Physics
OSAKA UNIVERSITY

Radiative Emission of Neutrino Pair from atoms/molecules

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Refs. : D.N. Dinh, S.T. Petcov, N. Sasao, M.T., M.Yoshimura arXiv:1209.4808
(to be published in PLB)

A.Fukumi et al. PTEP (2012) 04D002

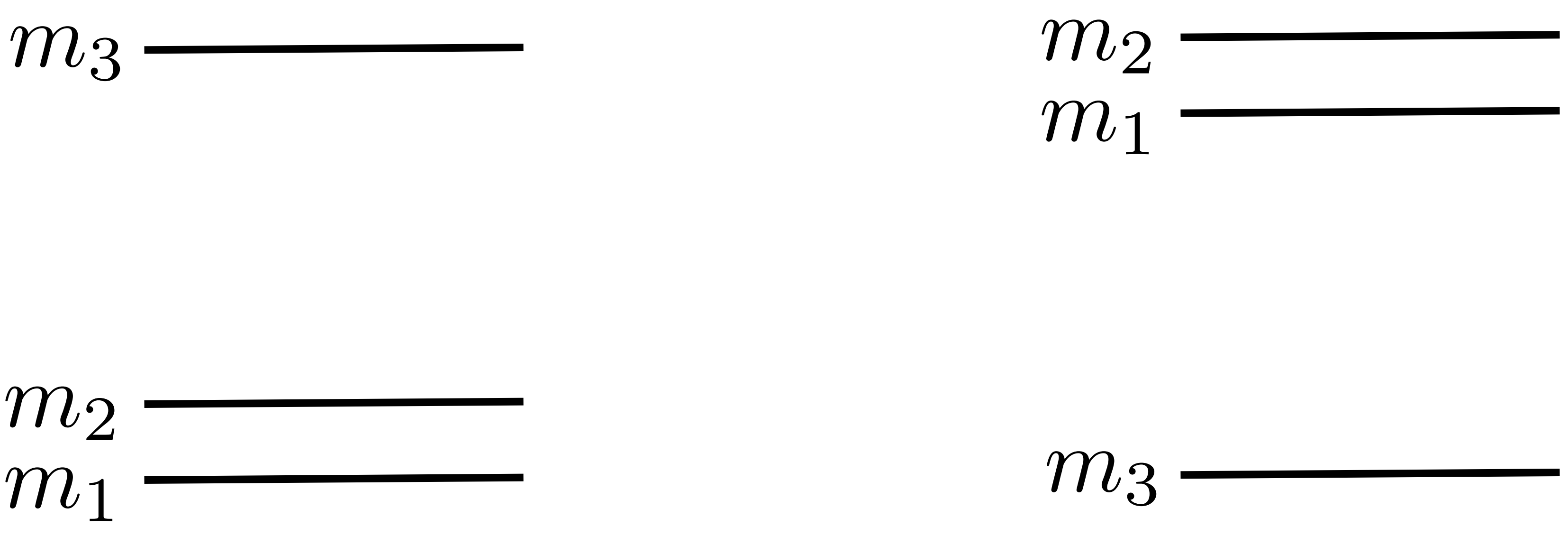
Nagoya University, 2013/01/15

INTRODUCTION

What we know about neutrino mass and mixing

Masses: two possible hierarchy patters

Normal Hierarchy (NH)　　Inverted Hierarchy (IH)



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

Fogli et al. (2012)

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

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

$$V_{\rm PMNS} =$$

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

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

Remaining questions

Absolute mass

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

Hierarchy pattern

normal or inverted

Mass type

Dirac or Majorana

CP violation

one Dirac phase, two Majorana phases

RENP

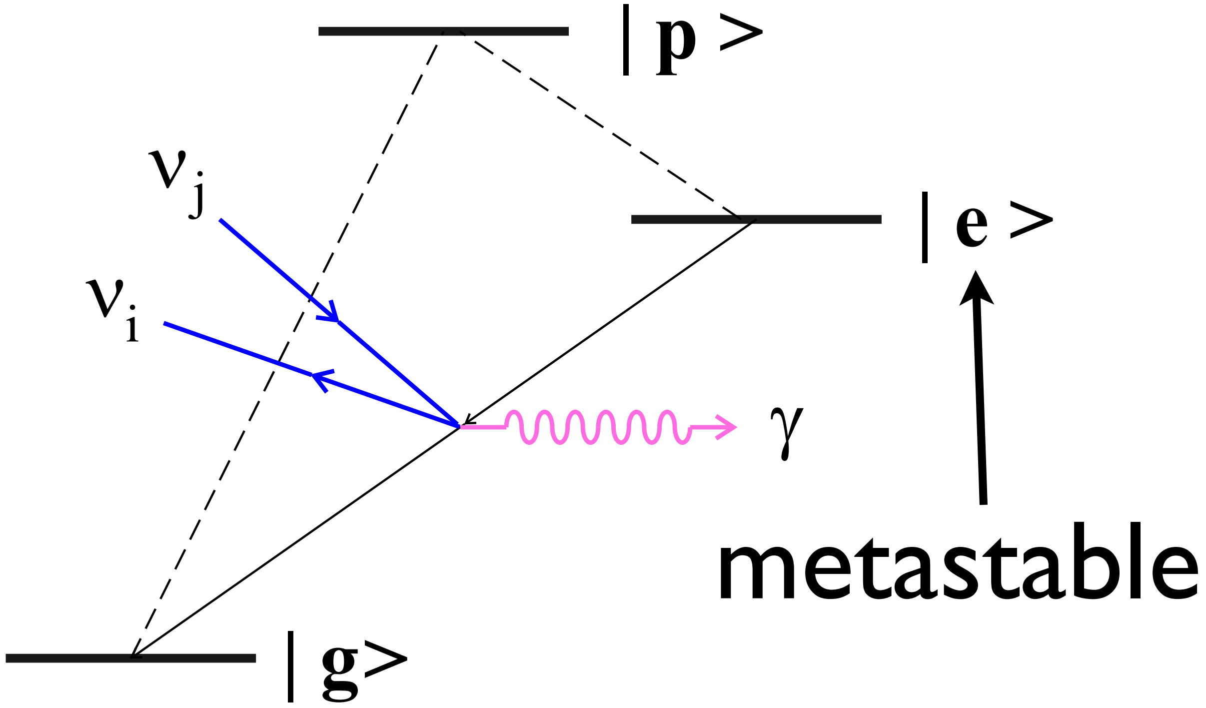
Neutrino spectroscopy with atoms

atomic/molecular energy scale ~ eV or less

cf. nuclear processes ~ MeV

Radiative Emission of Neutrino Pair (RENP) from atoms/molecules

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



Λ-type level structure

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

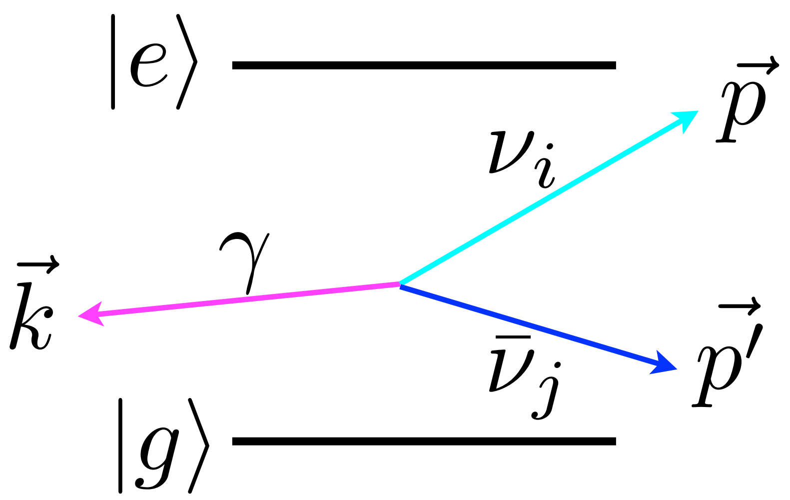
H_2, O_2, I_2, ...

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

rate enhancement by macro-coherence

Macro-coherence

Yoshimura et al. (2008)



position of atom

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

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

N atoms, Volume V (n=N/V)

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

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

macro-coherent amplification

RENP spectrum

Energy-momentum conservation
due to the macro-coherence

→ familiar 3-body decay kinematics

Six thresholds of the photon energy

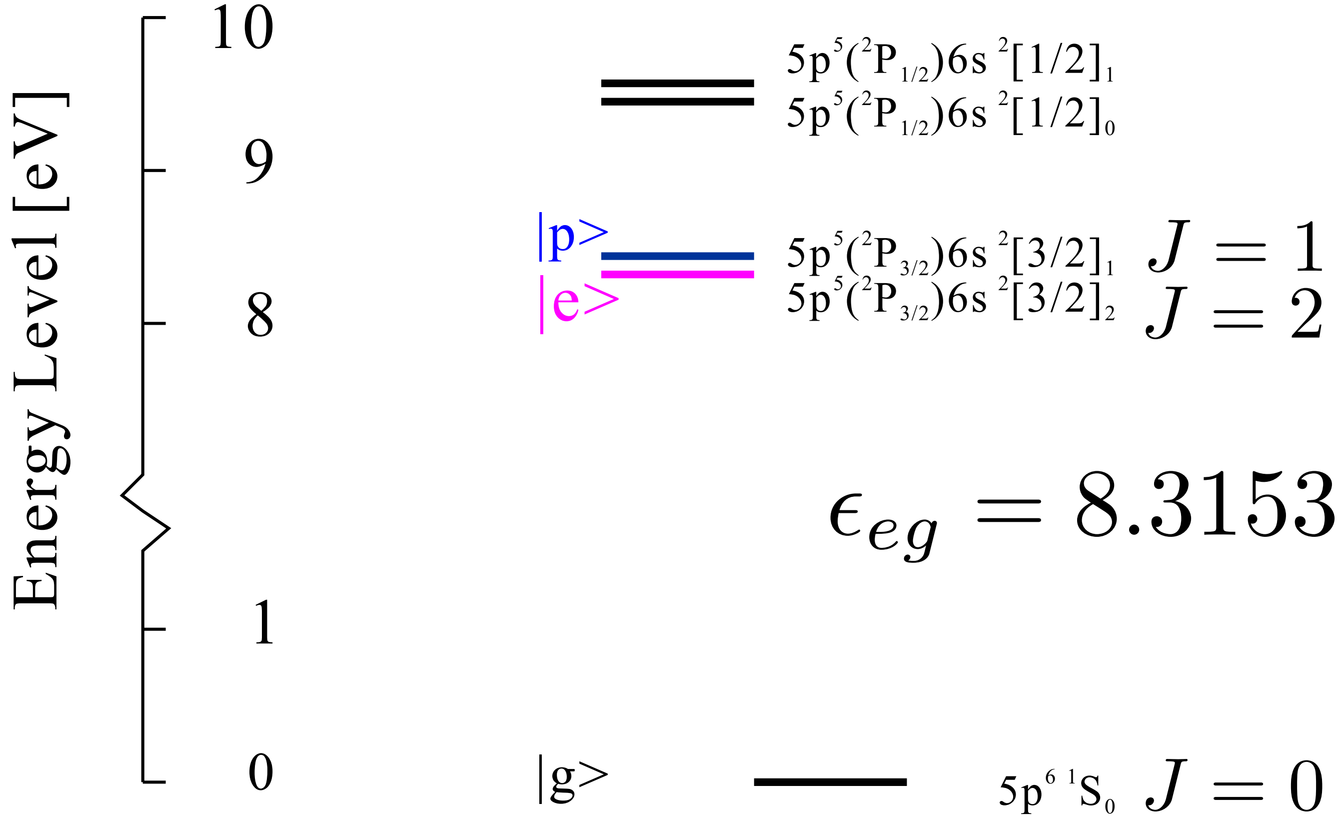
$$\omega_{ij} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}} \qquad i, j = 1, 2, 3$$

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

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

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

Xe



$5p^5(^2P_{1/2})6s\ ^2[1/2]_1$

$5p^5(^2P_{1/2})6s\ ^2[1/2]_0$

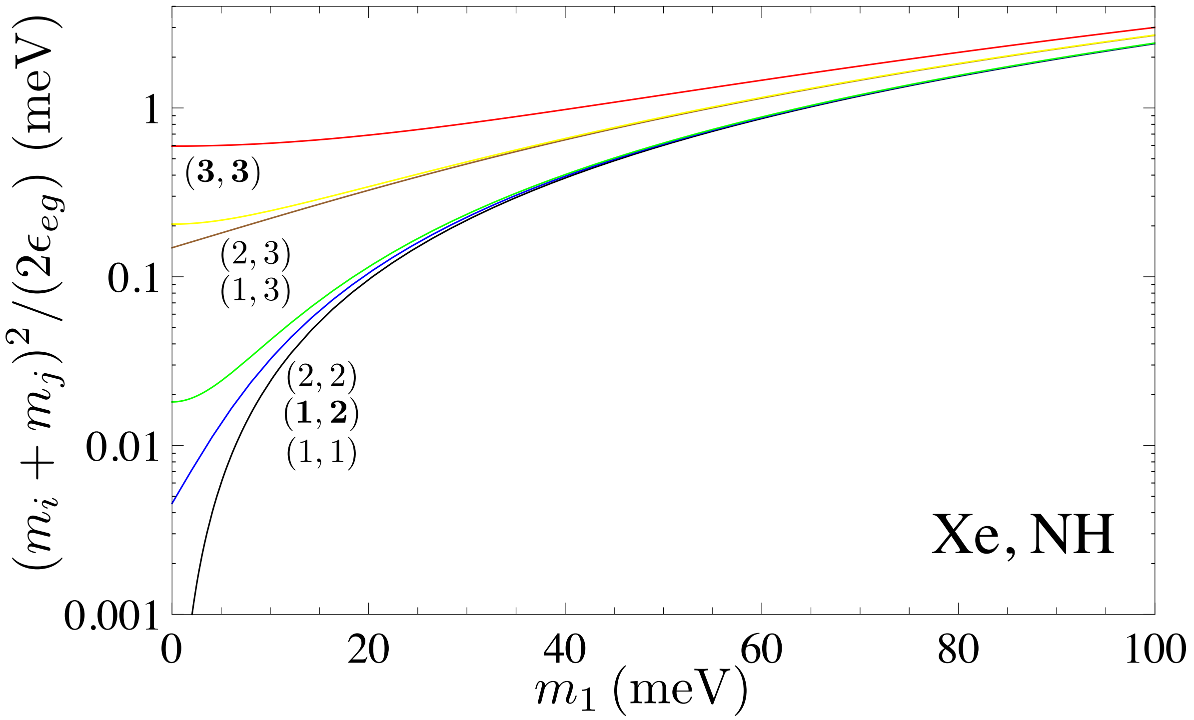
|p> $5p^5(^2P_{3/2})6s\ ^2[3/2]_1$ $J = 1$

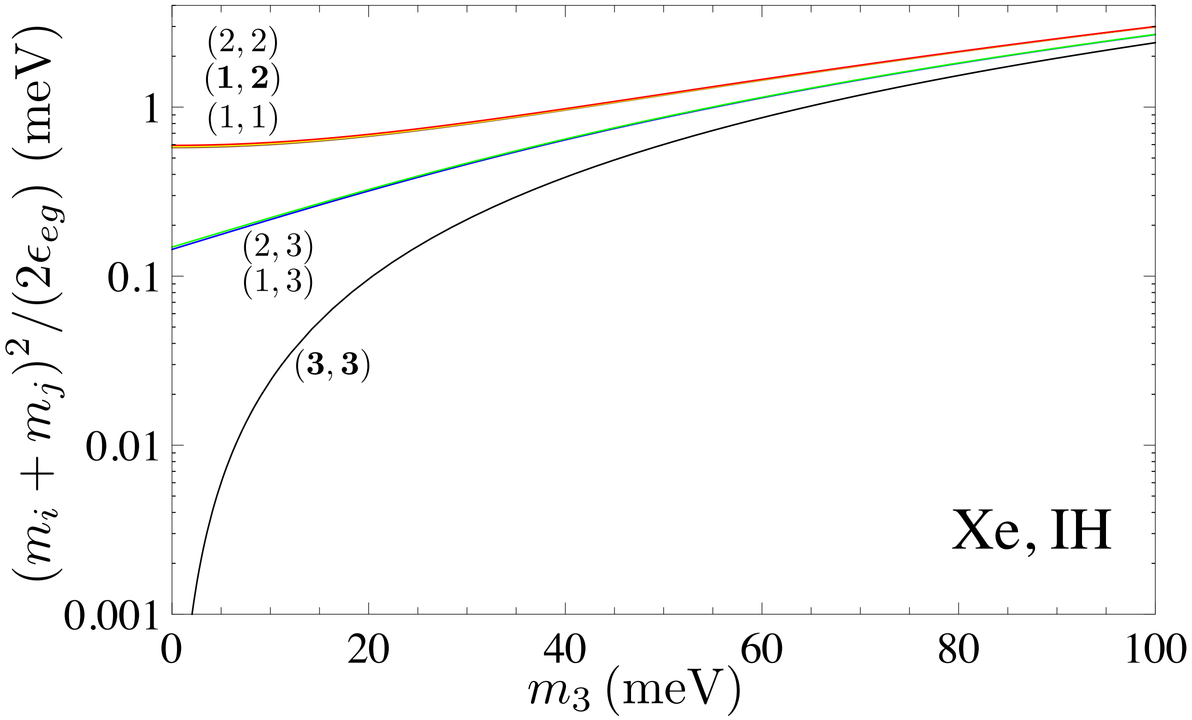
|e> $5p^5(^2P_{3/2})6s\ ^2[3/2]_2$ $J = 2$

|g> $5p^6\ ^1S_0$ $J = 0$

$$|e\rangle \leftrightarrow |p\rangle \quad \text{M1}$$
$$|p\rangle \leftrightarrow |g\rangle \quad \text{E1}$$

$$\epsilon_{eg} = 8.3153\,\text{eV}$$





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

$$\Gamma_0 = \frac{3\boxed{n^2 V} G_F^2 \gamma_{pg} \boxed{\epsilon_{eg} n}}{2\epsilon_{pg}^3}(2J_p + 1)C_{ep} \sim 1\,\mathrm{Hz}\,(n/10^{22}\mathrm{cm}^{-3})^3 (V/10^2\,\mathrm{cm}^3)$$

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

$(2J_p + 1)C_{ep}$: atomic spin factor

Spectral function

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

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

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

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

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

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

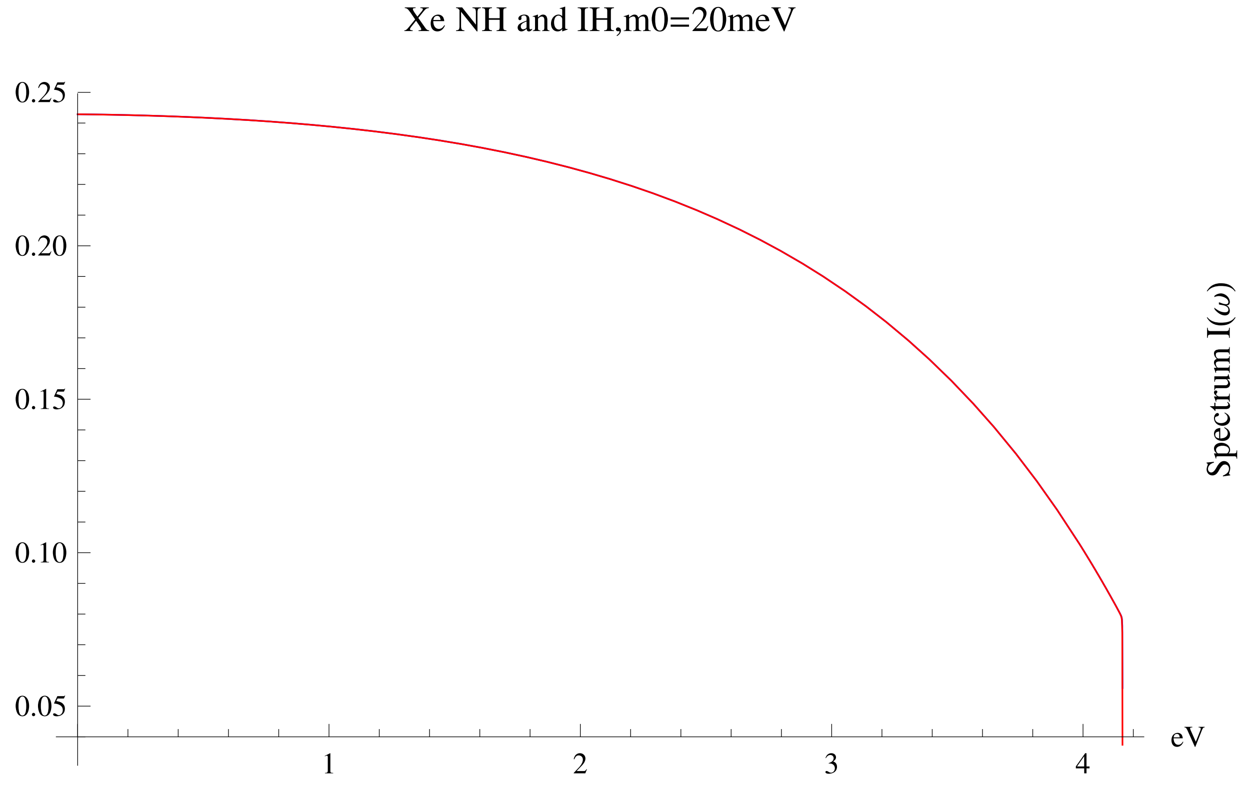
Dynamical factor

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

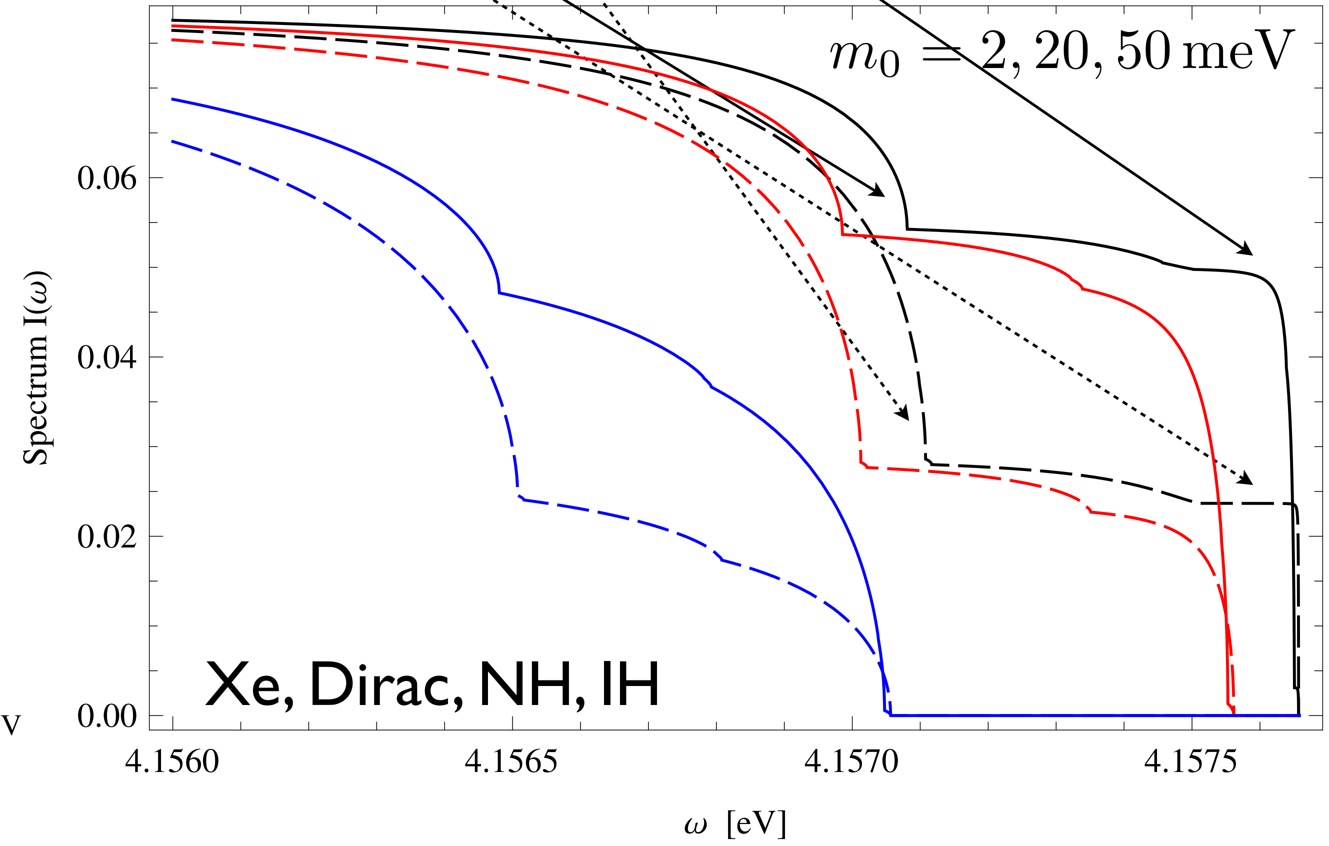
The threshold weight factors

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

Global shape



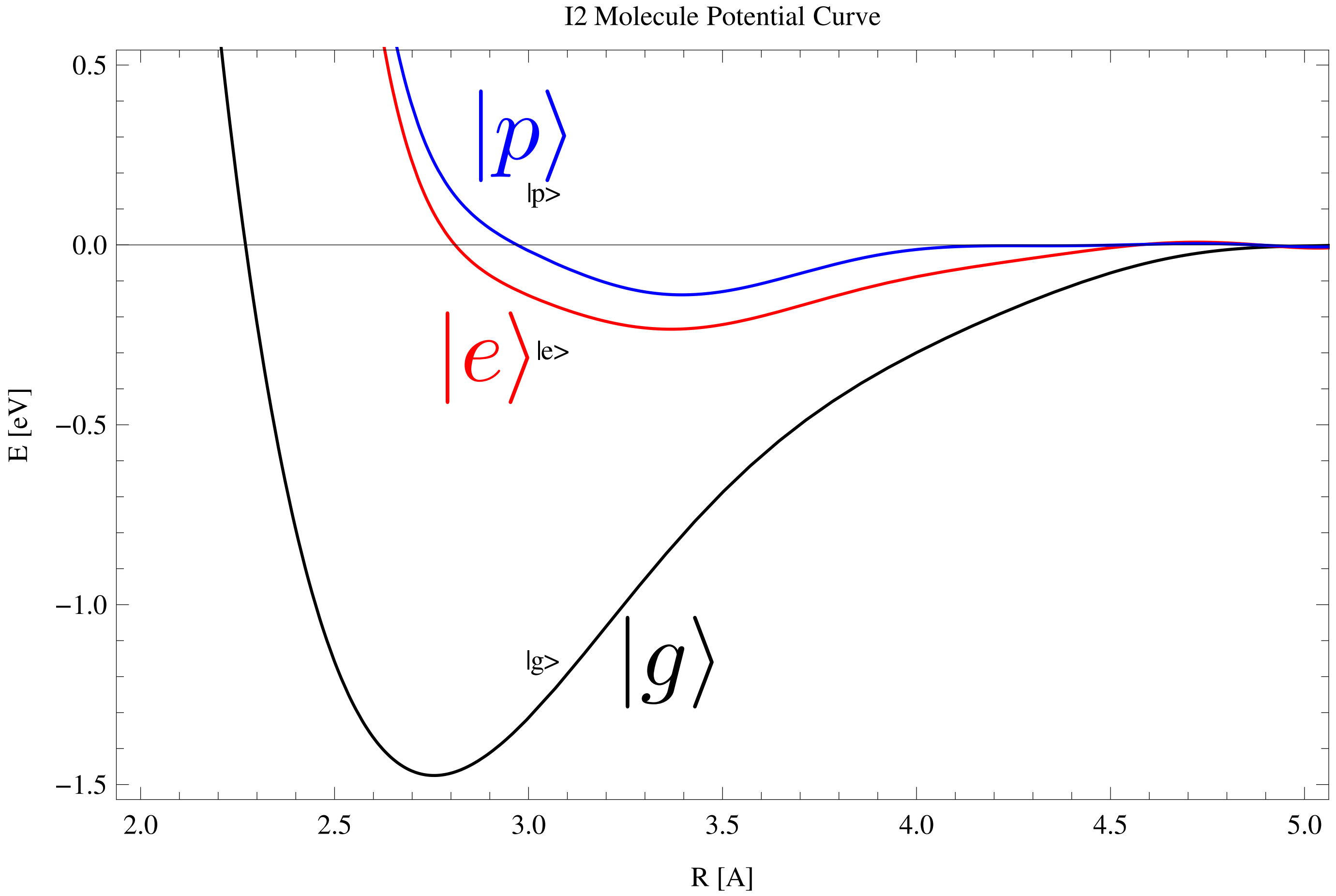
Threshold region



I_2 molecule

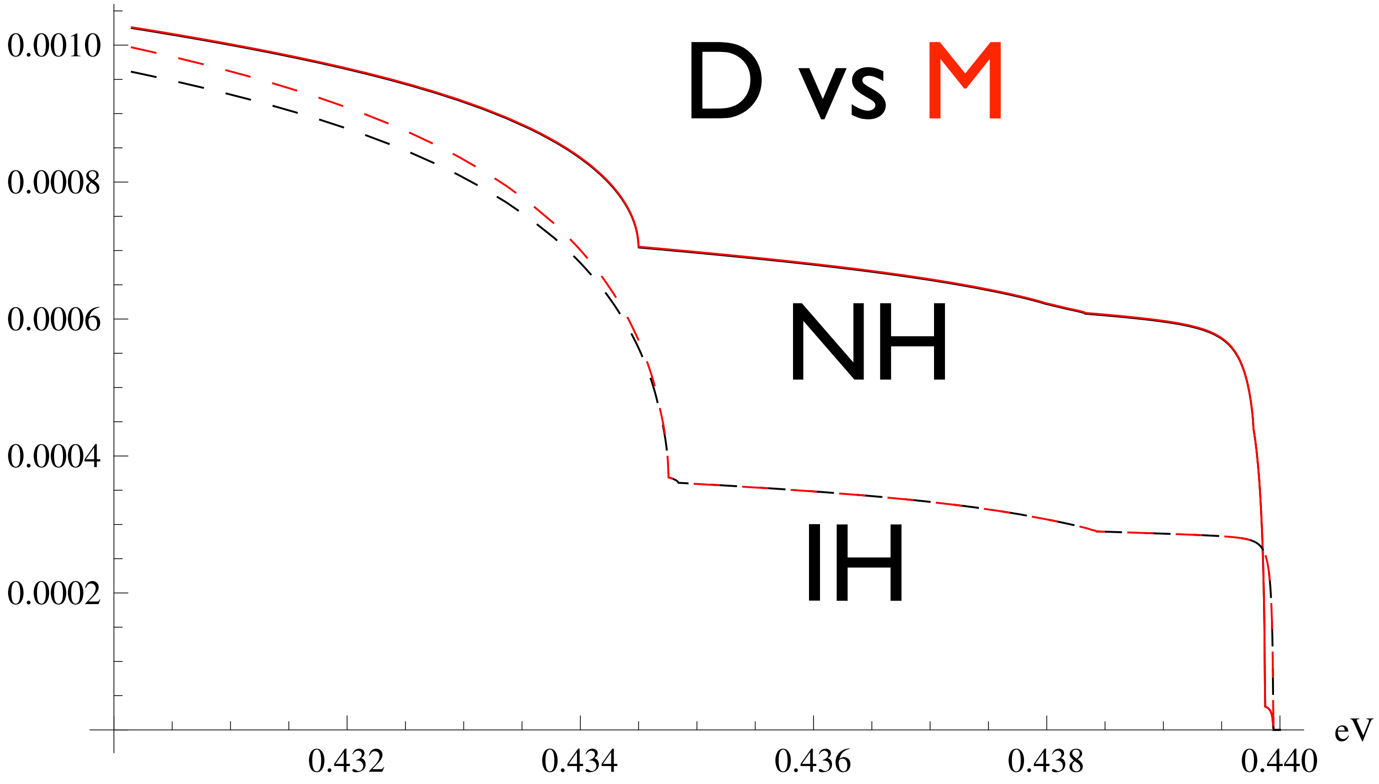
potential curves

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


I2 Molecule Potential Curve

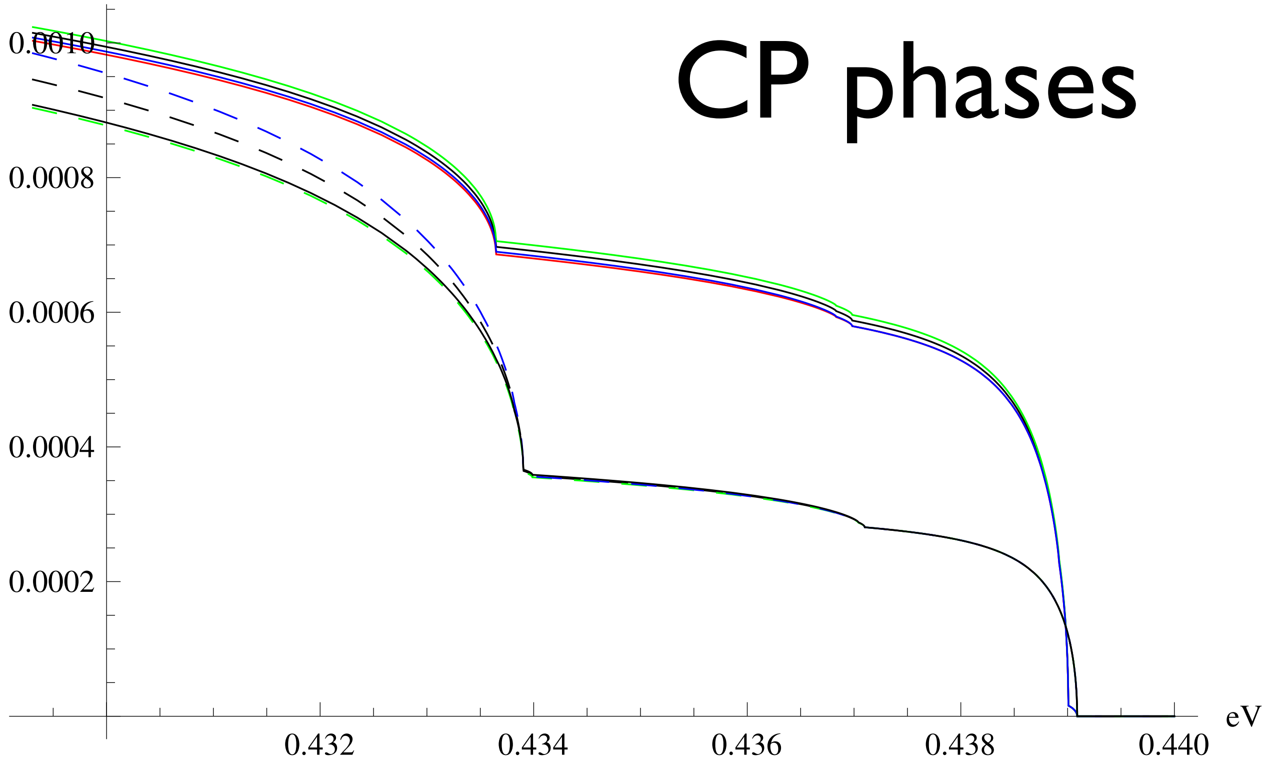
I2 A'v=1−>Xv=15: m0=5meV

D vs M



I2 A'v=1−>Xv=15: m0=20meV

CP phases

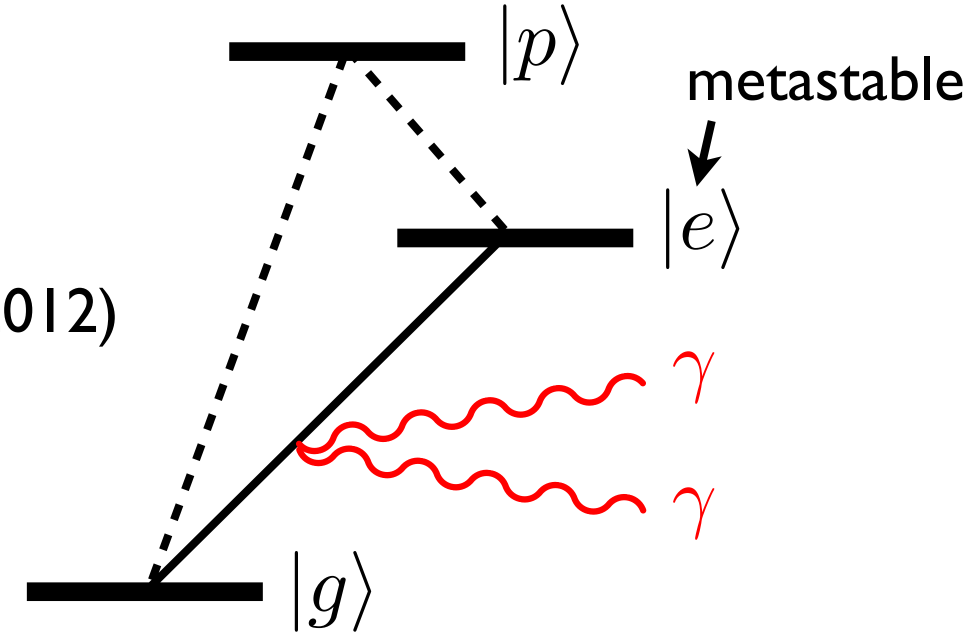


D-M diff. < 10%

PSR

Paired Super-Radiance

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



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

prototype for RENP

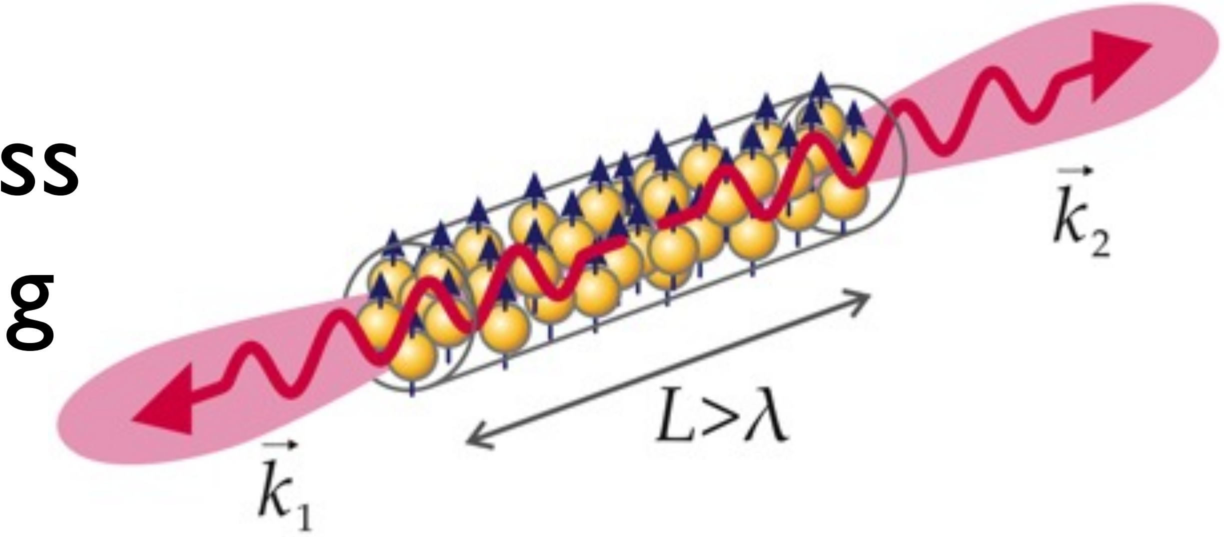
proof-of-concept for the macro-coherence

preparation of initial state for RENP

dynamical factor $\eta_\omega(t)$

background for RENP

A novel coherent process with counter-propagating fields/triggers



PSR Equation

Effective two-level interaction Hamiltonian

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

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

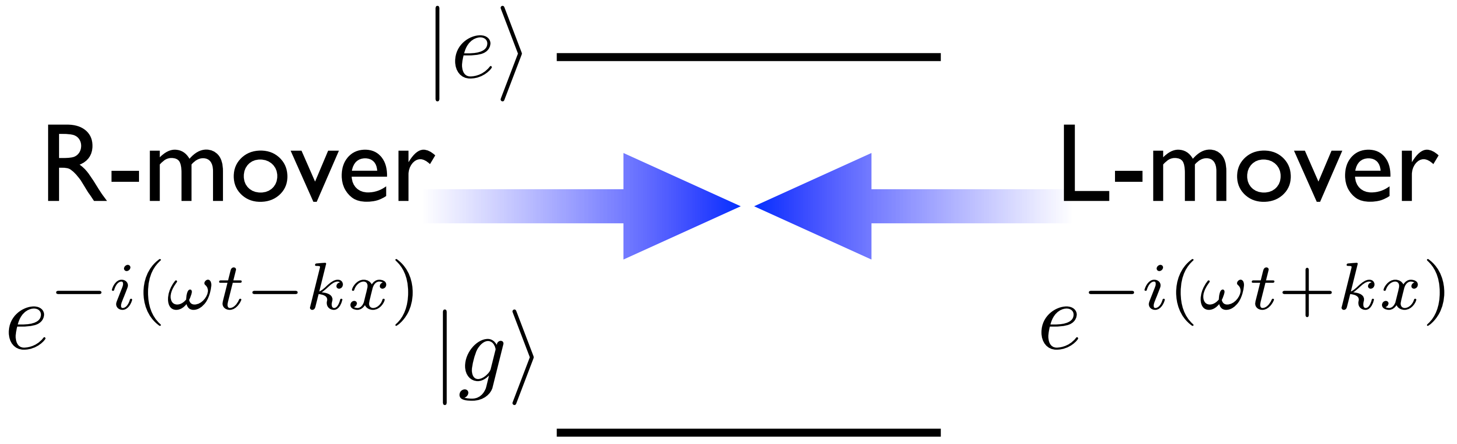
d_{pa} : dipole matrix element

Field (1+1 dim.)

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

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

$$k = \omega$$



$|e\rangle$

R-mover

L-mover

$e^{-i(\omega t - kx)}$

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

$|g\rangle$

$$\sim e^{-i2\omega t} = e^{-i\varepsilon_{eg} t}$$

macro-coherence

Bloch equation: $\partial_t \rho = i[\rho, \mathcal{H}_I]$

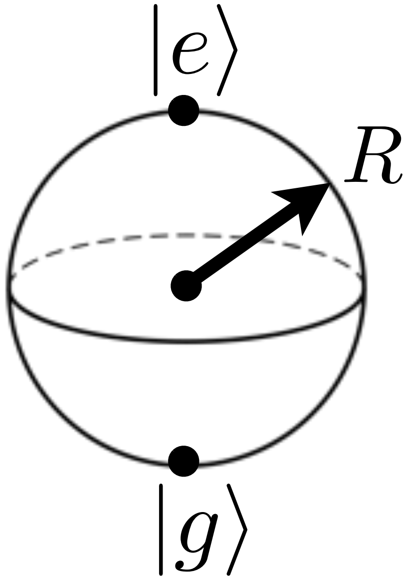
Maxwell equation: $\partial_t^2 \boldsymbol{E} = -[H, [H, \boldsymbol{E}]]$

$$H = \int d^3x \, [\mathcal{H}_{em} + \mathrm{tr}(\rho \mathcal{H}_I)]$$

Bloch vector: $R_i(x, t) = \mathrm{tr}(\rho \sigma_i)$

spatial grating

$$R_i = R_i^{(0)} + R_i^{(+)} e^{2ikx} + R_i^{(-)} e^{-2ikx}$$



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Rotating wave approximation (RWA)

omitting fast oscillation terms

Slowly varying envelope approximation (SVEA)

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

Rescaling: $1/t_* = \alpha_{ge}\omega n$

$$x = t_*\xi,\ t = t_*\tau,\ E_{R,L}^2 = \omega n e_{R,L}^2,\ R_i^{(0,\pm)} = n r_i^{(0,\pm)}$$

$$r_T^{(0,\pm)} = r_1^{(0,\pm)} + i r_2^{(0,\pm)}$$

The master equation

$$\gamma_\pm = \frac{\alpha_{ee} \pm \alpha_{gg}}{2\alpha_{ge}}$$

$$\begin{aligned}
\partial_\tau r_T^{(0)} &= -4i\left[\gamma_-\left\{r_T^{(0)}(|e_R|^2+|e_L|^2) + r_T^{(+)} e_R^* e_L + r_T^{(-)} e_R e_L^*\right\}\right. \\
&\qquad \left. - \left\{2r_3^{(0)} e_R^* e_L^* + r_3^{(+)} e_R^{*2} + r_3^{(-)} e_L^{*2}\right\}\right] - r_T^{(0)}/\tau_2\,, \\
\partial_\tau r_T^{(+)} &= -4i\left[\gamma_-\left\{r_T^{(+)}(|e_R|^2+|e_L|^2) + r_T^{(0)} e_R e_L^*\right\} - \left\{2r_3^{(+)} e_R^* e_L^* + r_3^{(0)} e_L^{*2}\right\}\right] - r_T^{(+)}/\tau_2\,, \\
\partial_\tau r_T^{(-)} &= -4i\left[\gamma_-\left\{r_T^{(-)}(|e_R|^2+|e_L|^2) + r_T^{(0)} e_R^* e_L\right\} - \left\{2r_3^{(-)} e_R^* e_L^* + r_3^{(0)} e_R^{*2}\right\}\right] - r_T^{(-)}/\tau_2\,, \\
\partial_\tau r_3^{(0)} &= 2i\left[\left(2r_T^{(0)} e_R e_L + r_T^{(+)} e_L^2 + r_T^{(-)} e_R^2\right) - (\text{c.c.})\right] - (r_3^{(0)}+1)/\tau_1\,, \\
\partial_\tau r_3^{(+)} &= 2i\left[2r_T^{(+)} e_R e_L + r_T^{(0)} e_R^2 - \left(2r_T^{(-)*} e_R^* e_L^* + r_T^{(0)*} e_L^{*2}\right)\right] - r_3^{(+)}/\tau_1\,.
\end{aligned}$$

$$\begin{aligned}
(\partial_\tau + \partial_\xi)e_R &= \frac{i}{2}\left[\left(\gamma_+ + \gamma_- r_3^{(0)}\right)e_R + \gamma_- r_3^{(+)} e_L + r_T^{(0)*} e_L^* + r_T^{(-)*} e_R^*\right] \\
(\partial_\tau - \partial_\xi)e_L &= \frac{i}{2}\left[\left(\gamma_+ + \gamma_- r_3^{(0)}\right)e_L + \gamma_- r_3^{(-)} e_R + r_T^{(0)*} e_R^* + r_T^{(+)*} e_L^*\right]
\end{aligned}$$

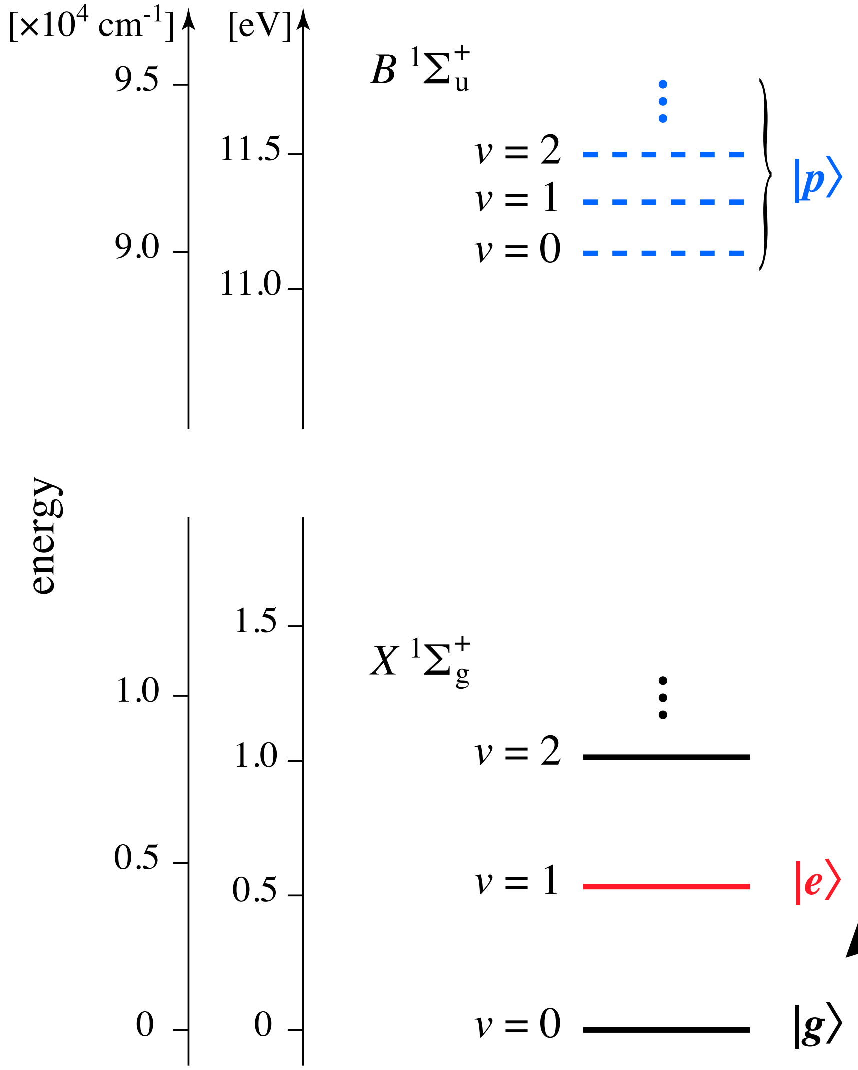
$\tau_i = T_i/t_*$ dimensionless relaxation times

Numerical results

Target system: para-hydrogen molecule

gas or solid

vibrational transition (electronic ground state)



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

no E1 transition

two-photon life ~ 10^{16} sec.

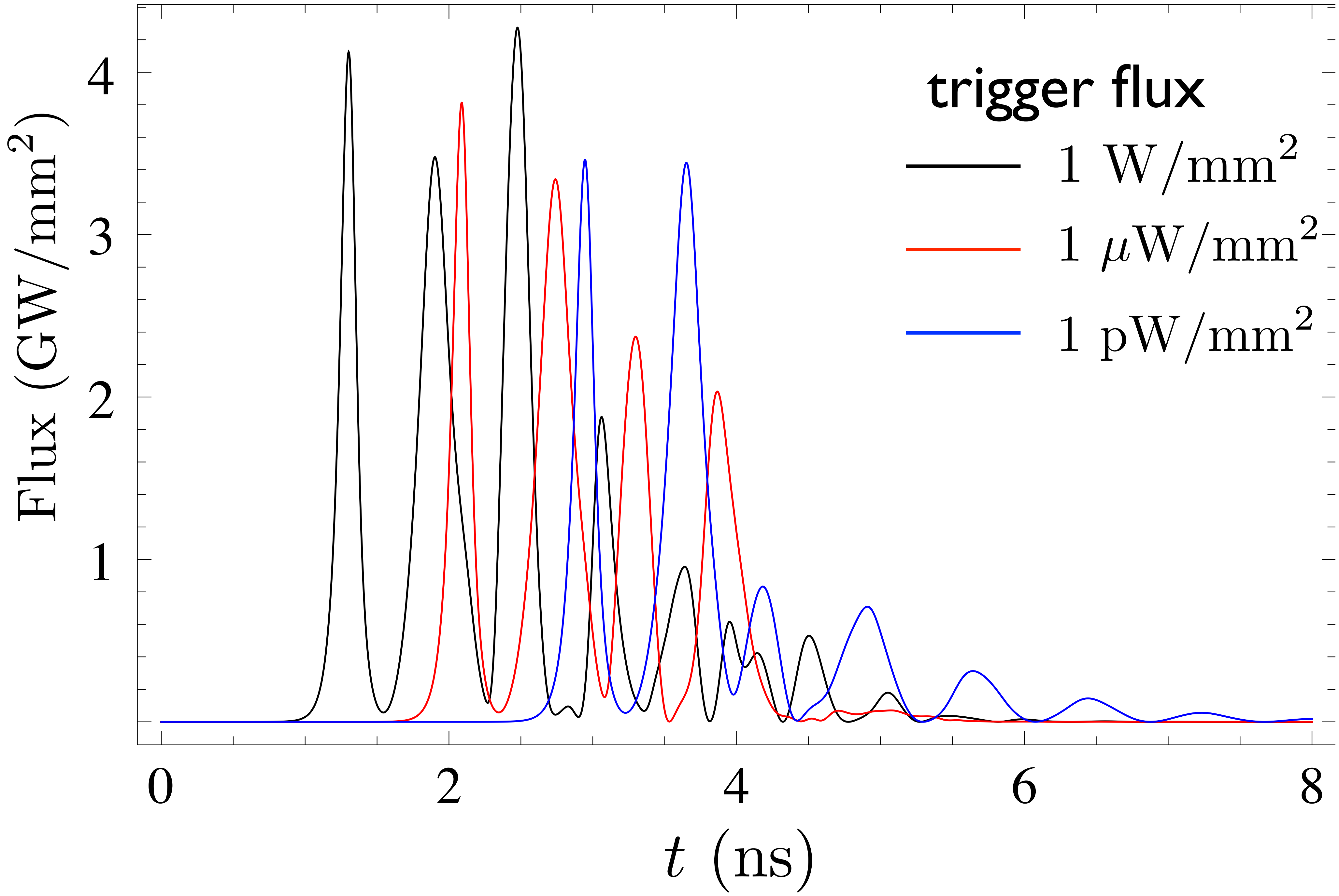
$$\epsilon_{eg} = 0.52\,\mathrm{eV}, \;\; \gamma_{\pm} = 15.3,\; 0.64$$

$$t_* \sim 50\,\mathrm{ps}\,\frac{10^{21}\,\mathrm{cm}^{-3}}{n}$$

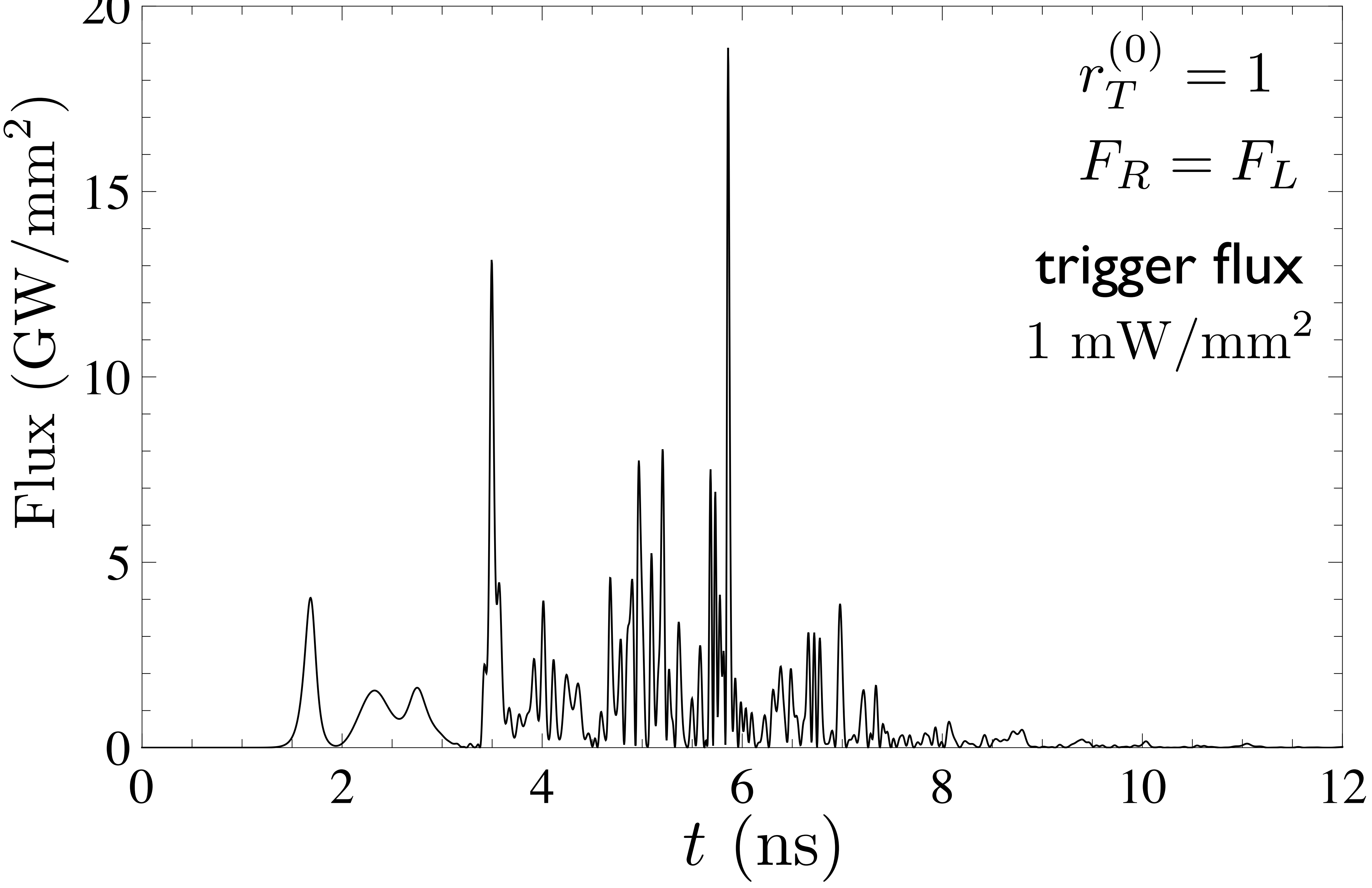
Explosive PSR

$n = 1 \times 10^{21}/\mathrm{cm}^3 \quad T_1 = 1\,\mu\mathrm{s},\ T_2 = 10\,\mathrm{ns}$

target length $L = 30\,\mathrm{cm}$ $r_T^{(0)} = 1$



$L = 100\,\mathrm{cm}$



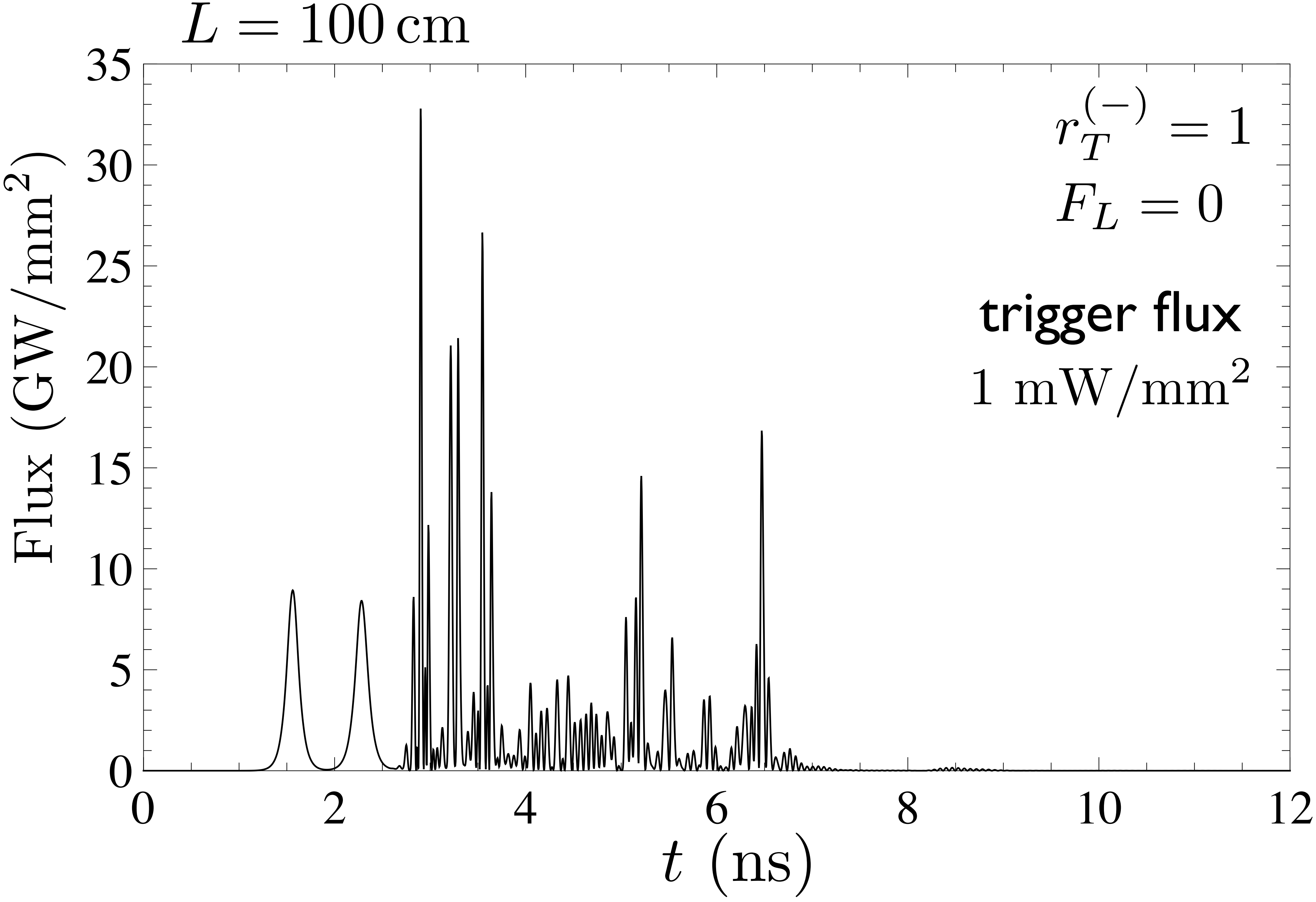
$r_T^{(0)} = 1$

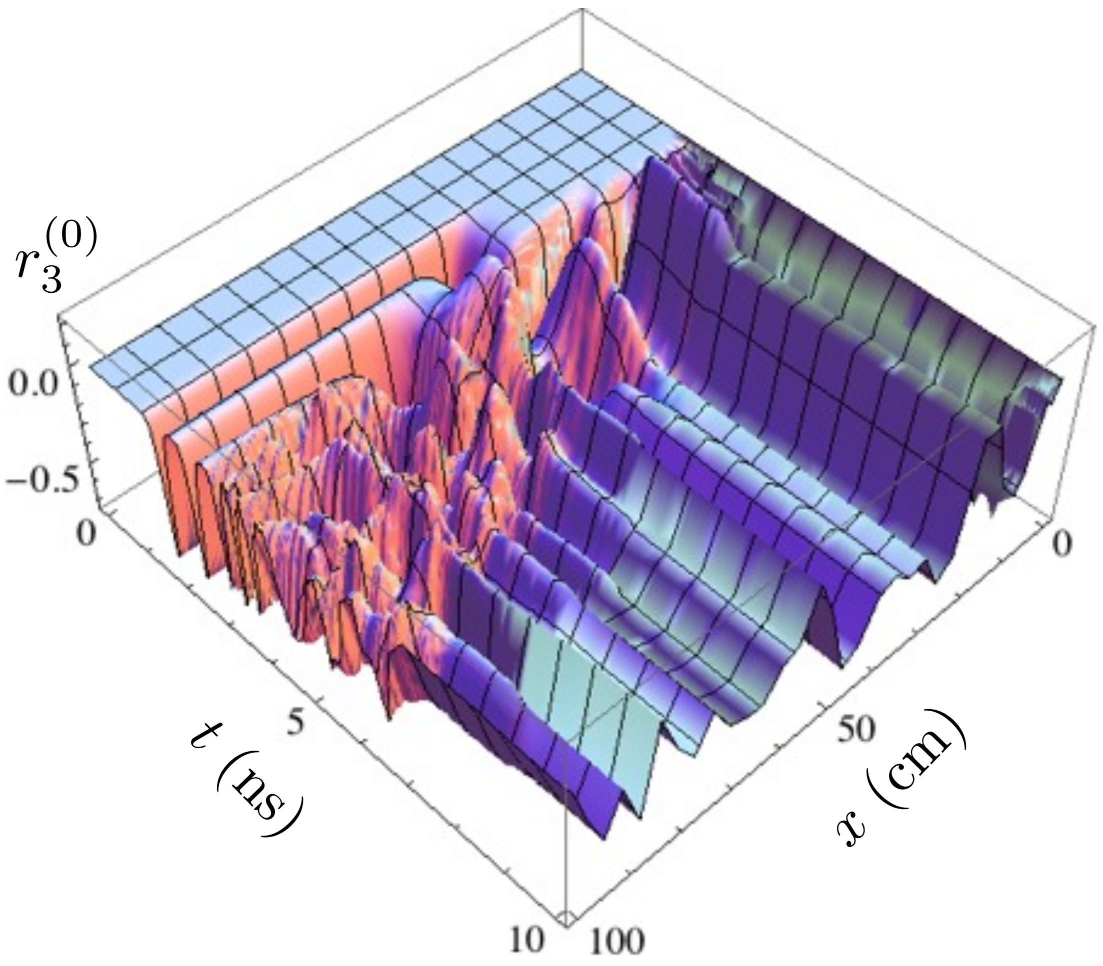
$F_R = F_L$

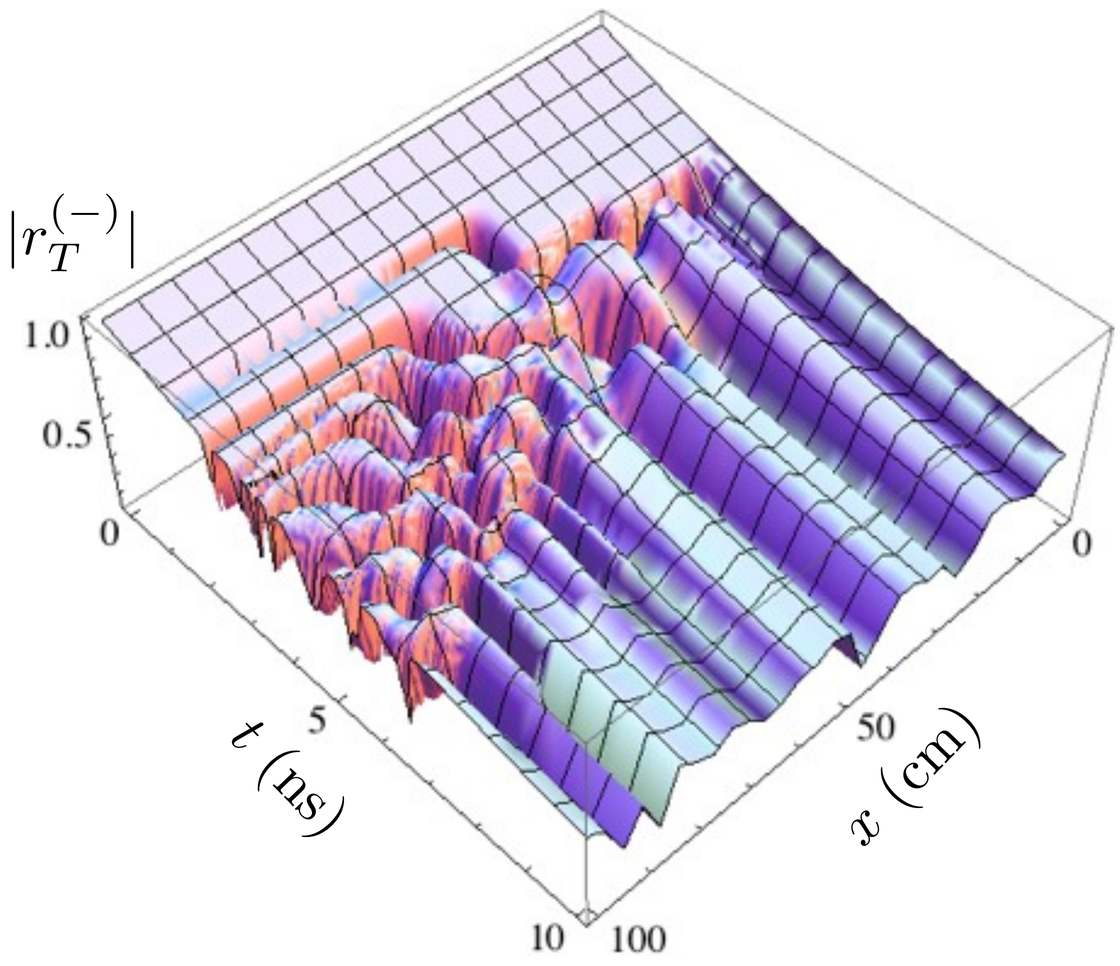
trigger flux

$1\ \mathrm{mW/mm}^2$

spatial grating




$r_3^{(0)}$
0.0
−0.5
0
5
10
t (ns)
0
50
100
x (cm)


$|r_T^{(-)}|$
1.0
0.5
0
5
10
t (ns)
0
50
100
x (cm)

The dynamical factor

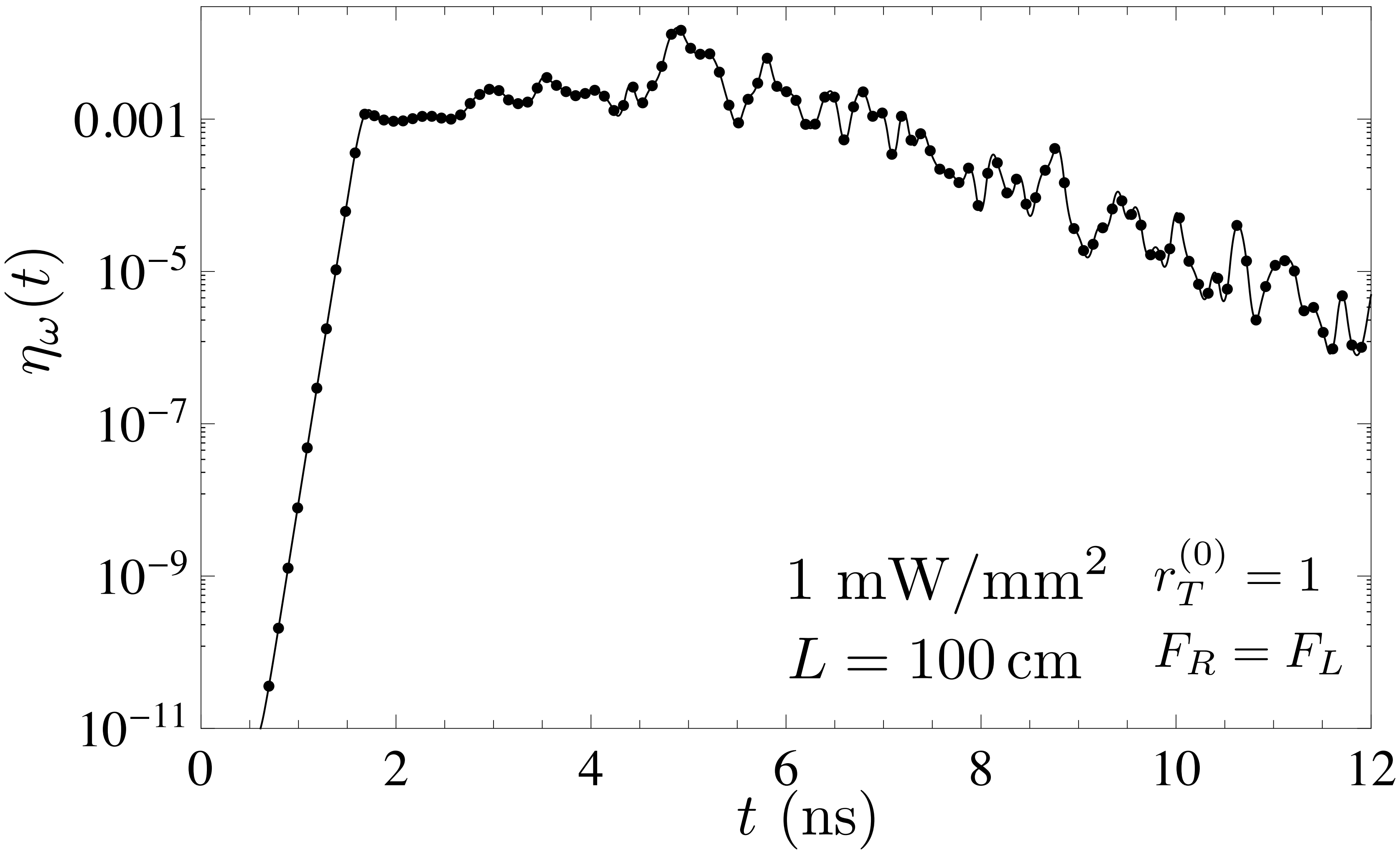
local field-medium activity

$$\eta_\omega(\xi,\tau) = \frac{1}{\epsilon_{eg} n^3}\left|\vec{E}^- \frac{R_1 - iR_2}{2}\right|^2 = \left|\left(e_R^* e^{-i\kappa\xi} + e_L^* e^{i\kappa\xi}\right)\frac{r_1 - ir_2}{2}\right|^2$$

$$= \frac{1}{4}\left[(|e_R|^2 + |e_L|^2)(|r_T^{(0)}|^2 + |r_T^{(+)}|^2 + |r_T^{(-)}|^2) + 2\Re\{e_R^* e_L (r_T^{(0)*} r_T^{(+)} + r_T^{(0)} r_T^{(-)*})\}\right]$$

average over the target length

$$\eta_\omega(t) = \langle \eta_\omega(\xi,\tau)\rangle_\xi$$



SUMMARY

Summary and Future Prospect

- ✶ RENP spectra are sensitive to unknown neutrino parameters.
- ✶ The macro-coherence is essential.

  We are about to test it by paired super-radiance.
- ✶ Choice of the target atom/molecule is vital.
  - small energy difference
  - large E1xM1 matrix element
  - high density, large coherence, ...

Backup Slides

RENP Formula Derivation

$$|e\rangle \to |g\rangle + \gamma(\vec{k}) + \nu_i(\vec{p}) + \bar{\nu}_j(\vec{p}')$$

$$\mathcal{A}_{ij} = \frac{i\mathcal{M}_d \mathcal{M}_W^{ij}}{\epsilon_{pg} - \omega} e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a} (2\pi)\delta(\epsilon_{eg} - \omega - E_p - E_{p'})$$

$$d\Gamma_{ij} = n^2 V \frac{|\mathcal{M}_d \mathcal{M}_W^{ij}|^2}{(\epsilon_{pg} - \omega)^2} d\Phi_2$$

$$\mathcal{M}_d = -\langle g|\vec{d}|p\rangle \cdot \vec{E}$$

$$\mathcal{M}_W^{ij} = \frac{G_F}{\sqrt{2}} \langle \nu_i(p,\lambda)\bar{\nu}_j(p',\lambda')| \sum_{a,b} \bar{\nu}_a \gamma_\mu (1-\gamma_5)\nu_b |0\rangle (v_{ab} J_V^\mu - a_{ab} J_A^\mu)$$

NR $J_V^\mu \simeq 0$ $\quad$ $J_A^\mu \simeq (0, 2\langle p|\vec{S}|e\rangle)$

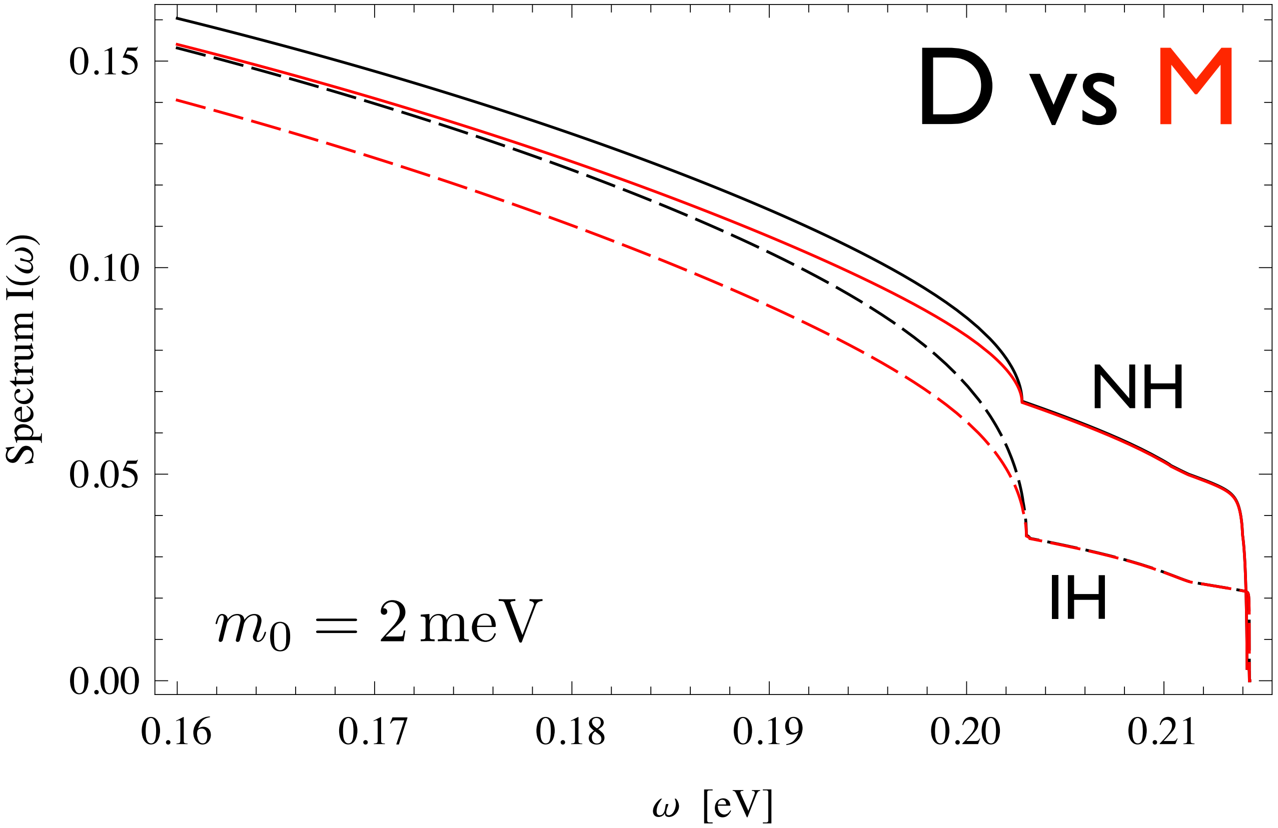
$$\mathcal{M}_W^{ij} = -\frac{G_F}{\sqrt{2}} \left(a_{ij} L_{ij}^\mu - \delta_M a_{ji} R_{ij}^\mu \right) J_{A\mu}$$

$$L_{ij}^\mu (R_{ij}^\mu) = \bar{u}_i(p,\lambda)\gamma^\mu (1 \mp \gamma_5) v_j(p',\lambda')$$

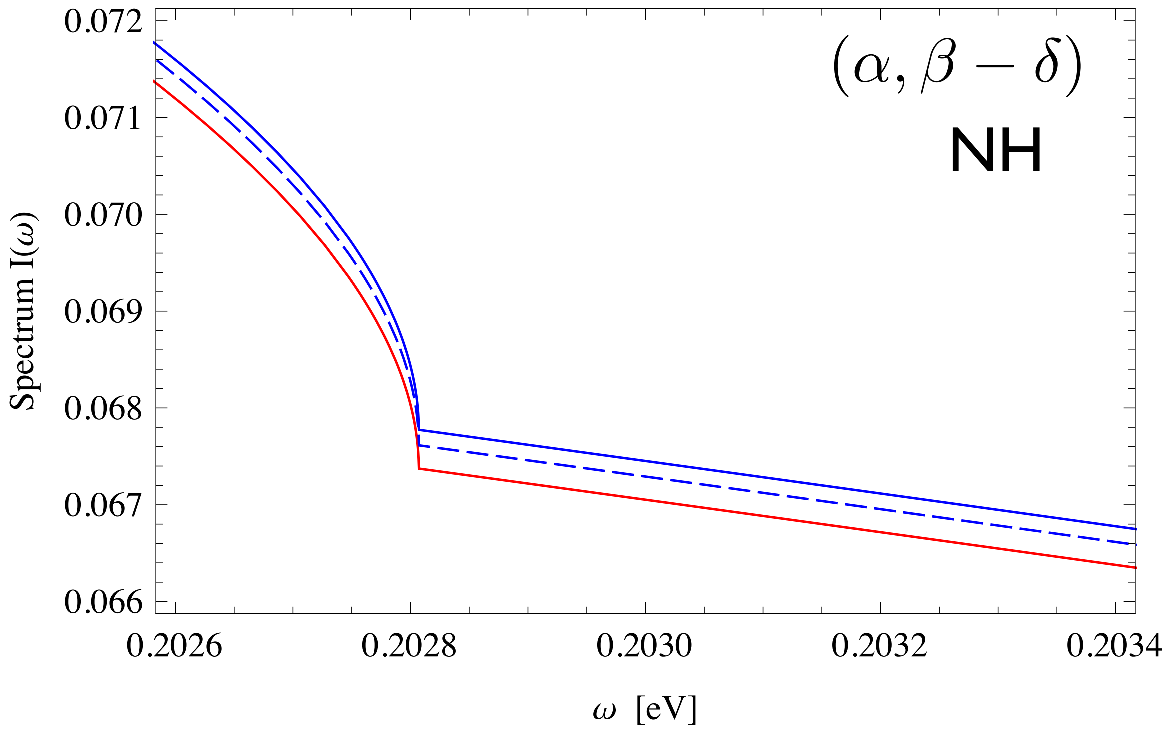
More on Dirac vs Majorana and CP phases

hypothetical atom

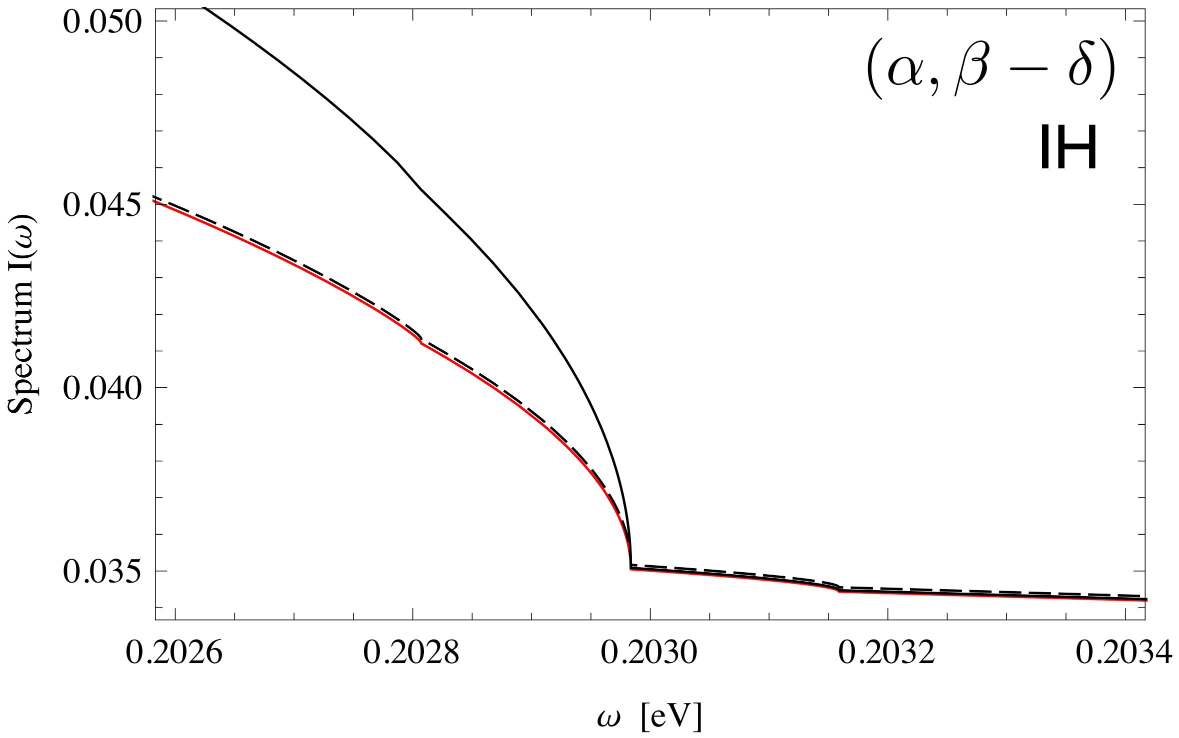
$$\epsilon_{eg} = 0.43\,\mathrm{eV}$$



CP phases (NH); Red=(0,0), Blue=(π/2,0), Blue Dashed=(0,π/2)



CP phases (IH); Red=(0,0), Black=(π/2,0), Black Dashed=(0,π/2)

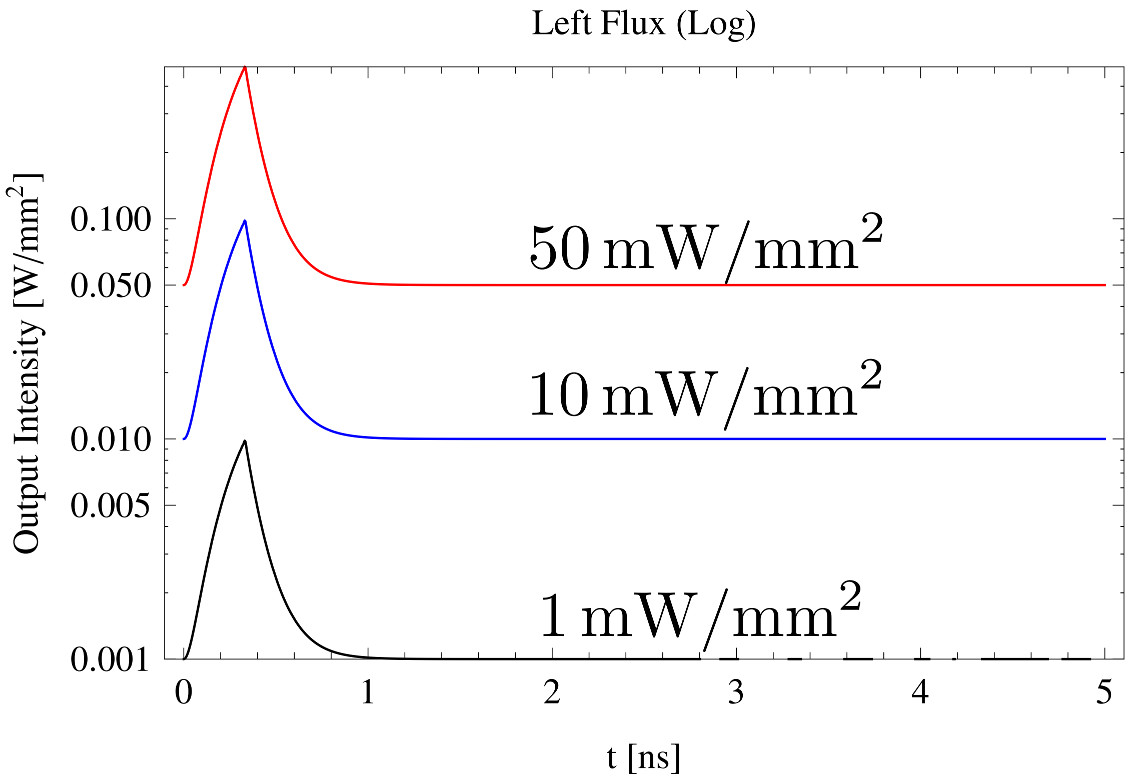


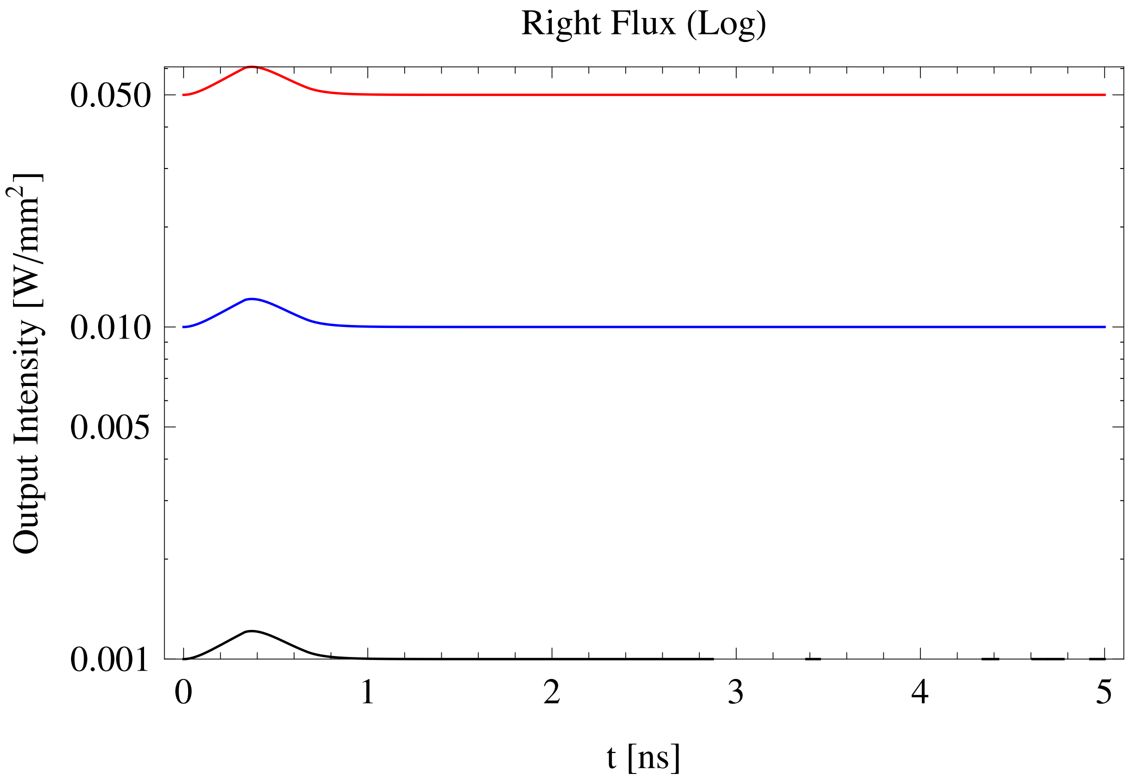
Linear Regime PSR

the expected first stage pH2 PSR experiment

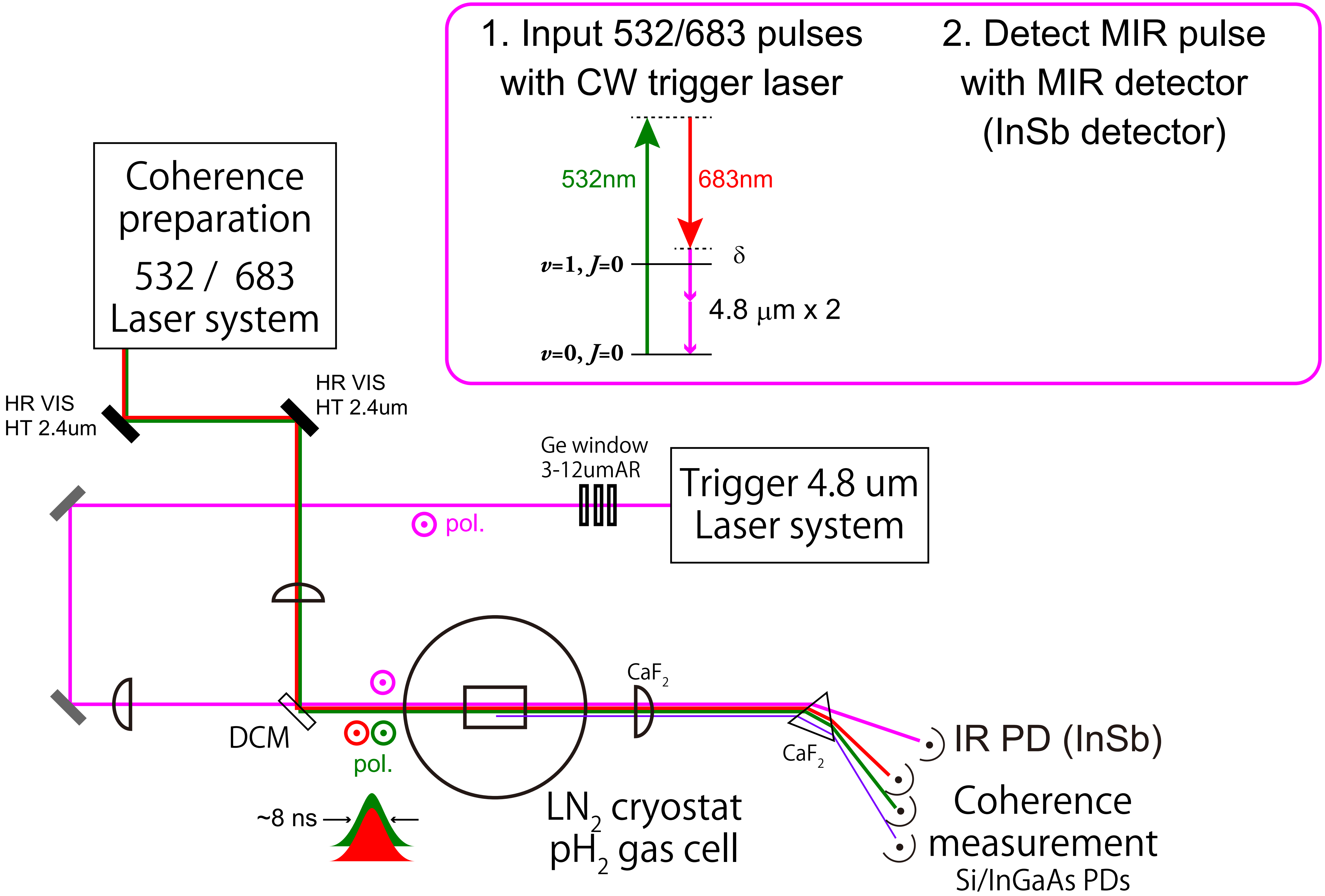
$$n = 8 \times 10^{20}\ [\mathrm{cm}^{-3}], \quad L = 10\ [\mathrm{cm}], \quad T_2 = T_3 = 0.2\ [\mathrm{ns}]$$

$$r_1^{(0)} = 0.1, \quad r_1^{(+)} = 0.9$$





Experimental Setup Overview



1. Input 532/683 pulses with CW trigger laser

2. Detect MIR pulse with MIR detector (InSb detector)

532nm

683nm

v=1, J=0

δ

4.8 μm x 2

v=0, J=0

Coherence preparation 532 / 683 Laser system

HR VIS HT 2.4um

HR VIS HT 2.4um

Ge window 3-12umAR

Trigger 4.8 um Laser system

pol.

DCM

pol.

~8 ns

CaF_2

CaF_2

LN_2 cryostat pH_2 gas cell

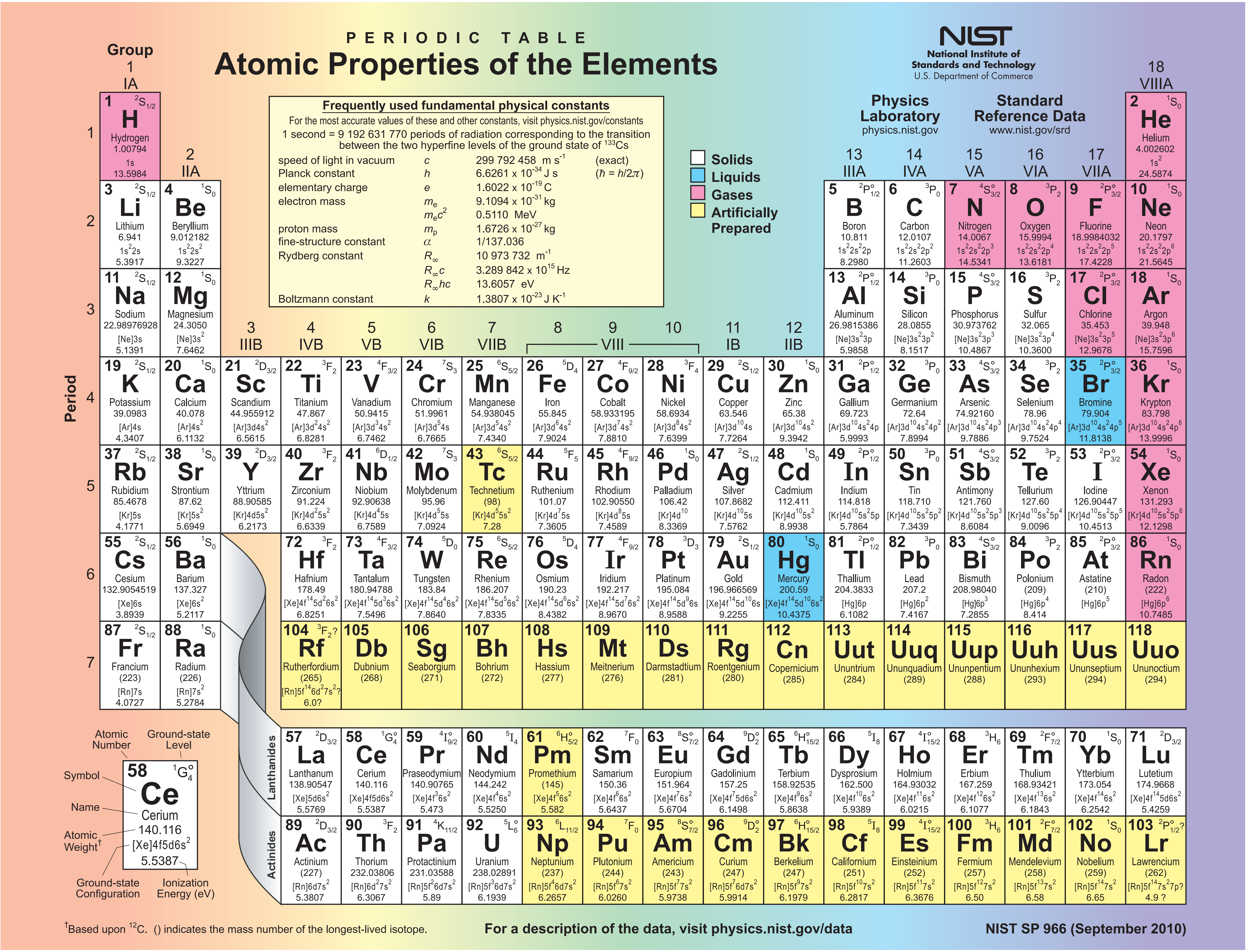
IR PD (InSb)

Coherence measurement

Si/InGaAs PDs

27 Dec. 2012, X00 meeting

S. Uetake



PERIODIC TABLE

Atomic Properties of the Elements

National Institute of Standards and Technology
U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261 x 10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022 x 10^{-19} C	
electron mass	m_e	9.1094 x 10^{-31} kg	
	m_ec^2	0.5110 MeV	
proton mass	m_p	1.6726 x 10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	3.289 842 x 10^{15} Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807 x 10^{-23} J K^{-1}	

- ☐ **Solids**
- 🟦 **Liquids**
- 🟥 **Gases**
- 🟨 **Artificially Prepared**

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	**1** $^2S_{1/2}$ **H** Hydrogen 1.00794 $1s$ 13.5984																	**2** $^1S_0$ **He** Helium 4.002602 $1s^2$ 24.5874
2	**3** $^2S_{1/2}$ **Li** Lithium 6.941 $1s^22s$ 5.3917	**4** $^1S_0$ **Be** Beryllium 9.012182 $1s^22s^2$ 9.3227											**5** $^2P^\circ_{1/2}$ **B** Boron 10.811 $1s^22s^22p$ 8.2980	**6** $^3P_0$ **C** Carbon 12.0107 $1s^22s^22p^2$ 11.2603	**7** $^4S^\circ_{3/2}$ **N** Nitrogen 14.0067 $1s^22s^22p^3$ 14.5341	**8** $^3P_2$ **O** Oxygen 15.9994 $1s^22s^22p^4$ 13.6181	**9** $^2P^\circ_{3/2}$ **F** Fluorine 18.9984032 $1s^22s^22p^5$ 17.4228	**10** $^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 21.5645
3	**11** $^2S_{1/2}$ **Na** Sodium 22.98976928 $[Ne]3s$ 5.1391	**12** $^1S_0$ **Mg** Magnesium 24.3050 $[Ne]3s^2$ 7.6462											**13** $^2P^\circ_{1/2}$ **Al** Aluminum 26.9815386 $[Ne]3s^23p$ 5.9858	**14** $^3P_0$ **Si** Silicon 28.0855 $[Ne]3s^23p^2$ 8.1517	**15** $^4S^\circ_{3/2}$ **P** Phosphorus 30.973762 $[Ne]3s^23p^3$ 10.4867	**16** $^3P_2$ **S** Sulfur 32.065 $[Ne]3s^23p^4$ 10.3600	**17** $^2P^\circ_{3/2}$ **Cl** Chlorine 35.453 $[Ne]3s^23p^5$ 12.9676	**18** $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^23p^6$ 15.7596
4	**19** $^2S_{1/2}$ **K** Potassium 39.0983 $[Ar]4s$ 4.3407	**20** $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	**21** $^2D_{3/2}$ **Sc** Scandium 44.955912 $[Ar]3d4s^2$ 6.5615	**22** $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	**23** $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	**24** $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^54s$ 6.7665	**25** $^6S_{5/2}$ **Mn** Manganese 54.938045 $[Ar]3d^54s^2$ 7.4340	**26** $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9024	**27** $^4F_{9/2}$ **Co** Cobalt 58.933195 $[Ar]3d^74s^2$ 7.8810	**28** $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^84s^2$ 7.6399	**29** $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	**30** $^1S_0$ **Zn** Zinc 65.38 $[Ar]3d^{10}4s^2$ 9.3942	**31** $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	**32** $^3P_0$ **Ge** Germanium 72.64 $[Ar]3d^{10}4s^24p^2$ 7.8994	**33** $^4S^\circ_{3/2}$ **As** Arsenic 74.92160 $[Ar]3d^{10}4s^24p^3$ 9.7886	**34** $^3P_2$ **Se** Selenium 78.96 $[Ar]3d^{10}4s^24p^4$ 9.7524	**35** $^2P^\circ_{3/2}$ **Br** Bromine 79.904 $[Ar]3d^{10}4s^24p^5$ 11.8138	**36** $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	**37** $^2S_{1/2}$ **Rb** Rubidium 85.4678 $[Kr]5s$ 4.1771	**38** $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	**39** $^2D_{3/2}$ **Y** Yttrium 88.90585 $[Kr]4d5s^2$ 6.2173	**40** $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^25s^2$ 6.6339	**41** $^6D_{1/2}$ **Nb** Niobium 92.90638 $[Kr]4d^45s$ 6.7589	**42** $^7S_3$ **Mo** Molybdenum 95.96 $[Kr]4d^55s$ 7.0924	**43** $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^55s^2$ 7.28	**44** $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	**45** $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^85s$ 7.4589	**46** $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	**47** $^2S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	**48** $^1S_0$ **Cd** Cadmium 112.411 $[Kr]4d^{10}5s^2$ 8.9938	**49** $^2P^\circ_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	**50** $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	**51** $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	**52** $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0096	**53** $^2P^\circ_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	**54** $^1S_0$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	**55** $^2S_{1/2}$ **Cs** Cesium 132.9054519 $[Xe]6s$ 3.8939	**56** $^1S_0$ **Ba** Barium 137.327 $[Xe]6s^2$ 5.2117		**72** $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	**73** $^4F_{3/2}$ **Ta** Tantalum 180.94788 $[Xe]4f^{14}5d^36s^2$ 7.5496	**74** $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	**75** $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	**76** $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	**77** $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	**78** $^3D_3$ **Pt** Platinum 195.084 $[Xe]4f^{14}5d^96s$ 8.9588	**79** $^2S_{1/2}$ **Au** Gold 196.966569 $[Xe]4f^{14}5d^{10}6s$ 9.2255	**80** $^1S_0$ **Hg** Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	**81** $^2P^\circ_{1/2}$ **Tl** Thallium 204.3833 $[Hg]6p$ 6.1082	**82** $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	**83** $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98040 $[Hg]6p^3$ 7.2855	**84** $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.414	**85** $^2P^\circ_{3/2}$ **At** Astatine (210) $[Hg]6p^5$	**86** $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	**87** $^2S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	**88** $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		**104** $^3F_2$? **Rf** Rutherfordium (265) $[Rn]5f^{14}6d^27s^2$? 6.0?	**105** **Db** Dubnium (268)	**106** **Sg** Seaborgium (271)	**107** **Bh** Bohrium (272)	**108** **Hs** Hassium (277)	**109** **Mt** Meitnerium (276)	**110** **Ds** Darmstadtium (281)	**111** **Rg** Roentgenium (280)	**112** **Cn** Copernicium (285)	**113** **Uut** Ununtrium (284)	**114** **Uuq** Ununquadium (289)	**115** **Uup** Ununpentium (288)	**116** **Uuh** Ununhexium (293)	**117** **Uus** Ununseptium (294)	**118** **Uuo** Ununoctium (294)

Lanthanides	**57** $^2D_{3/2}$ **La** Lanthanum 138.90547 $[Xe]5d6s^2$ 5.5769	**58** $^1G^\circ_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	**59** $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.90765 $[Xe]4f^36s^2$ 5.473	**60** $^5I_4$ **Nd** Neodymium 144.242 $[Xe]4f^46s^2$ 5.5250	**61** $^6H^\circ_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	**62** $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	**63** $^8S^\circ_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	**64** $^9D^\circ_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	**65** $^6H^\circ_{15/2}$ **Tb** Terbium 158.92535 $[Xe]4f^96s^2$ 5.8638	**66** $^5I_8$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9389	**67** $^4I^\circ_{15/2}$ **Ho** Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215	**68** $^3H_6$ **Er** Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	**69** $^2F^\circ_{7/2}$ **Tm** Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843	**70** $^1S_0$ **Yb** Ytterbium 173.054 $[Xe]4f^{14}6s^2$ 6.2542	**71** $^2D_{3/2}$ **Lu** Lutetium 174.9668 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	**89** $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.3807	**90** $^3F_2$ **Th** Thorium 232.03806 $[Rn]6d^27s^2$ 6.3067	**91** $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	**92** $^5L^\circ_6$ **U** Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1939	**93** $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2657	**94** $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0260	**95** $^8S^\circ_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	**96** $^9D^\circ_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	**97** $^6H^\circ_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1979	**98** $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	**99** $^4I^\circ_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.3676	**100** $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	**101** $^2F^\circ_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	**102** $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	**103** $^2P^\circ_{1/2}$? **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$? 4.9 ?

Atomic Number	58
Ground-state Level	$^1G^\circ_4$
Symbol	**Ce**
Name	Cerium
Atomic Weight[†]	140.116
Ground-state Configuration	$[Xe]4f5d6s^2$
Ionization Energy (eV)	5.5387

[†] Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2010)