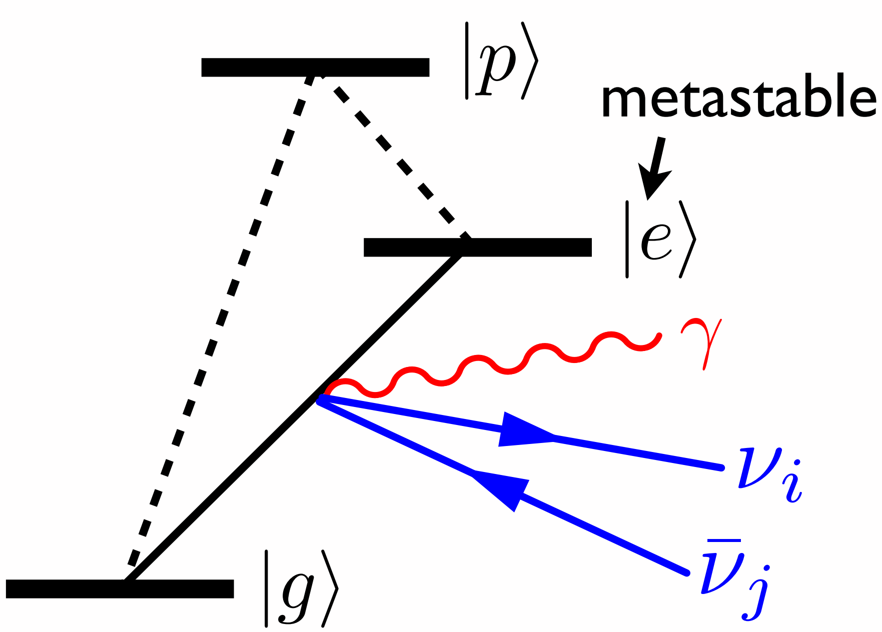
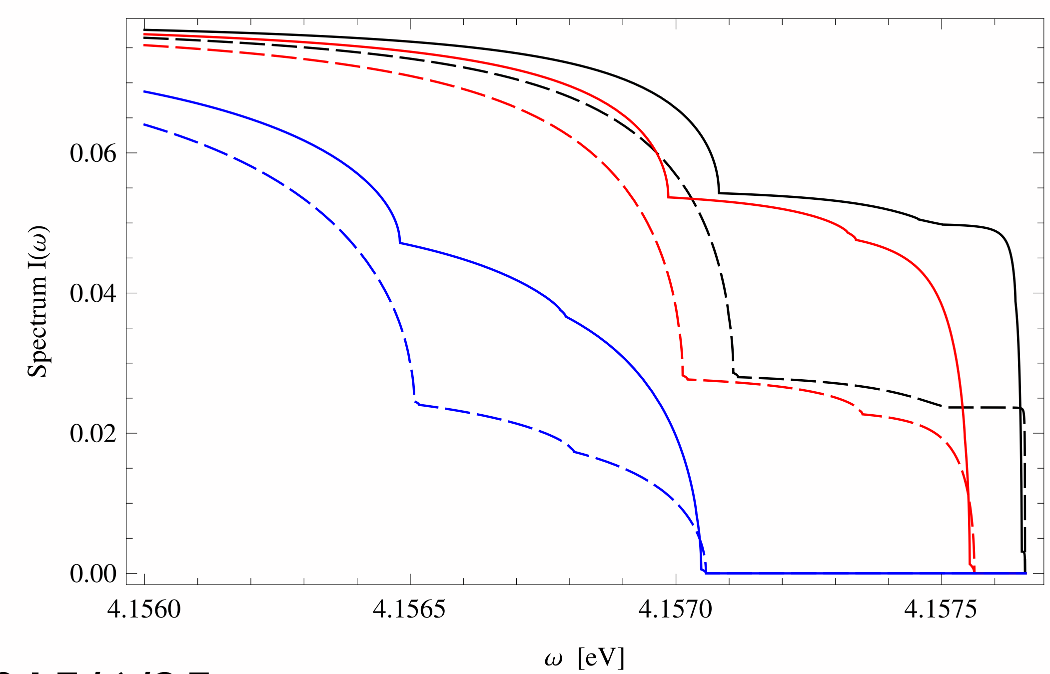
Physics
OSAKA UNIVERSITY

原子・分子過程による
ニュートリノ物理

田中　実

大阪大学





セミナー@新潟大学, 2015/6/25

SPAN project

SPectroscopy with Atomic Neutrino

Okayama U.

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

Other institute

M. T. (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:

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

NuFIT (2014)

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

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

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

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

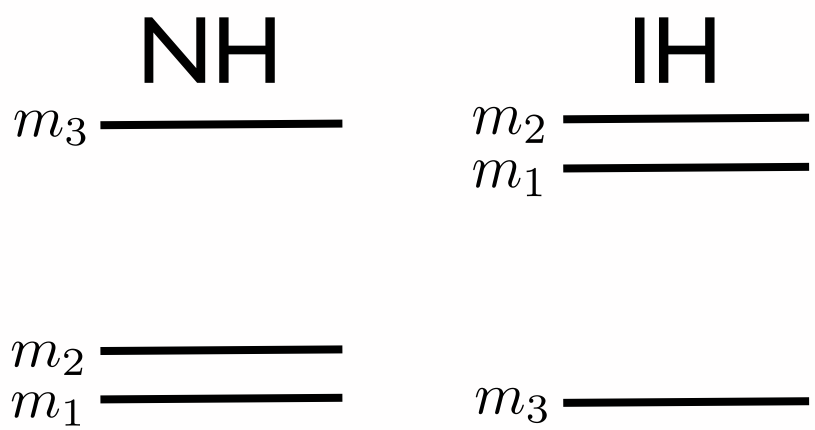
$$m_{1(3)} < 71(66)\ \text{meV},\ 50\ \text{meV} < m_{3(2)} < 87(82)\ \text{meV}$$

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

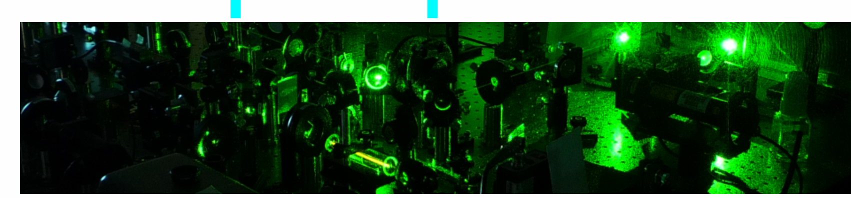
Dirac or Majorana, effective mass $\left|\sum_i m_i U_{ei}^2\right|^2$

Beta decay endpoint: KATRIN

absolute mass

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

Atomic/molecular processes

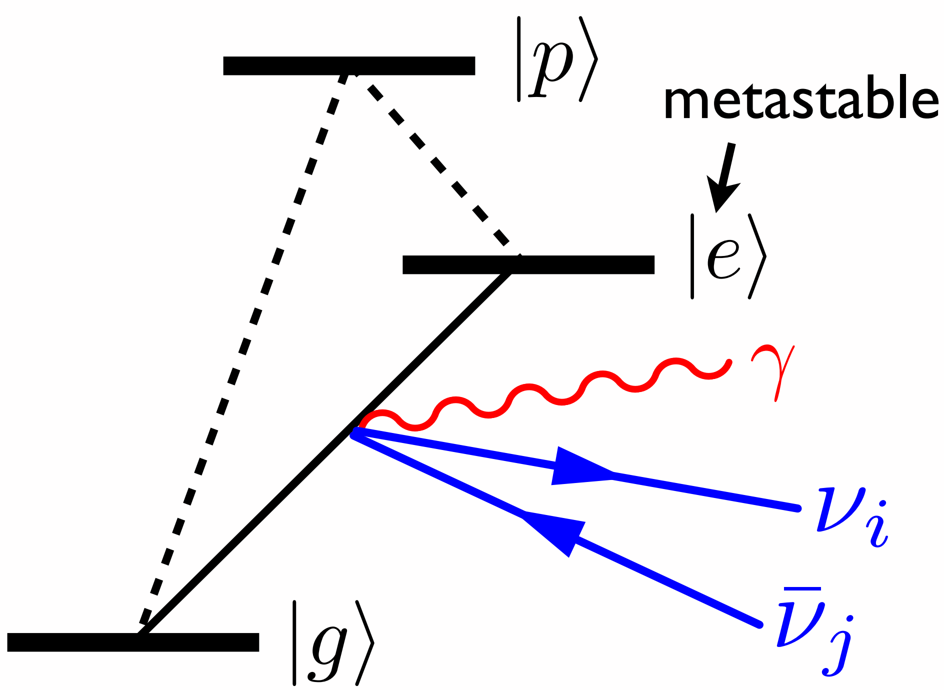


absolute mass, NH or IH, D or M, $\delta, \ \alpha, \ \beta$

RENP

Radiative Emission of Neutrino Pair (RENP)

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



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

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

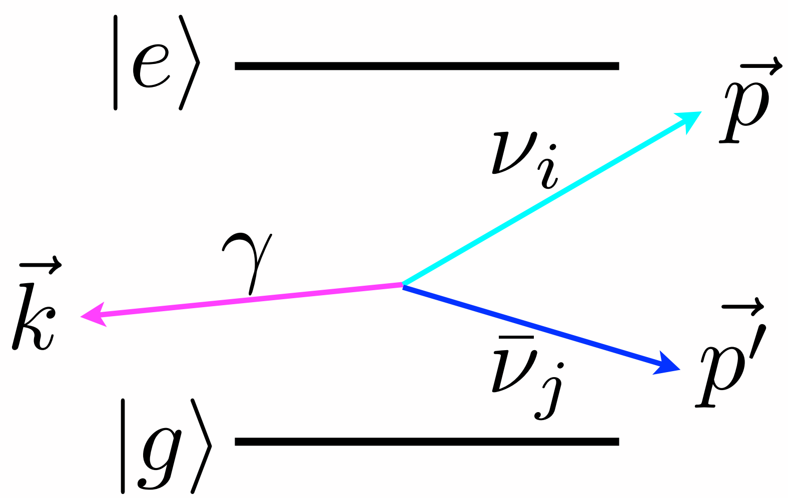
cf. nuclear processes ~ MeV

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)

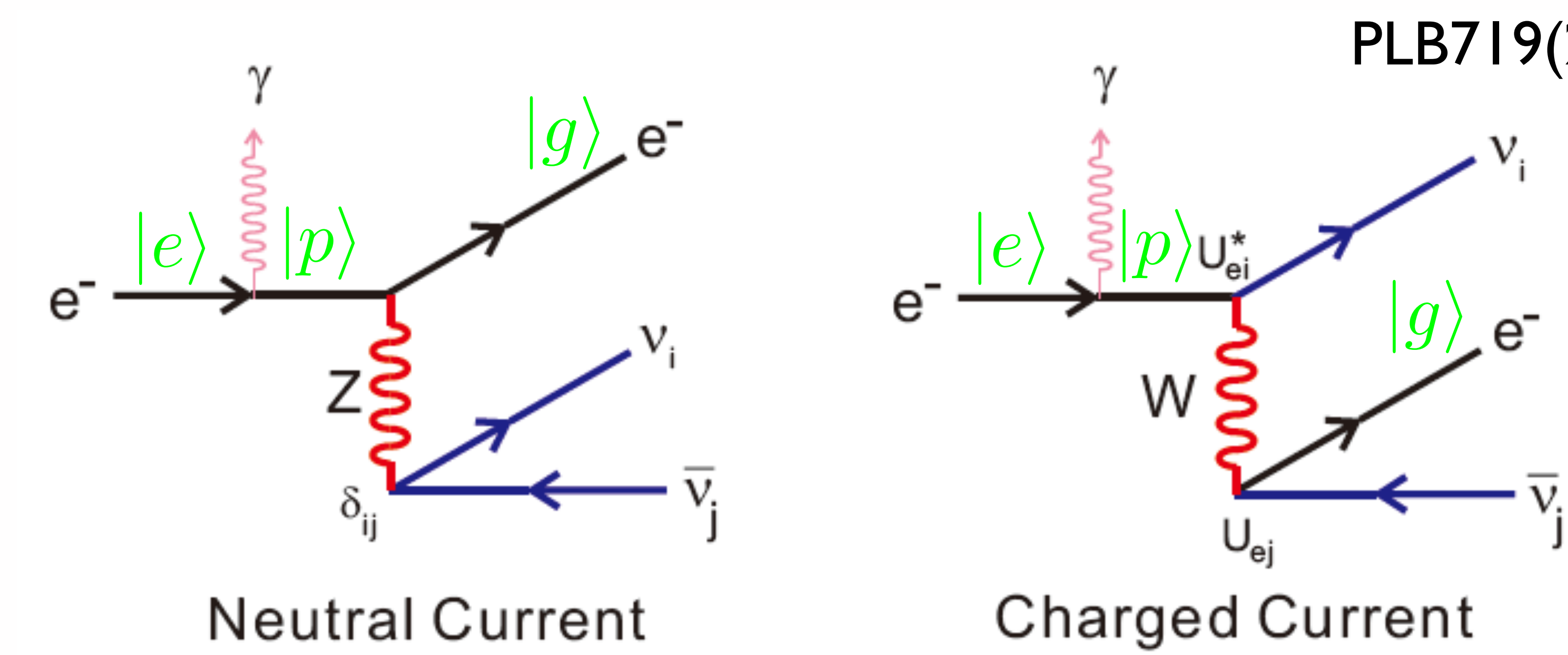
$$\text{total amp.} \propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p}')$$

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

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



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

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

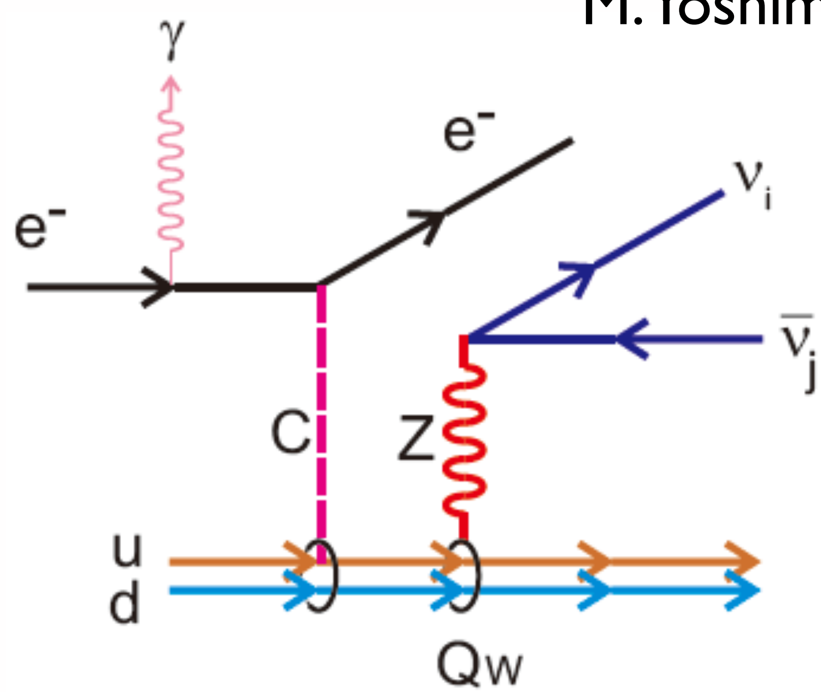
Atomic matrix element in the NR approximation

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

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

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

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

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

Spectral function (spin current)

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

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

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

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

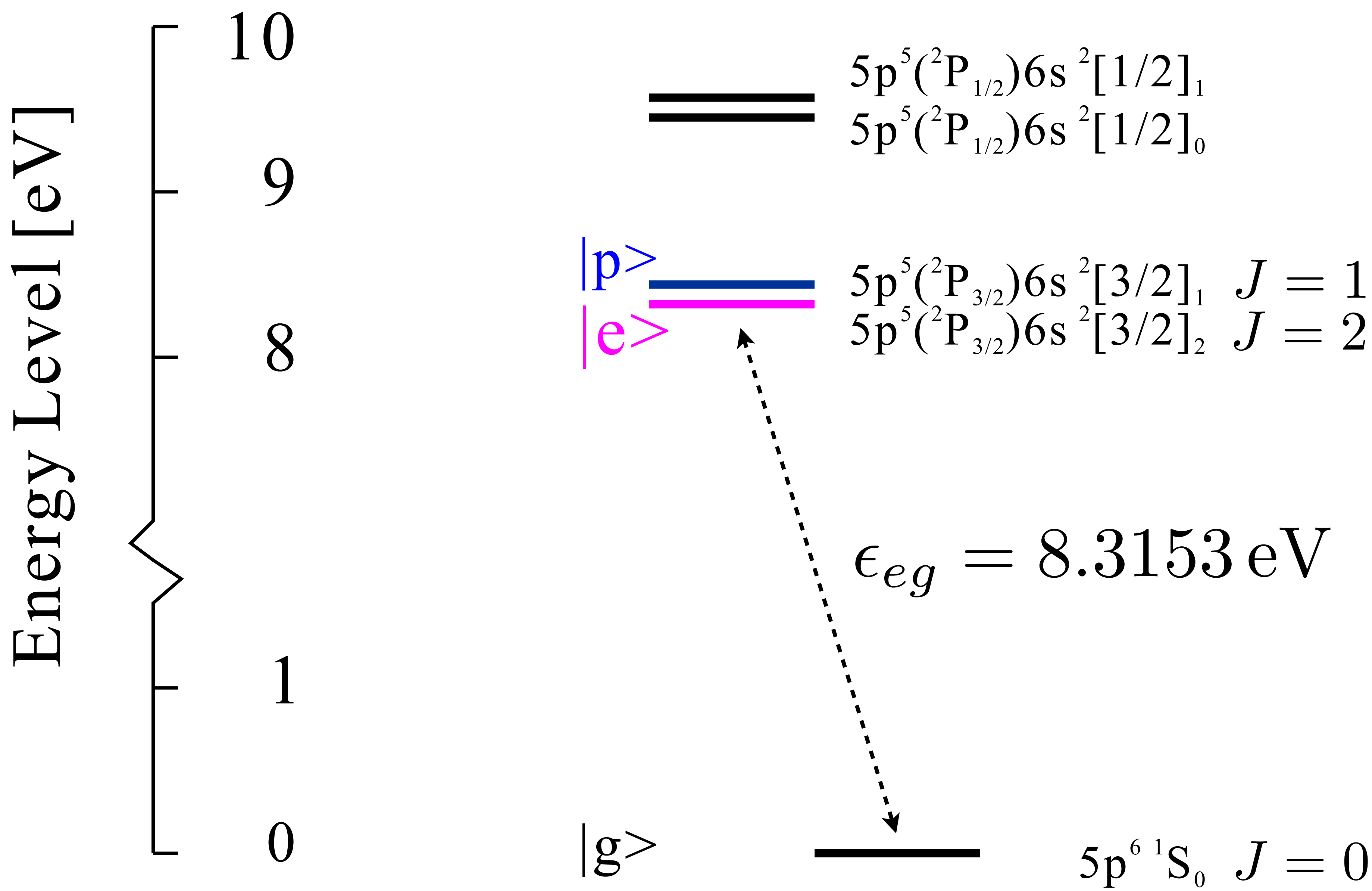
$\delta_M = 0(1)$ for Dirac(Majorana)

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

Dynamical factor

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

Xe (gas target)

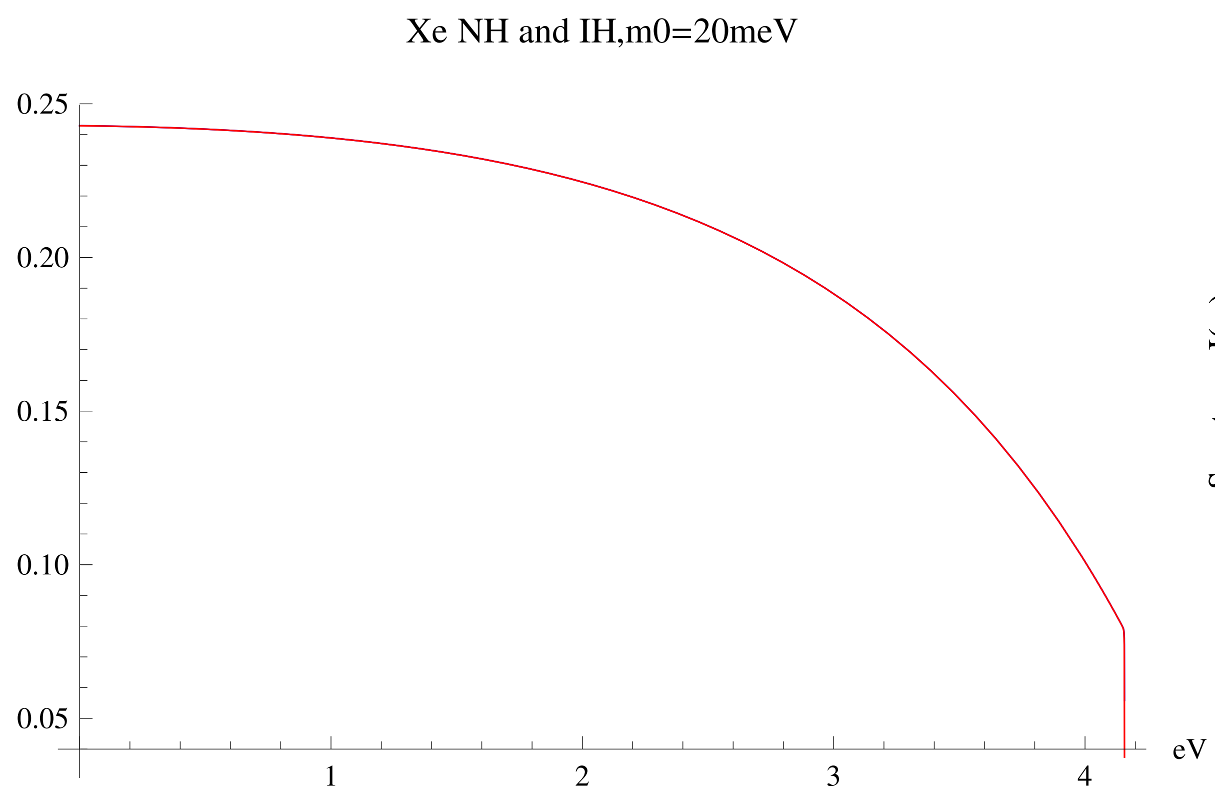


$|e\rangle \leftrightarrow |p\rangle$ M1

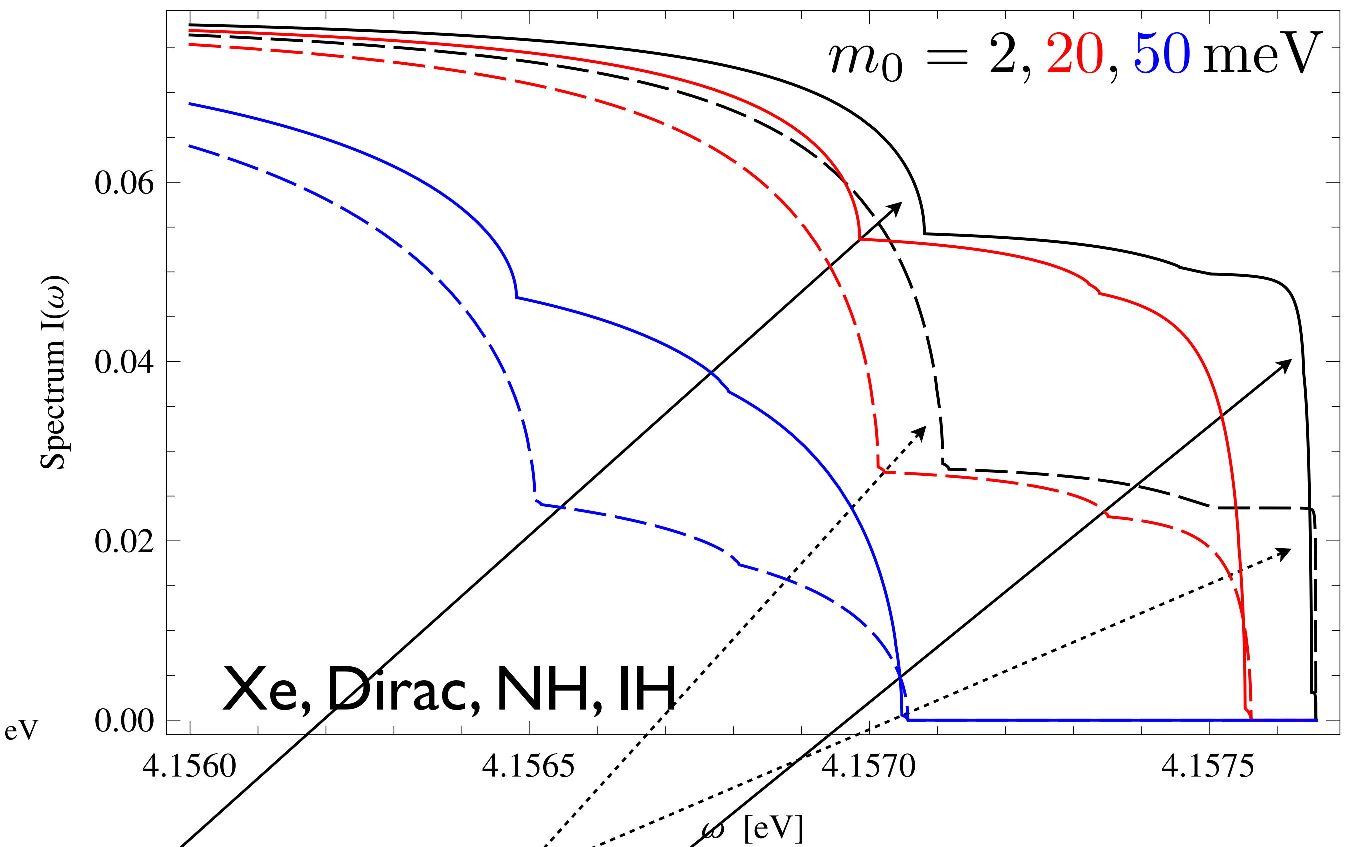
$|p\rangle \leftrightarrow |g\rangle$ E1

Photon spectrum (spin current)

Global shape



Threshold region



The threshold weight factors

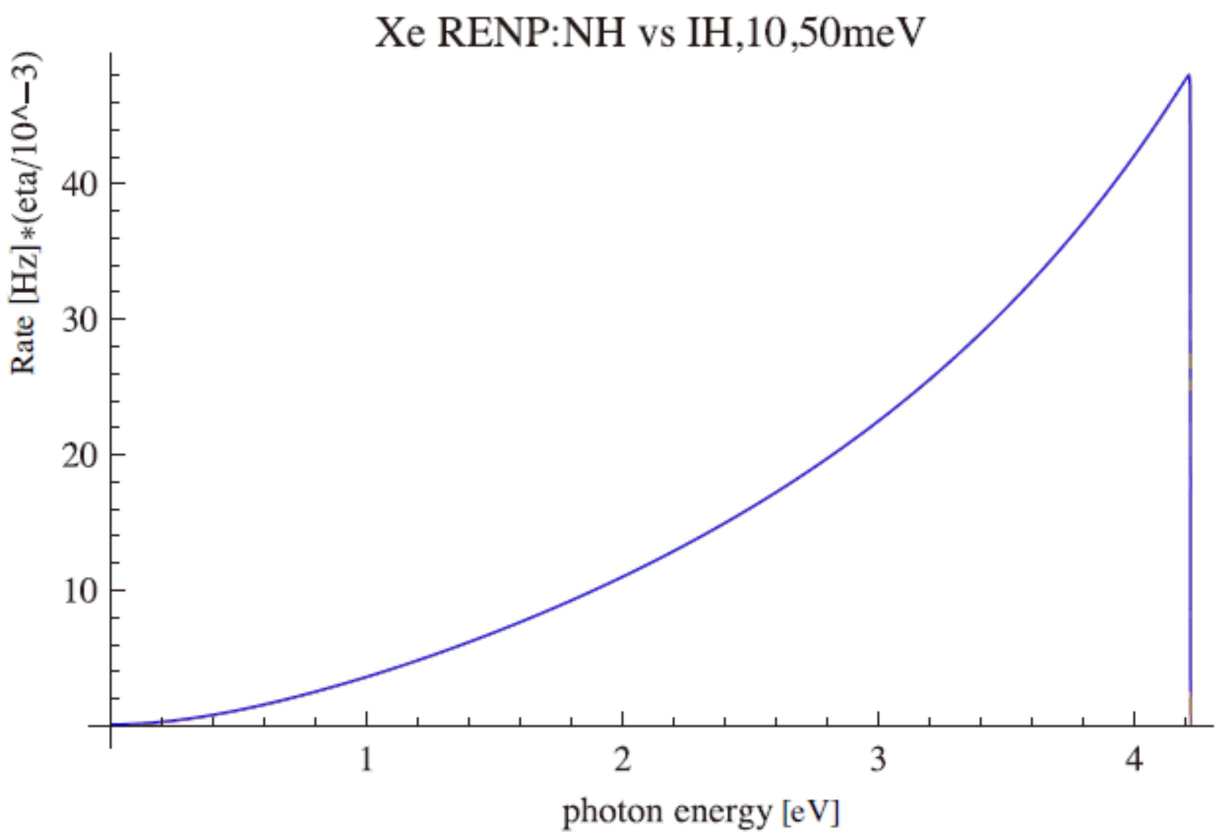
B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{13}^2 - 1/2)^2$	$2c_{12}^2 s_{12}^2 c_{13}^4$	$2s_{12}^2 c_{13}^2 s_{13}^2$	$2c_{12}^2 c_{13}^2 s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

Photon spectrum (nuclear monopole)

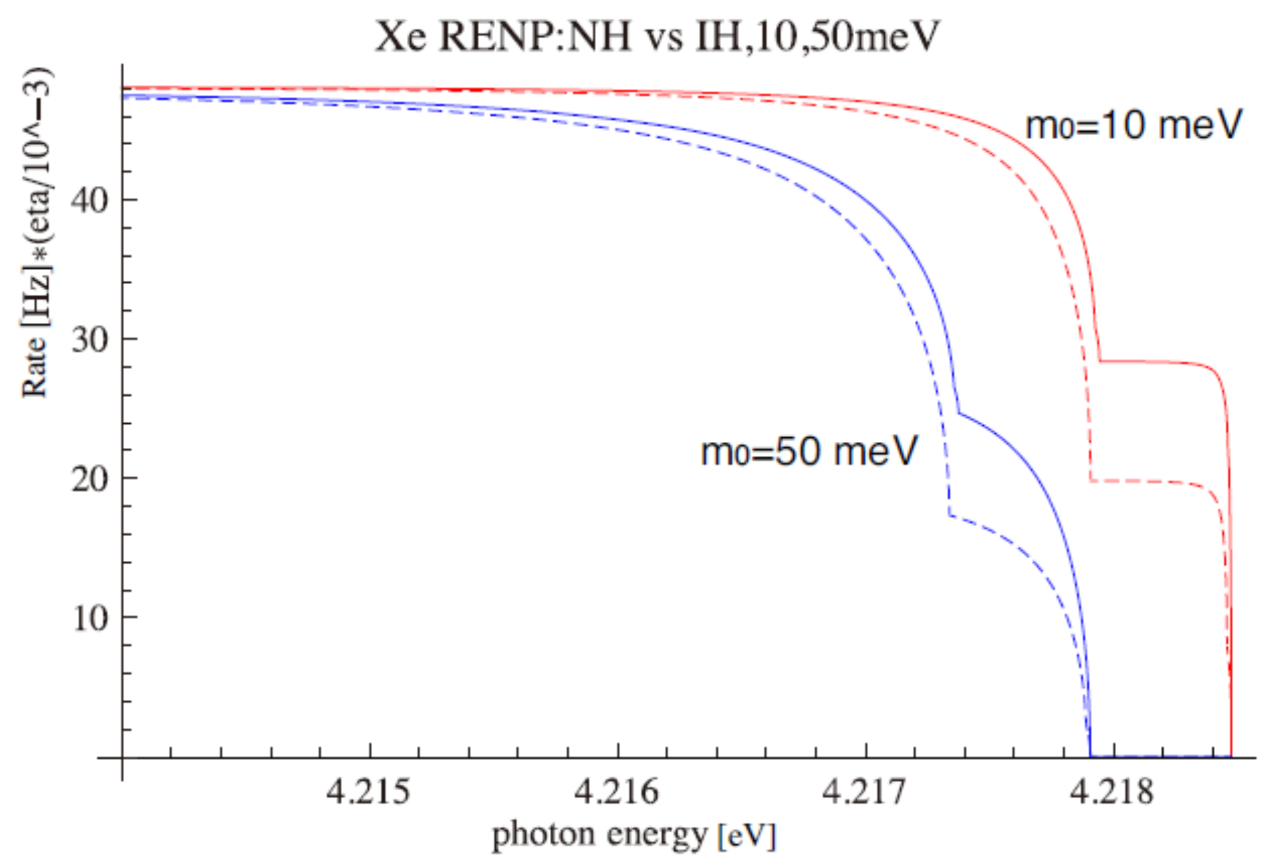
Xe $^3\mathrm{P}_1$ 8.4365 eV

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

Global shape



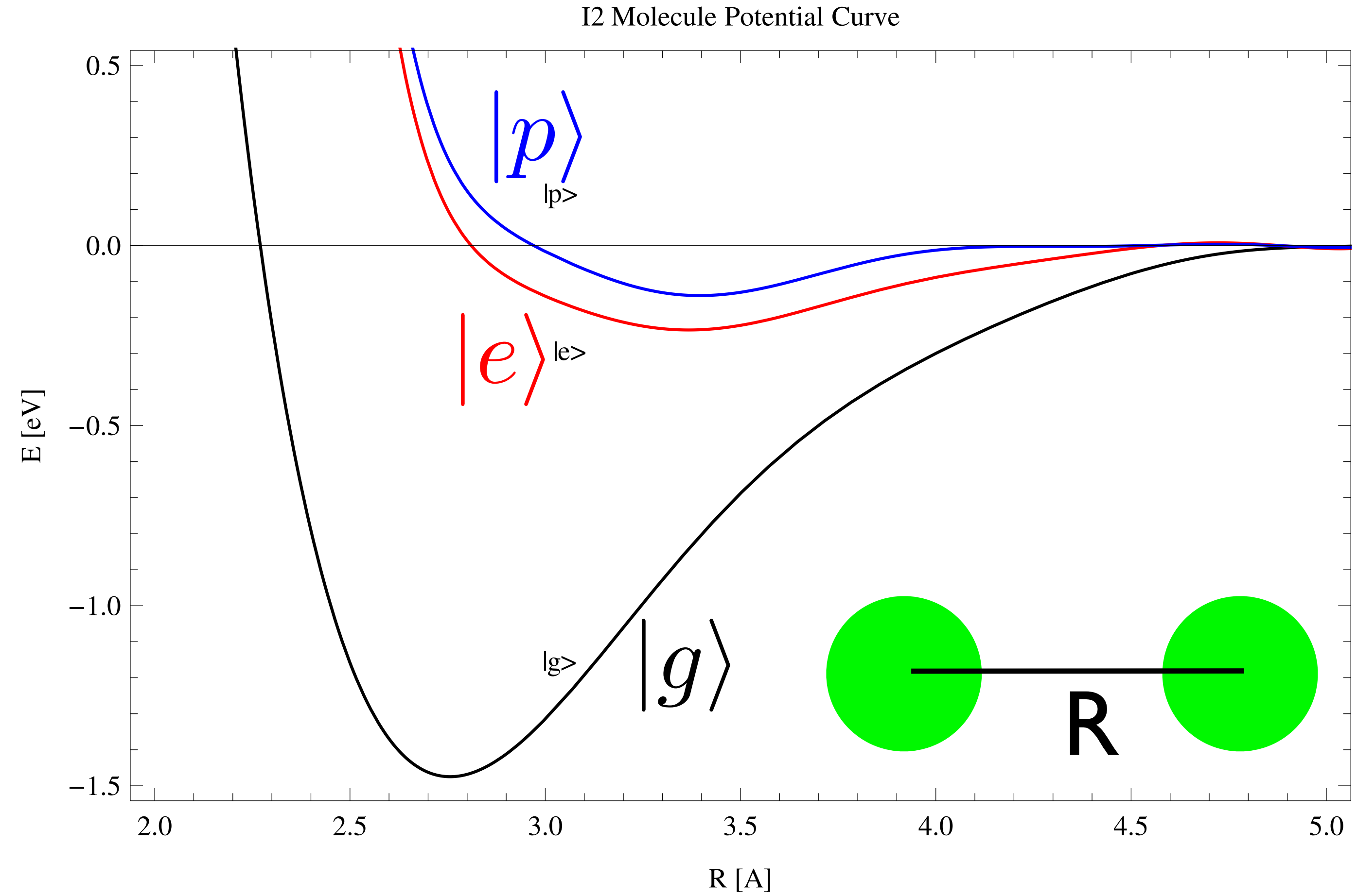
Threshold region

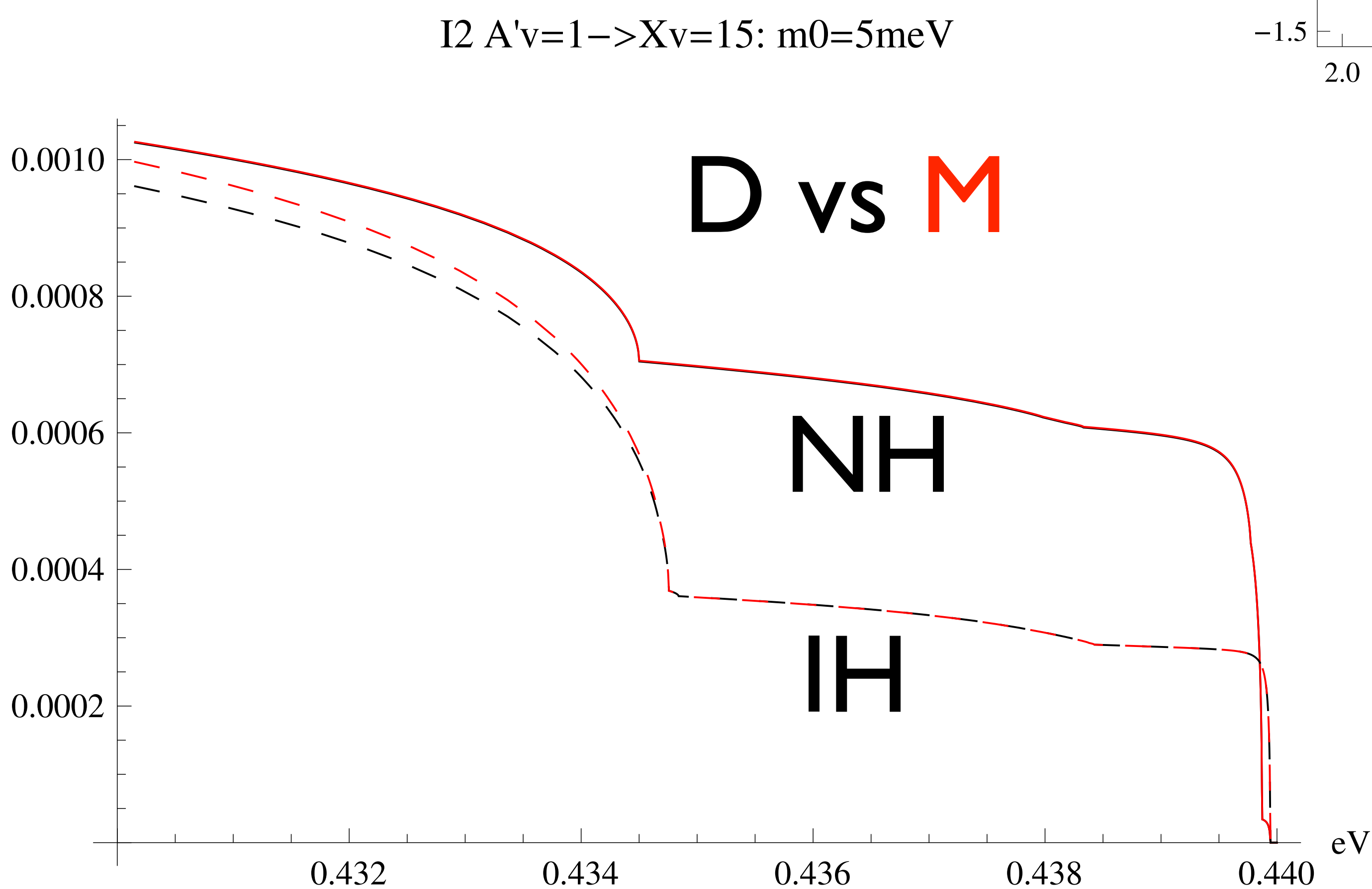


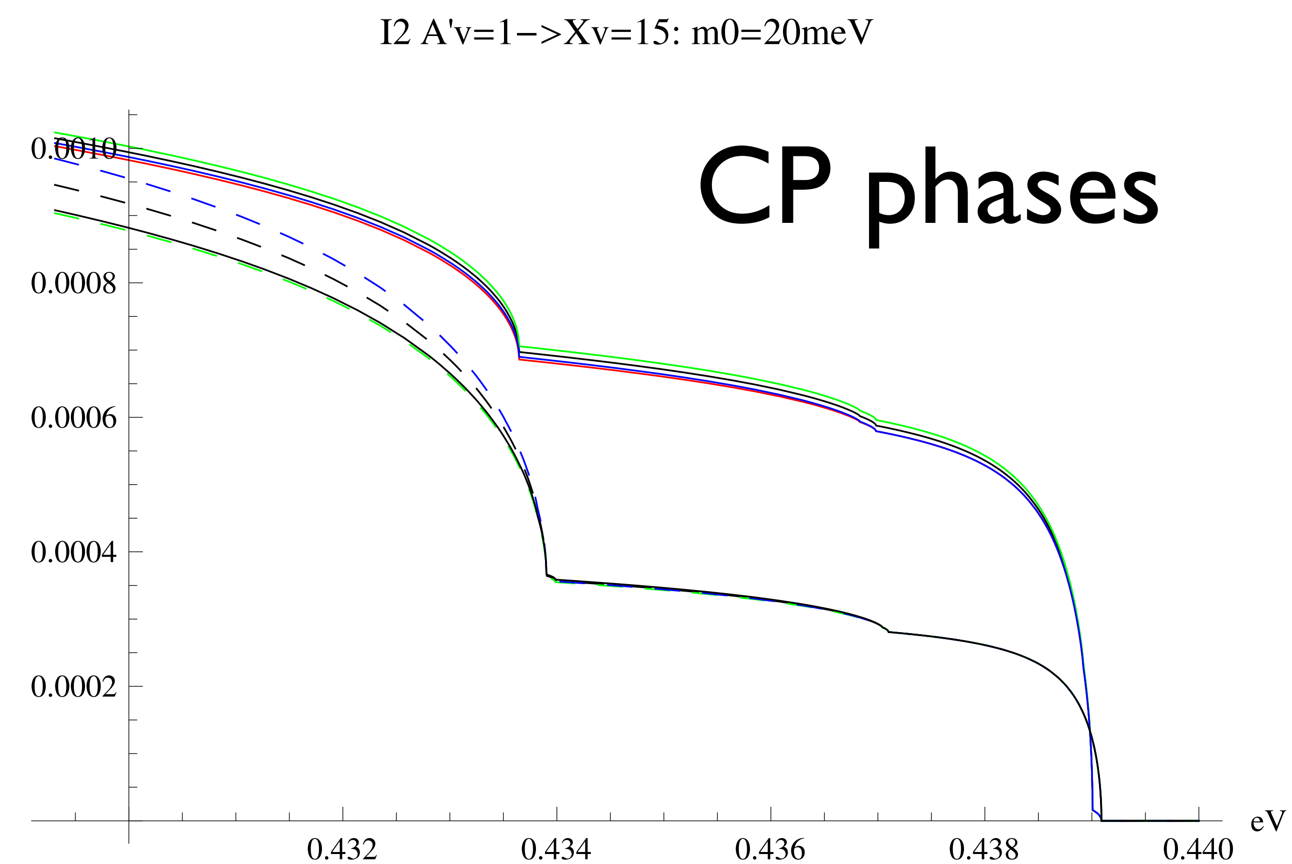
I2 molecule

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. $|\boldsymbol{p}| = \sqrt{E^2 - m_\nu^2}$

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

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

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

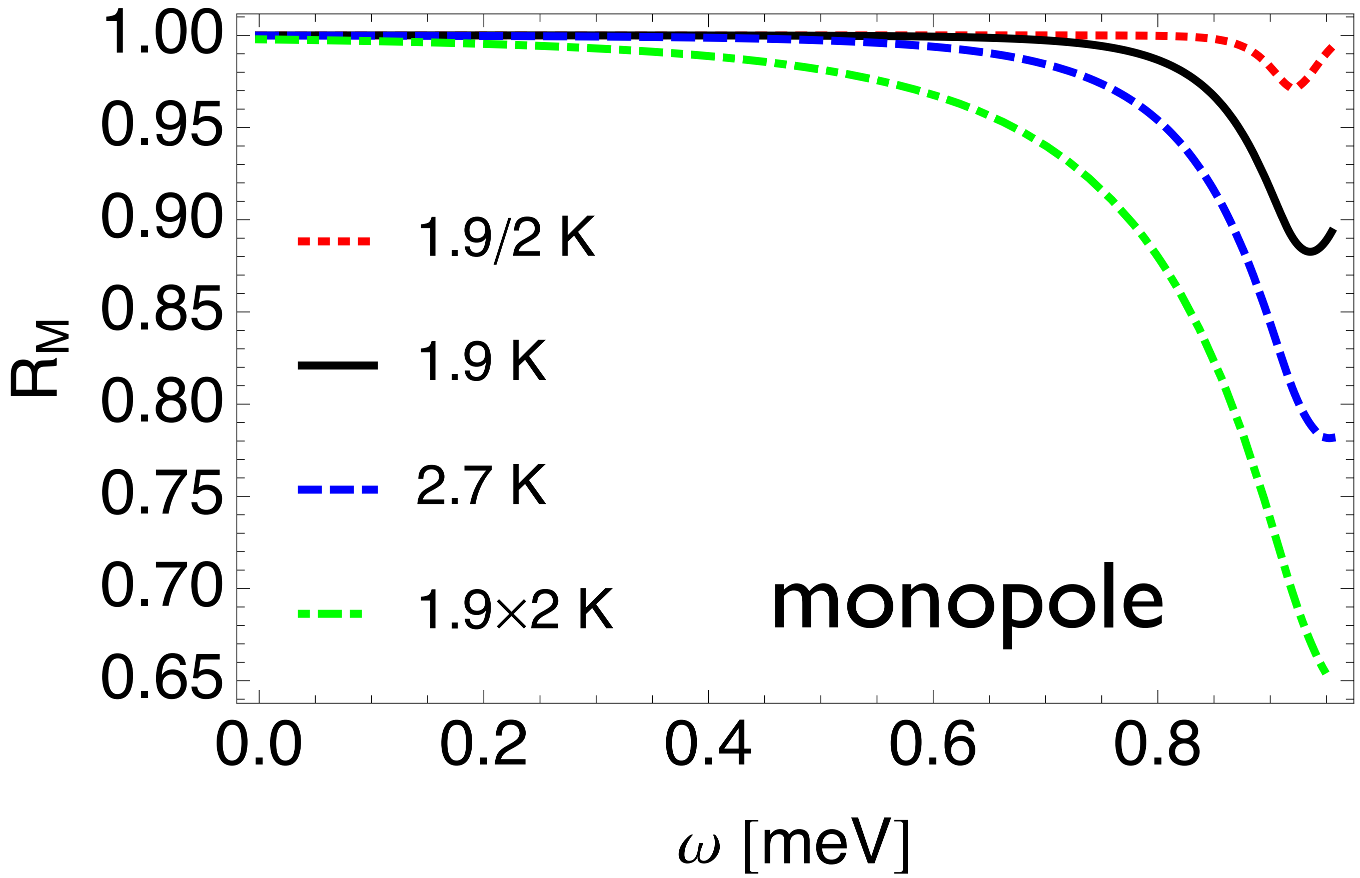
→ spectral distortion

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

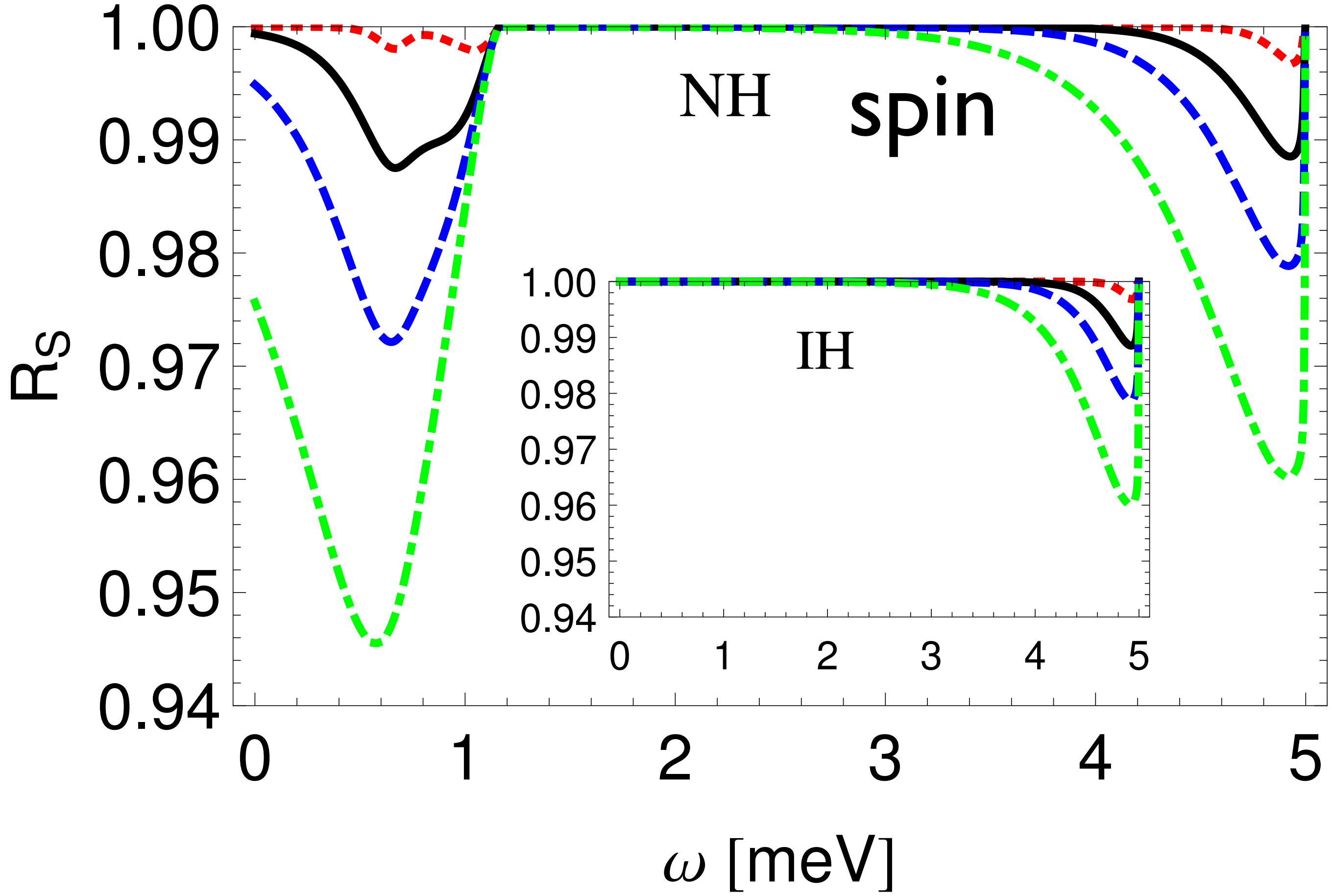
$\epsilon_{eg} = 11$ meV

smallest neutrino mass

$m_0 = 5$ meV

chemical potential

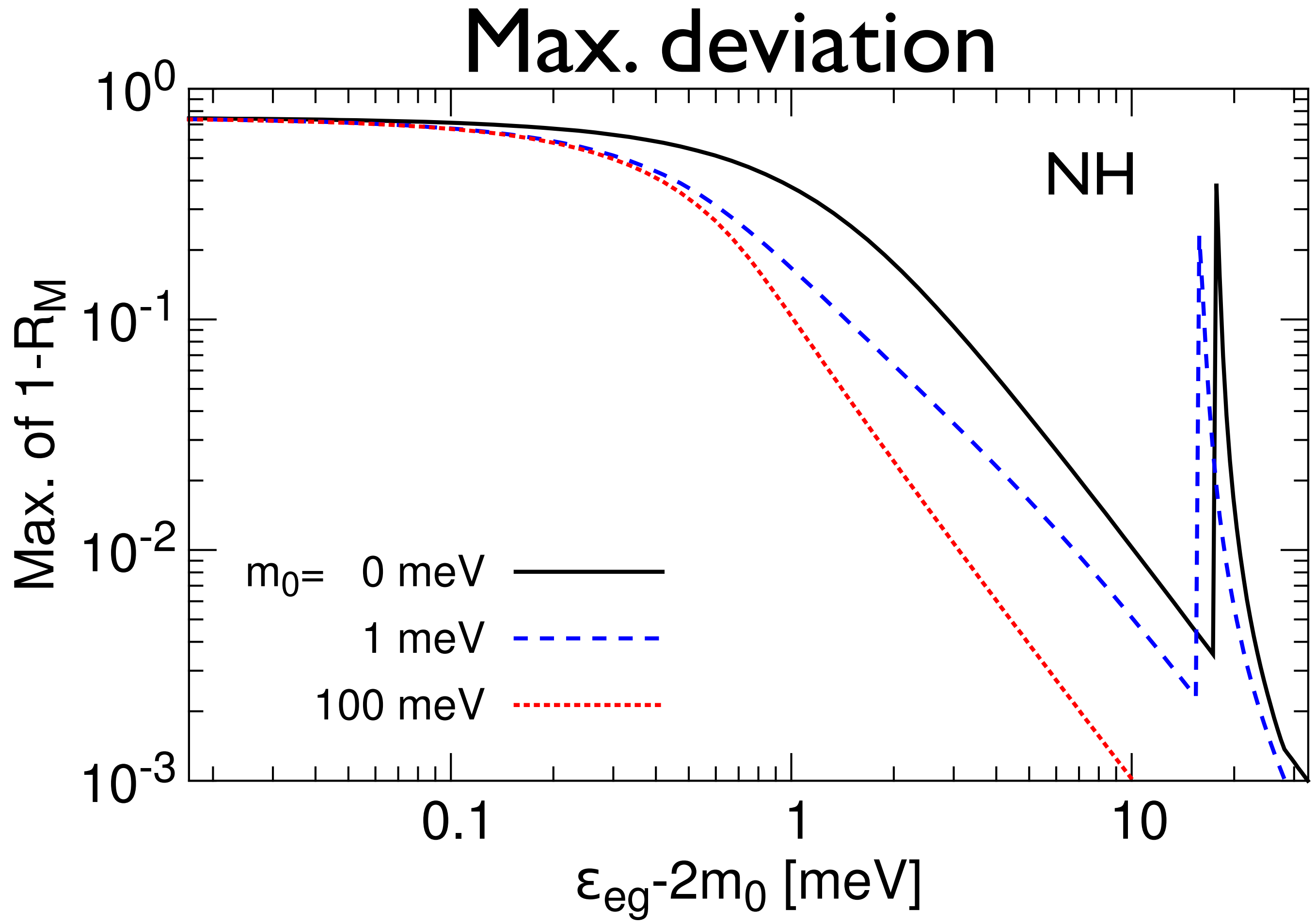
$\xi_i \equiv \mu_i / T_\nu = 0$

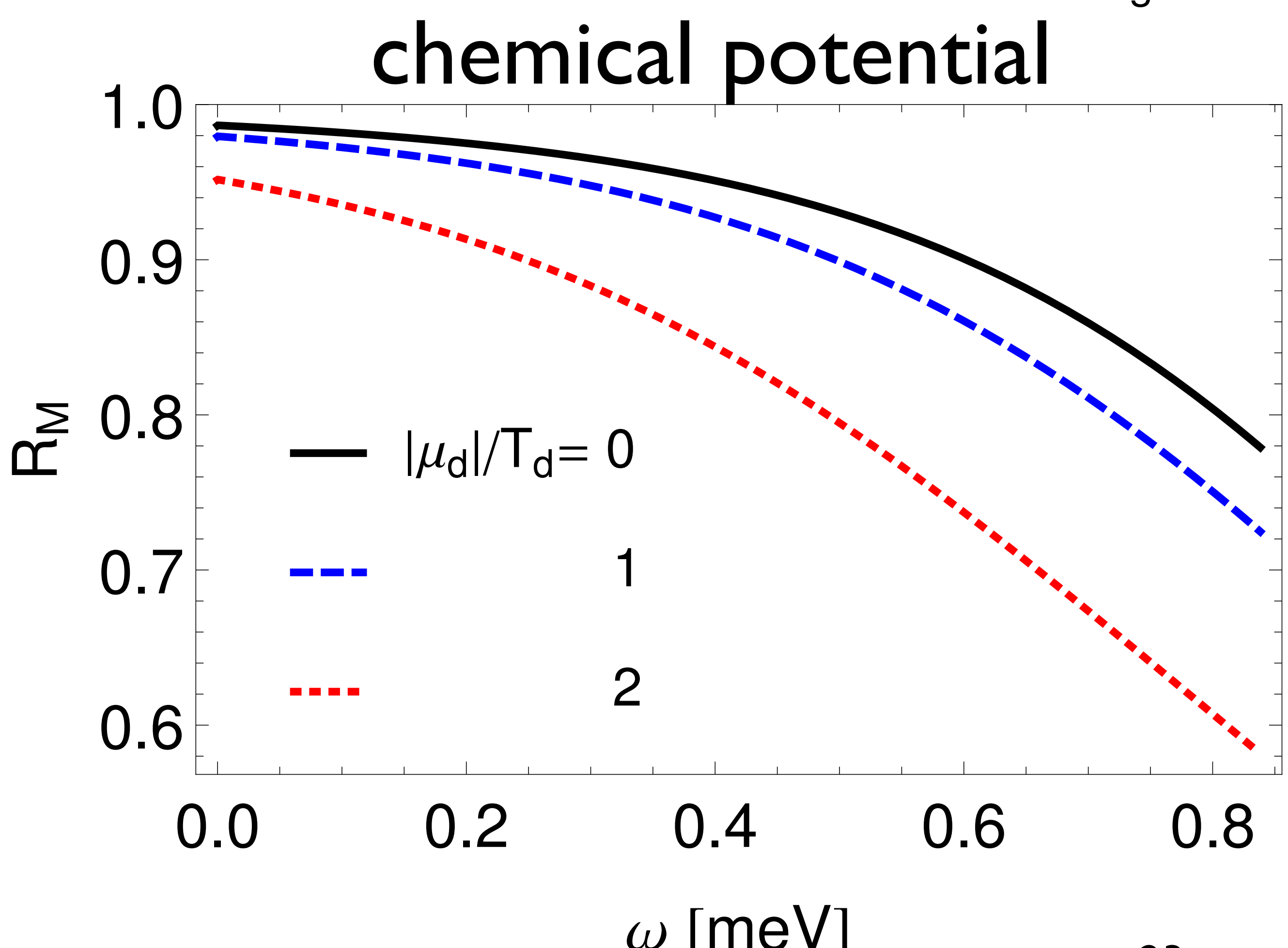


$\epsilon_{eg} = 10$ meV

$m_0 = 0.1$ meV

$\xi_i = 0$





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

$$m_0 = 0$$

BG-free RENP

Ref. M. Yoshimura, N. Sasao, M. T.
PTEP (2015) 053B06, arXiv:15010571

QED backgrounds

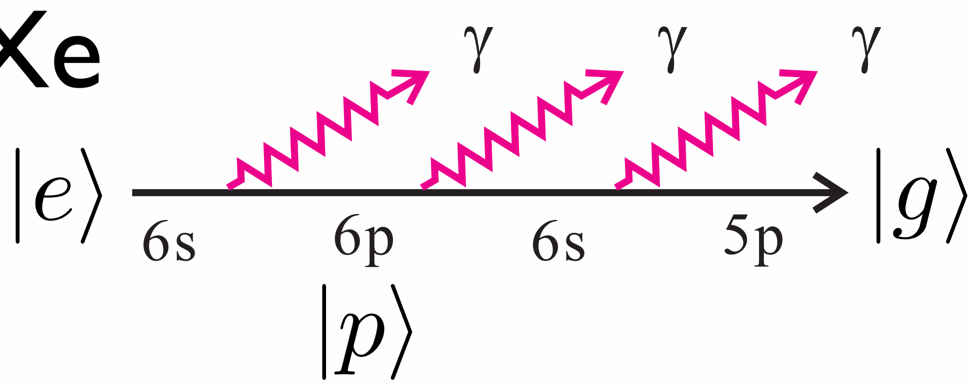
Macrocoherent amplification of RENP

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

Macrocoherent amplification of QED processes

$$|e\rangle \to |g\rangle + \gamma_0 + \gamma_1 \gamma_2 \quad \text{McQ3}$$

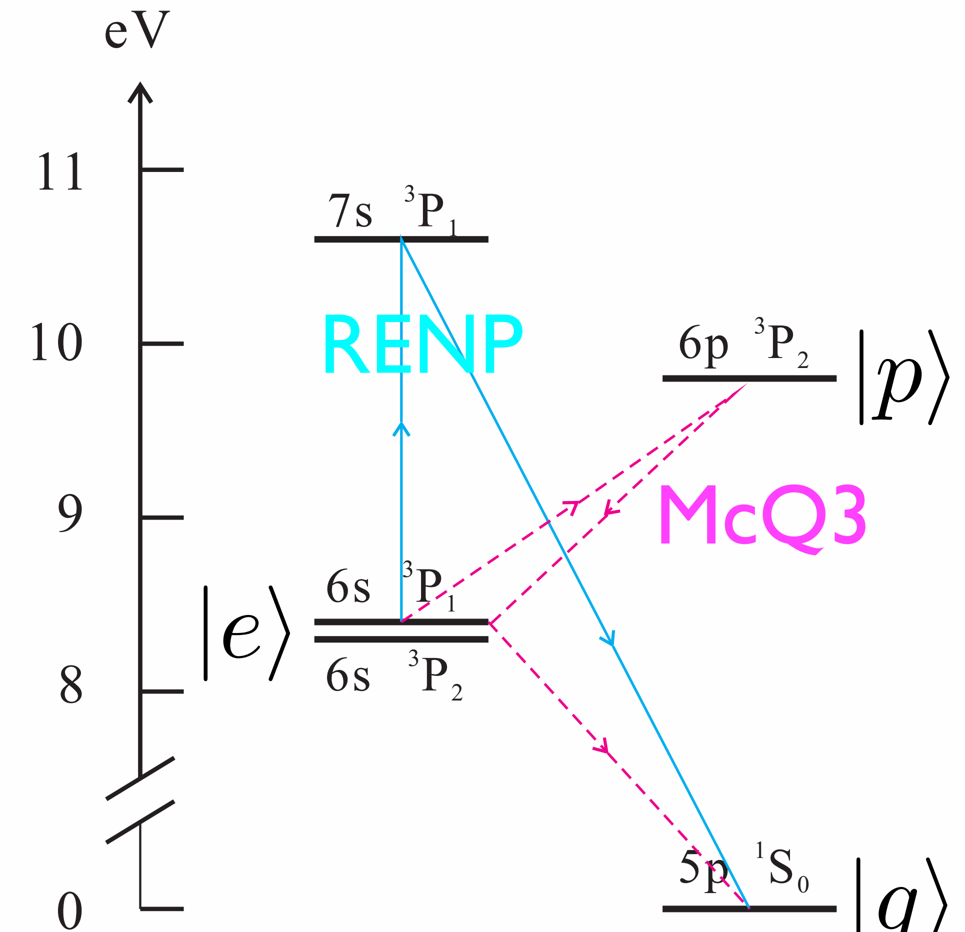
Ex. Xe



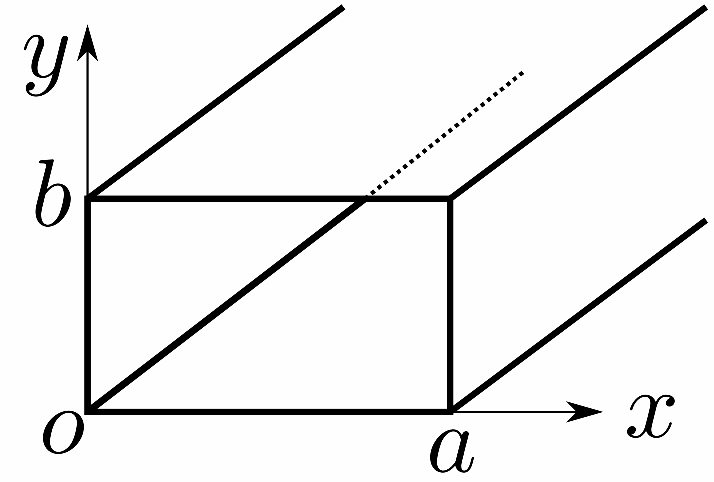
$$\frac{d\Gamma_3}{d\omega} = \frac{3\pi^2}{2} \frac{\gamma_{pe}\gamma_{pq}\gamma_{qg}}{\epsilon_{pe}^3 \epsilon_{pq}^3 \epsilon_{qg}^3} n^3 V \eta_3(t) \omega^2 (\epsilon_{eg} - \omega_0 - \omega)^2 F_3^2(\omega)$$

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

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

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

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