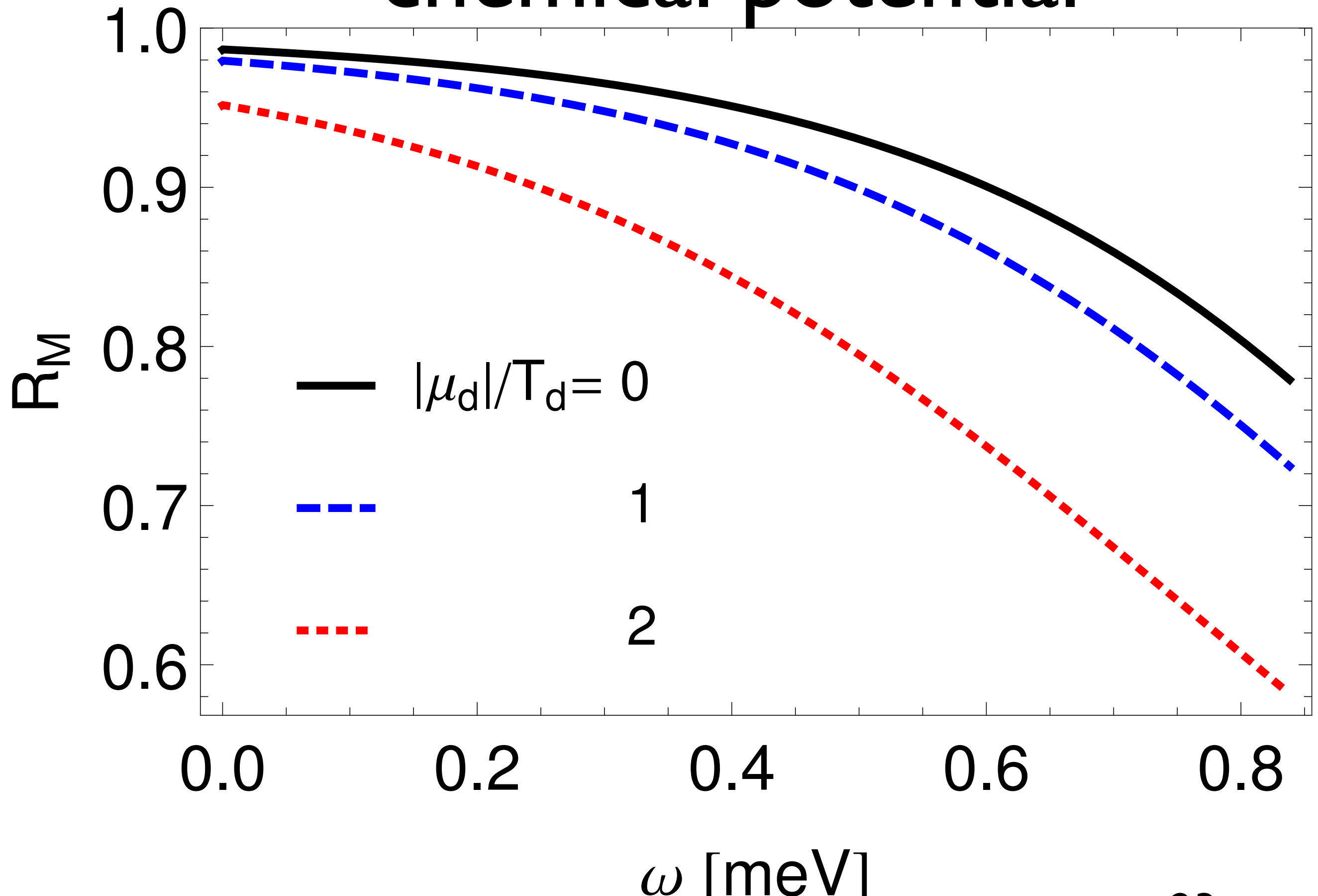
$m_0 = 0.1 \text{ meV}$

$\xi_i = 0$

Max. deviation



chemical potential



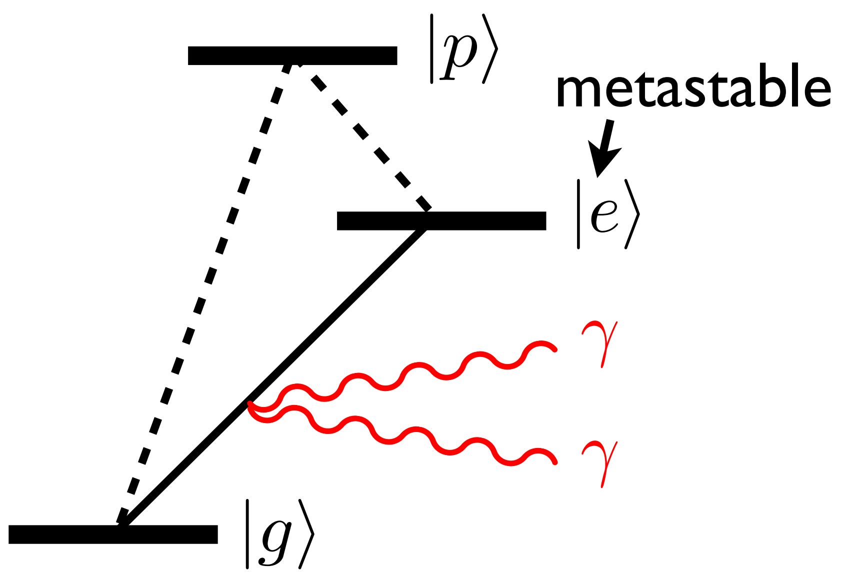
$$\epsilon_{eg} = 10T_\nu \simeq 1.7 \text{ meV}$$

$$m_0 = 0$$

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

$|g\rangle, |e\rangle,$ ~~$|p\rangle$~~

$$\mathcal{H}_I = \begin{pmatrix} \alpha_{ee} & \alpha_{ge} e^{i\varepsilon_{eg} t} \\ * & \alpha_{gg} \end{pmatrix} E^2$$

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

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

R-mover $e^{i\omega(t-x)}$

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

macrocoherence

$|g\rangle$

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

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) $|\rho_{eg}| \leq 1/2$

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

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

Rotating wave approximation (RWA)

omitting fast oscillation terms

Slowly varying envelope approximation (SVEA)

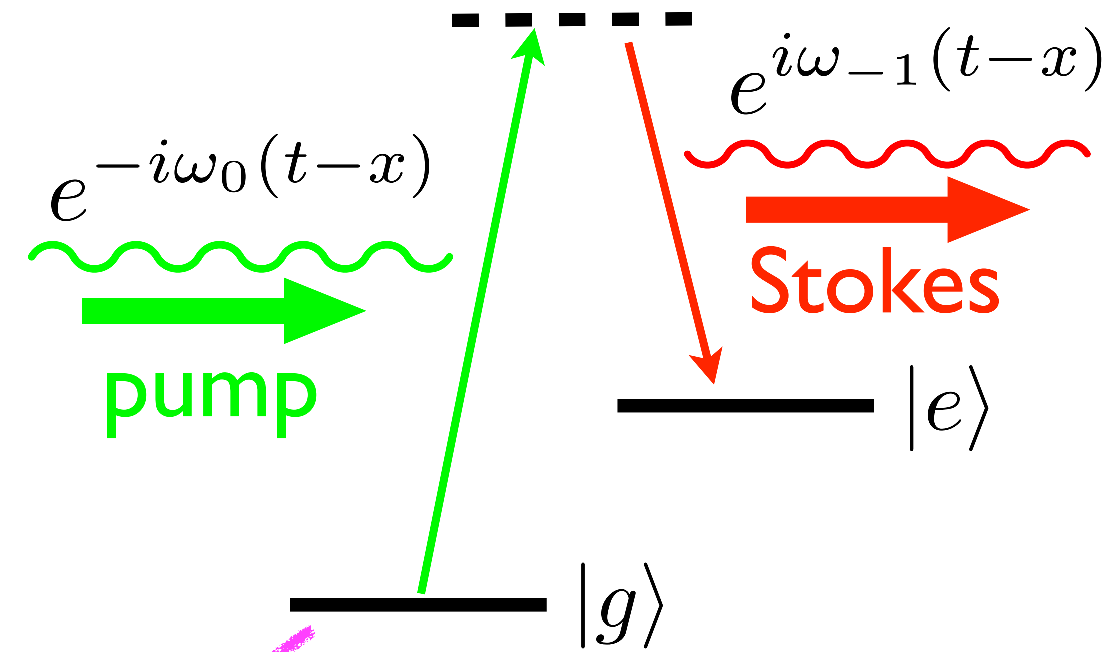
$$|\partial_{x,t} E_{R,L}| \ll \omega |E_{R,L}|, \ |\partial_{x,t} R_i^{(0,\pm)}| \ll \omega |R_i^{(0,\pm)}|$$

PSR with spatial gratings

How to populate $|e\rangle$

Raman scattering

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



Generated coherence

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

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

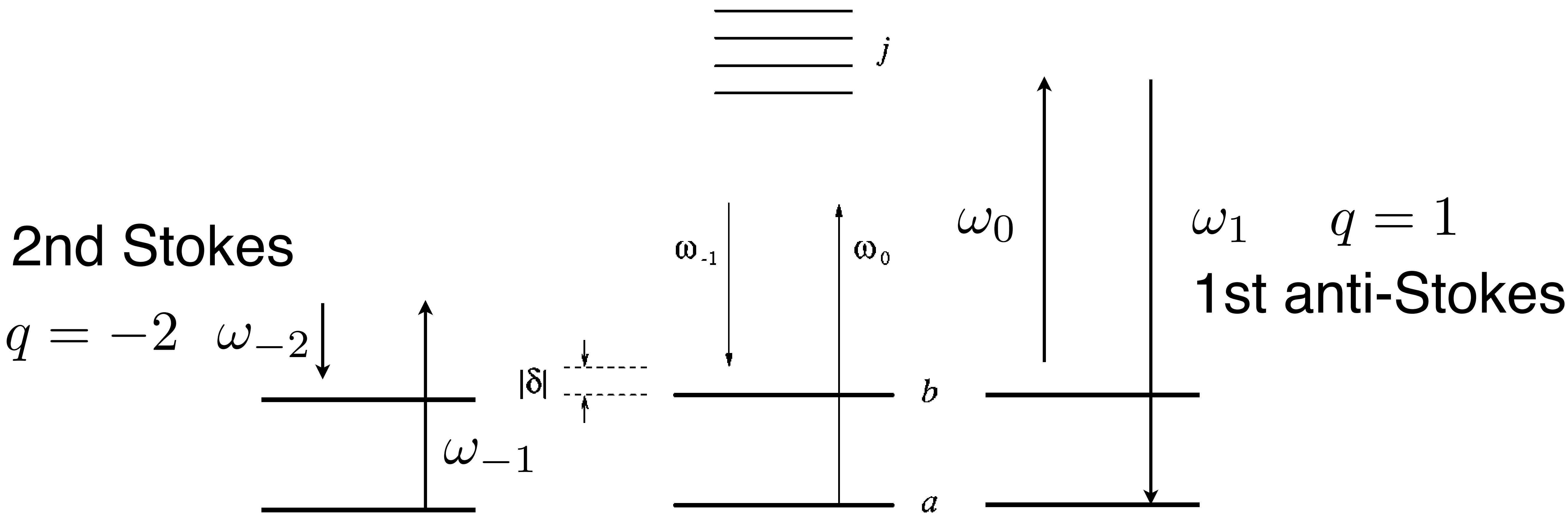
$$\omega_p + \omega_{\bar{p}} = \epsilon_{eg}$$

momentum conservation in the macrocoherence → 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

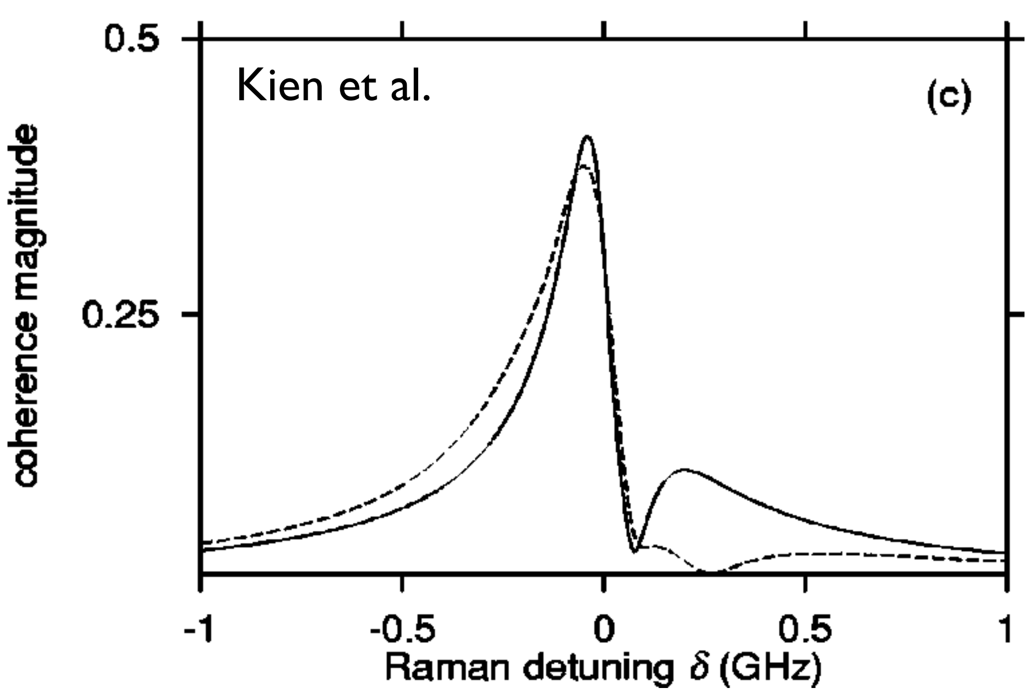
$$(\partial_t + \partial_z)E_q = in\hbar\omega_q \left(a_q \rho_{aa} E_q + b_q \rho_{bb} E_q + d_{q-1} \rho_{ba} E_{q-1} + d_q^* \rho_{ab} E_{q+1}\right)$$

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

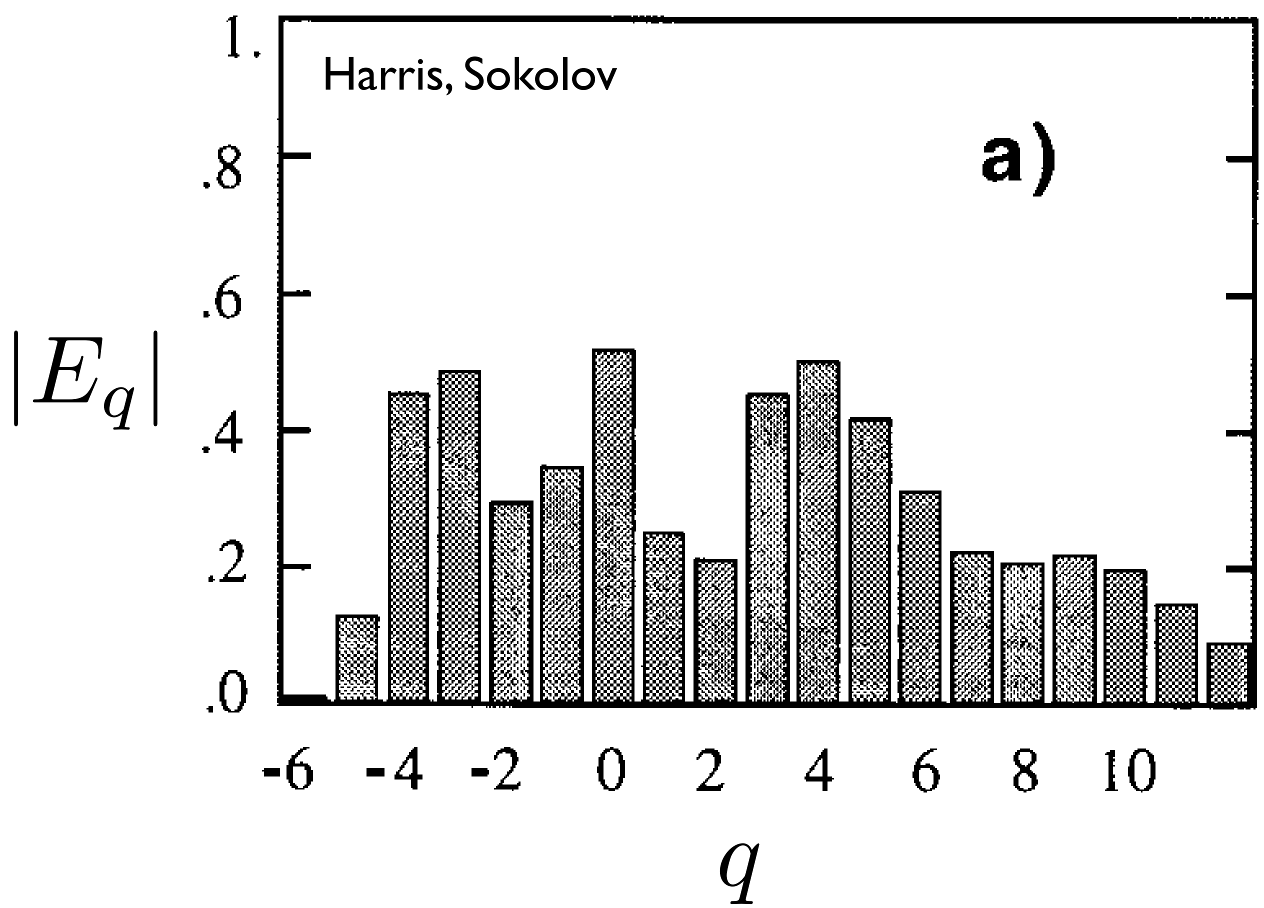
$\delta > 0\,,\ \sin\theta > 0$

phased state

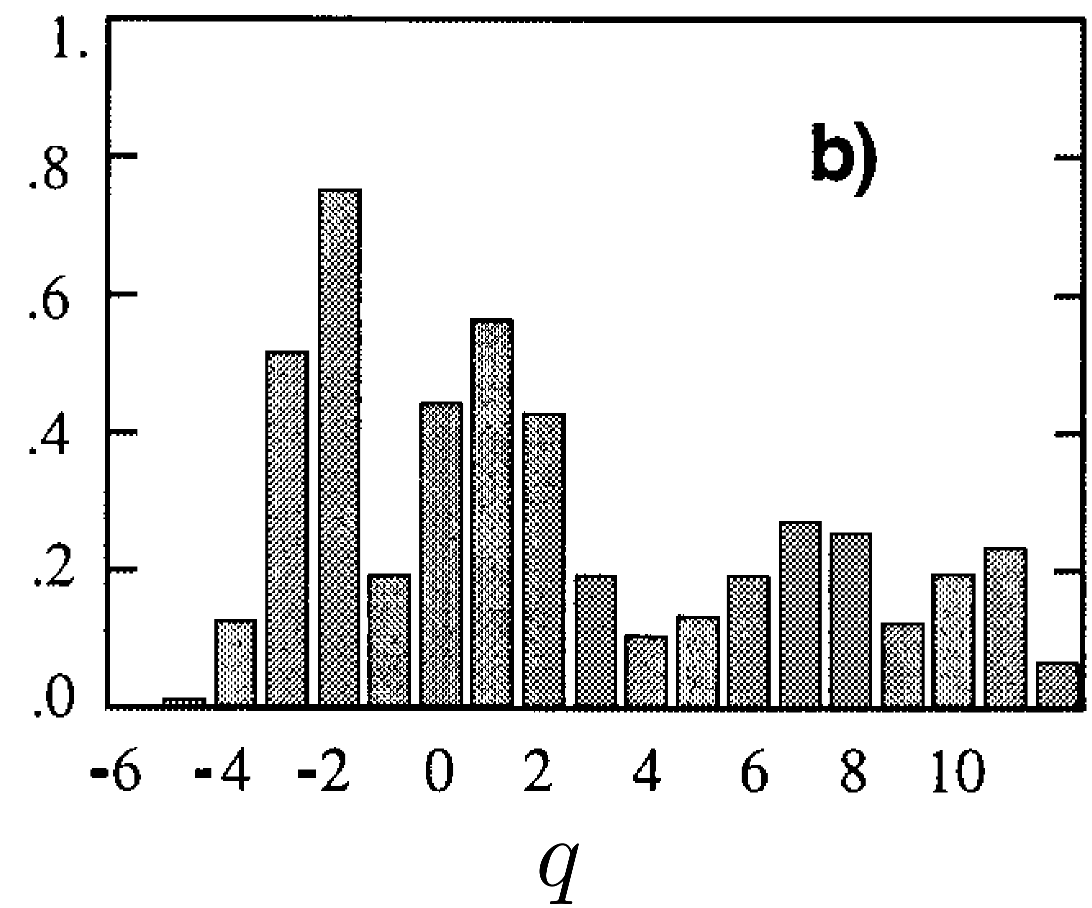
$\delta < 0\,,\ \sin\theta < 0$

antiphased state

antiphased

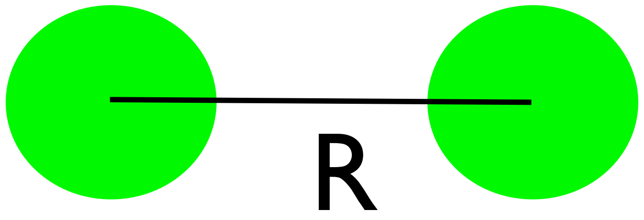


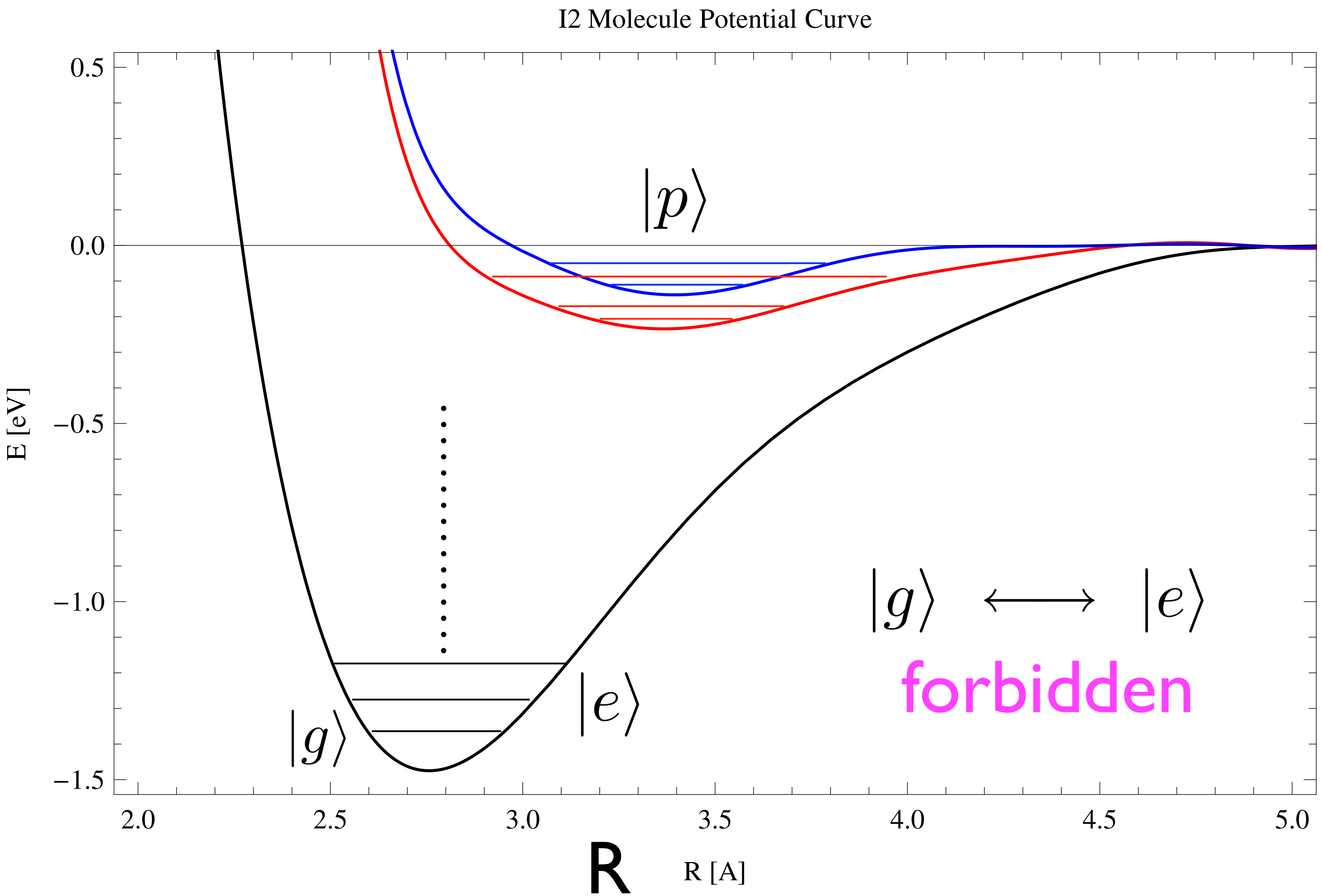
phased



Homonuclear diatomic molecule

Potential curves





Para-hydrogen gas PSR experiment

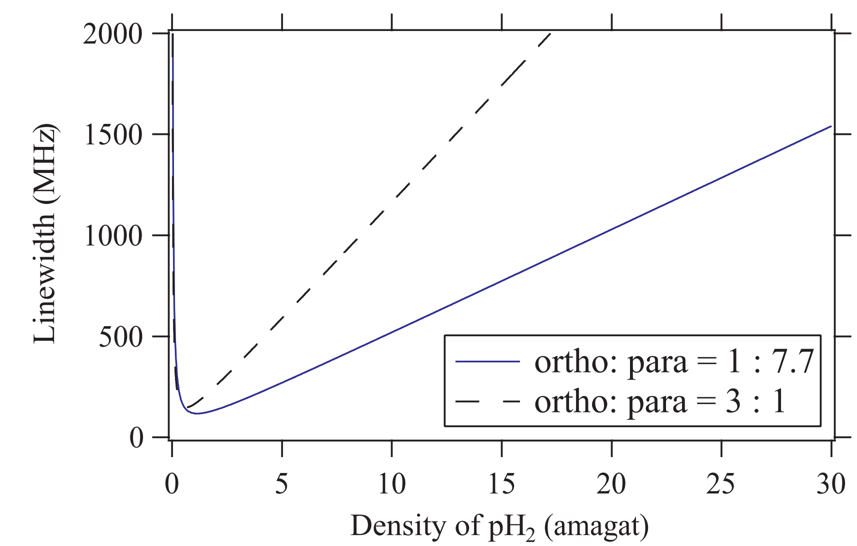
@ Okayama U

Y. Miyamoto et al., arXiv:1406.2198, to be published in PTEP

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

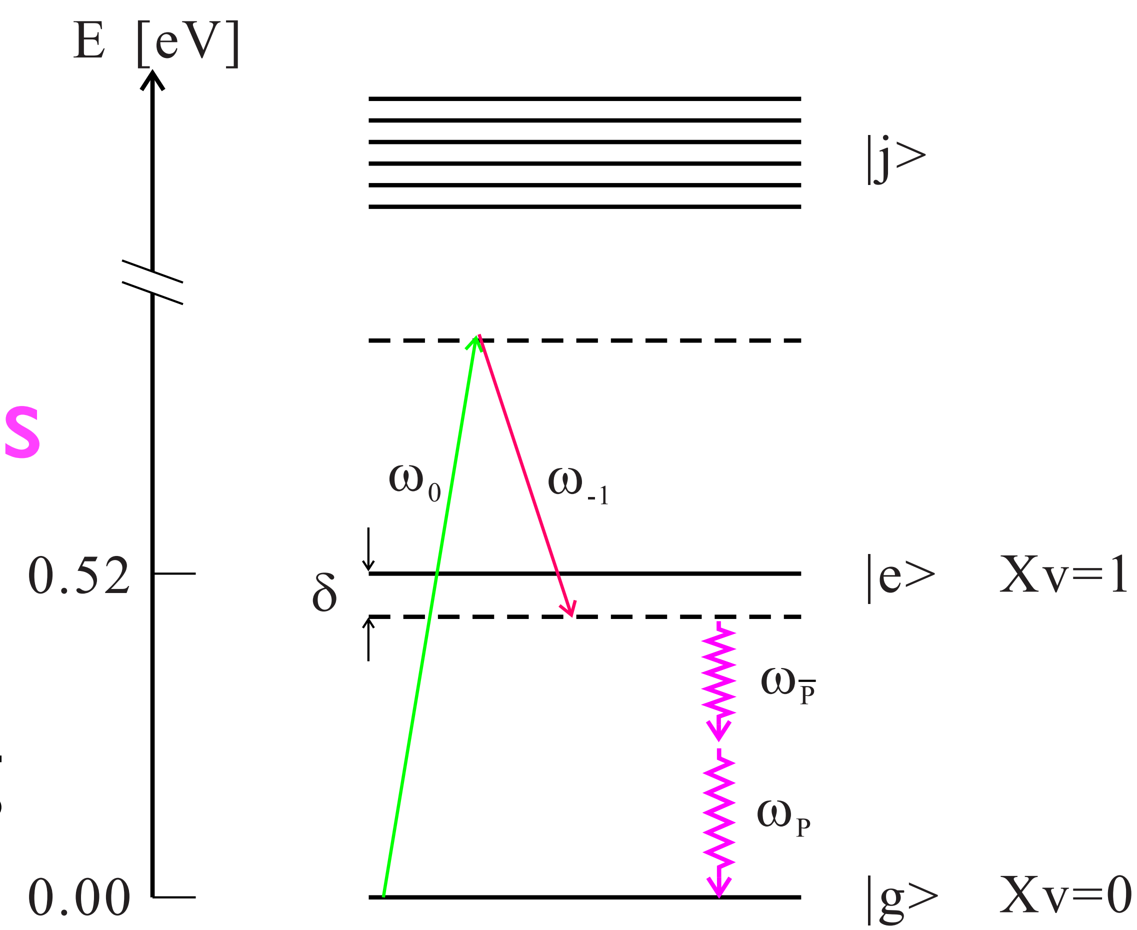
$$1/T_2 \sim 130 \text{ MHz}$$

coherence production

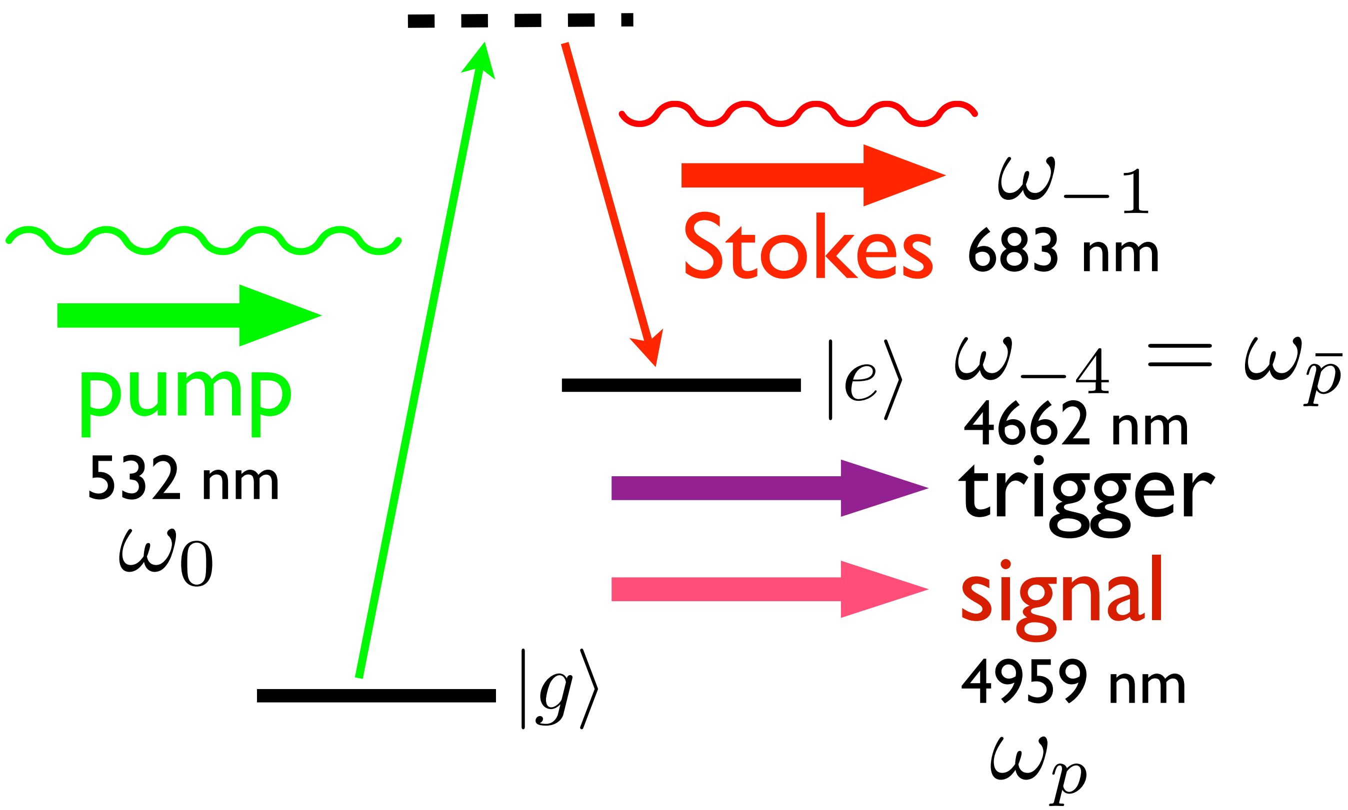
adiabatic Raman process

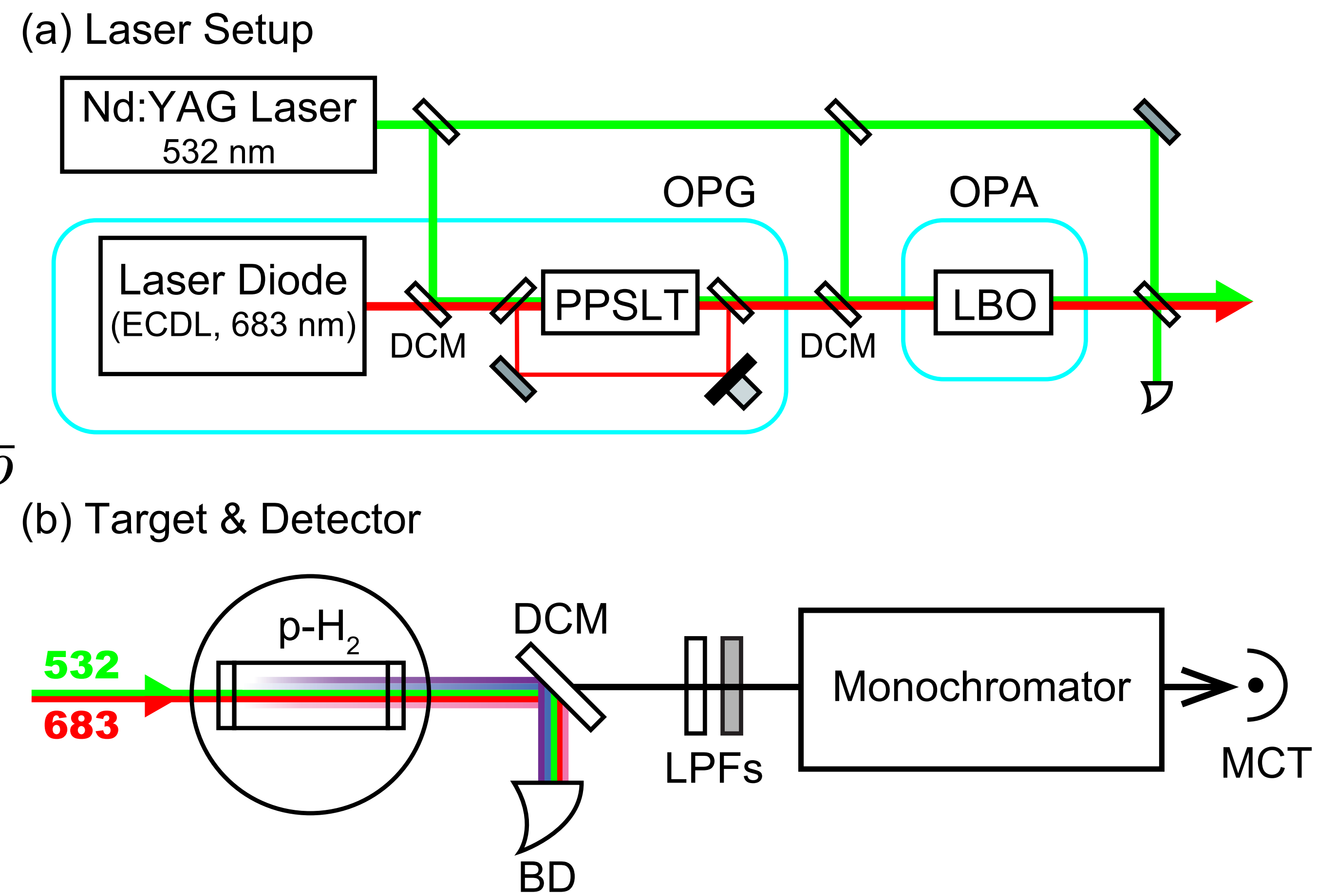
$$\Delta\omega = \omega_0 - \omega_{-1}$$
$$= \epsilon_{eg} - \delta$$
$$= \omega_p + \omega_{\bar{p}}$$

detuning



Experimental setup





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

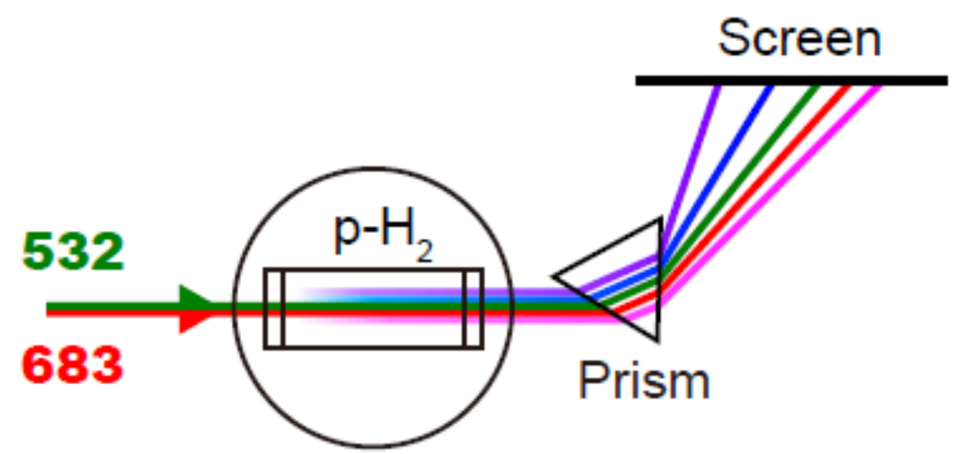
Target cell: length 15cm, diameter 2cm, 78K, 60kPa

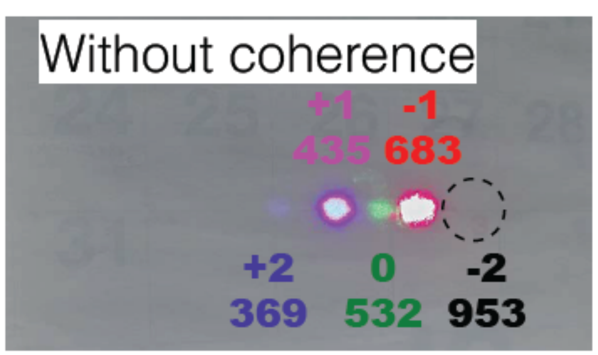
$n = 5.6 \times 10^{19}\ \mathrm{cm}^{-3} \qquad 1/T_2 \sim 130\ \mathrm{MHz}$

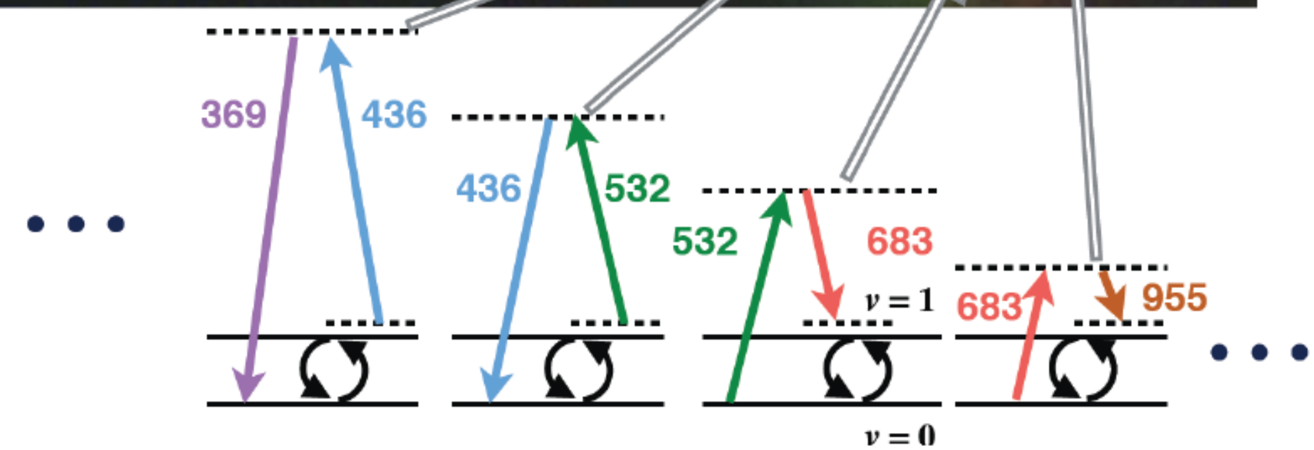
Driving lasers: $5\ \mathrm{mJ},\ 6\ \mathrm{ns},\ w_0 = 100\ \mu\mathrm{m}\ (5\ \mathrm{GW/cm^2})$

Ultra-broadband Raman sidebands

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







N. Sasao

Generated coherence

Maxwell-Bloch eq.

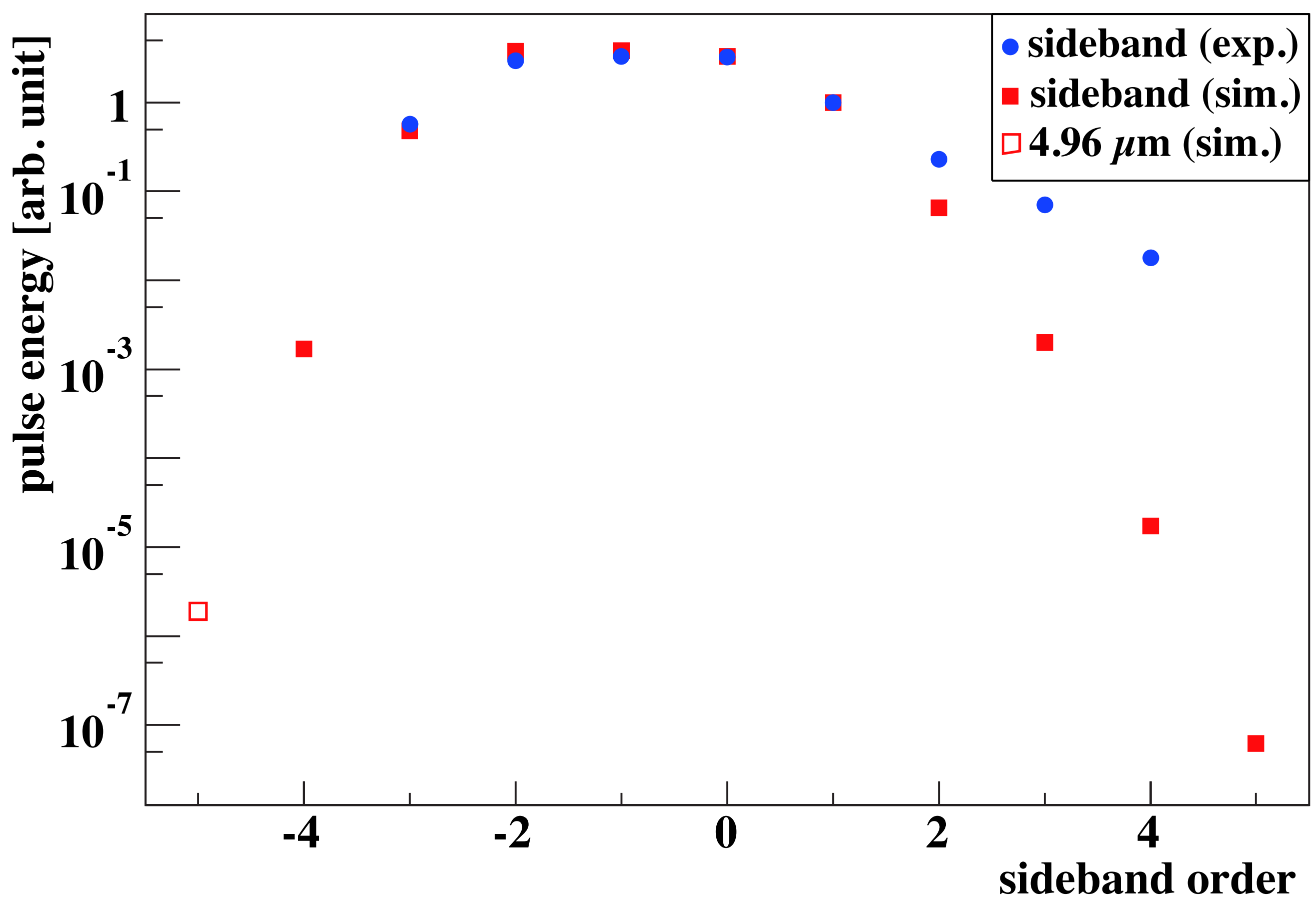
$$\frac{\partial \rho_{gg}}{\partial \tau} = i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{ee},$$

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

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

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

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

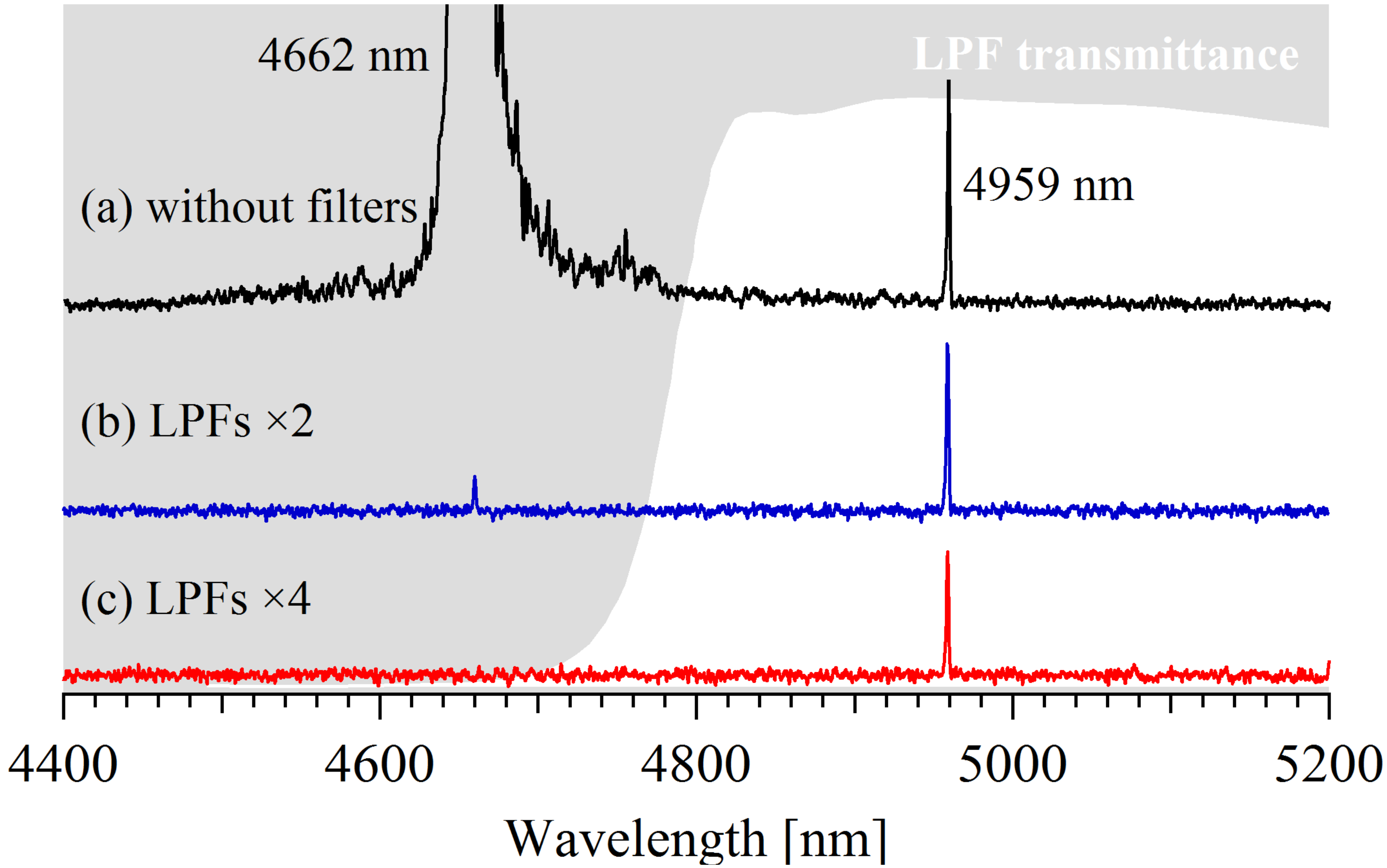


coherence estimation

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

(6% of max.)

Observed two-photon spectrum



of observed photons

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

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

- ✶ RENP spectra are sensitive to the cosmic neutrino background.

  temperature, chemical potential.

- ✶ Macrocoherent rate amplification is essential.

  demonstrated by a QED process, PSR.

A new approach to neutrino physics