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Towards neutrino mass spectroscopy and relic detection using atomic targets; theoretical aspects

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Towards neutrino mass spectroscopy and relic detection using atomic targets: theoretical aspects

- Introduction:

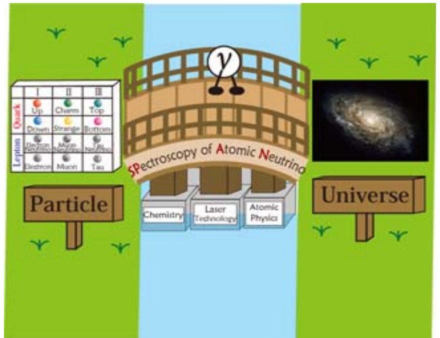
  merits and demerits using atoms
- SPAN (Spectroscopy of atomic neutrino)

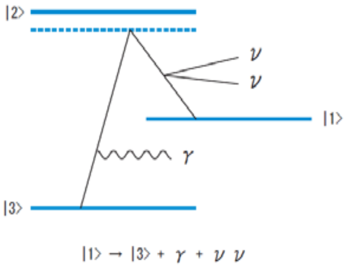
  new systematic experimental method for resolving remaining important questions

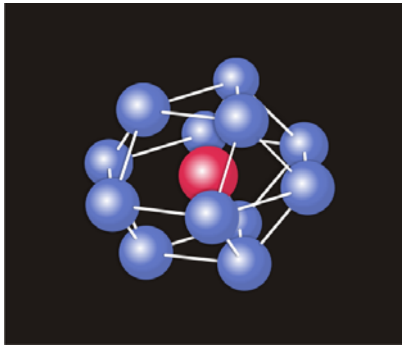
▪Macro-coherence; N^2 enhancement in macro region

▪ Photon spectrum, angular asymmetry, circular polarization in RNPE

- Future towards relic detection

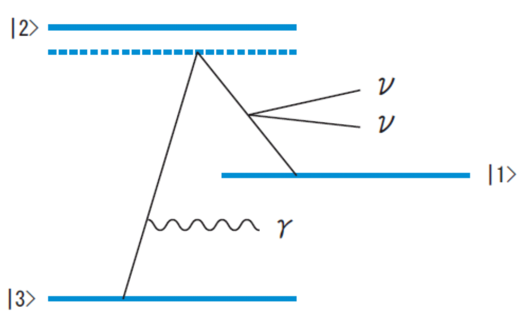






Radiative neutrino pair emission (RNPE)

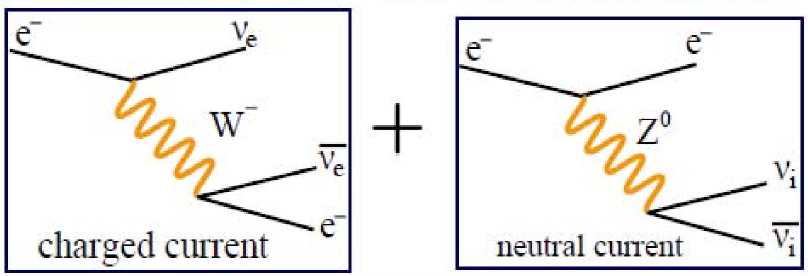
- 2^{nd} order electroweak process, 1^{st} orders in weak and QED. No question about existence of process, but yet to be discovered.



$|1\rangle \to |3\rangle + \gamma + \nu\ \nu$

Initial state metastable > 100 msec
Prepared by > 2 lasers

Neutrino interaction with atomic electron



4 Fermi interaction (after Fierz transformation)

Creation of atomic e

Annihilation of atomic e

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} \bar{\nu}^e \gamma_\alpha (1-\gamma_5) \nu^e \bar{e} \gamma^\alpha (1-\gamma_5) e$$
$$- \frac{G_F}{2\sqrt{2}} \sum_i \bar{\nu}^i \gamma_\alpha (1-\gamma_5) \nu^i \bar{e} (\gamma^\alpha (1 - 4\sin^2\theta_W - \gamma_5)) e$$

where $\nu_e = \sum_i U_{ei} \nu_i$ $\quad U_{\alpha i} =$ MNS matrix elements

Merits and demerits of atomic process

- Infinitely many small energies are available

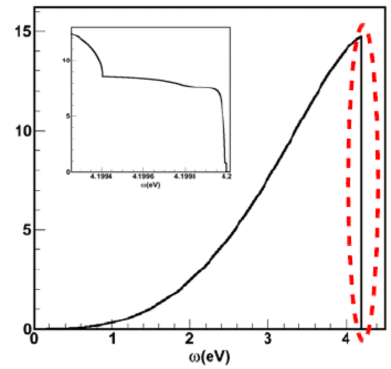
$$\Delta E_{n_1,n_2} \sim 13.6eV \times (\frac{1}{n_2^2} - \frac{1}{n_1^2})$$

- Small rate of neutrino pair emission

$$\frac{G_F^2 \Delta^5}{15\pi^3} \approx 3.3 \times 10^{-34} s^{-1} (\frac{\Delta}{eV})^5$$

- How to verify neutrino pair emission: 1 photon energy spectrum having 6 thresholds

$$\omega_{ij} = \Delta/2 - (m_i + m_j)^2/(2\Delta)$$



Xe

- How to enhance the rate is crucial

target coherence: O[10^4] N^2 expected

Significance of discovering Majorana neutrino

- Neutral fermions follow economic Majorana eq or the same Dirac eq as charged fermions ?

- Leading to lepton number violation and lepto-genesis

  particle = anti-particle

  missing partner for leptogenesis

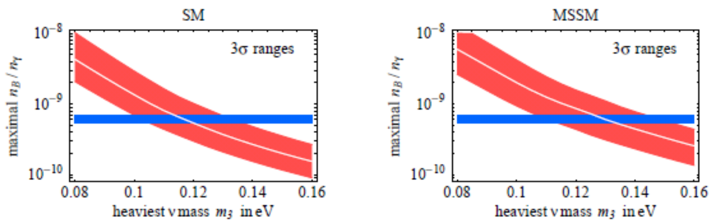


Figure 10: **Leptogenesis bound on neutrino masses**. *The plot shows the measured baryon asymmetry (horizontal line) compared with the maximal leptogenesis value as function of the heaviest neutrino mass m_3, renormalized at low energy. Error bars are at 3σ.*

- Contributing to better understanding of seesaw mechanism and GUT

$$m_\nu = \frac{m_{q,l}^{\ 2}}{M_{new\ physics}}$$

$$SO(10); \qquad \underline{16}\,,$$

$$\begin{pmatrix} u_R & u_G & u_B & \nu \\ d_R & d_G & d_B & e \end{pmatrix}_L + \begin{pmatrix} \overline{u_R} & \overline{u_G} & \overline{u_B} & \overline{N} \\ \overline{d_R} & \overline{d_G} & \overline{d_B} & \overline{e} \end{pmatrix}_L$$

M vs D in 2-component equations

In terms of 2-spinor of Lorentz group

$$(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla})\varphi = im\sigma_2\varphi^*$$

$$(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla})\varphi = m\chi$$
$$(i\partial_t + i\vec{\sigma}\cdot\vec{\nabla})\chi = m\varphi$$

Majorana vs Dirac equations: chirally projected solutions

$$(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla})\varphi = im\sigma_2\varphi^*$$

$$\varphi_{\vec{p},h}(x) = c(\vec{p},h)e^{-ip\cdot x}u(\vec{p},h) + c^\dagger(\vec{p},-h)e^{ip\cdot x}\sqrt{\frac{E_p + hp}{E_p - hp}}(-i\sigma_2)u^*(\vec{p},h)$$

$$u(\vec{p},h) = \frac{1}{2}\sqrt{\frac{E_p - hp}{pE_p(p+hp_3)}}\begin{pmatrix} p + hp_3 \\ h(p_1 + ip_2) \end{pmatrix}$$

$$(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla})\varphi = m\chi\,, \quad (i\partial_t + i\vec{\sigma}\cdot\vec{\nabla})\chi = m\varphi$$

$$\psi_D = \frac{1}{2}(1-\gamma_5)\psi$$

$$\psi_D = b(\vec{p},h)e^{-ip\cdot x}u(\vec{p},h) + d^\dagger(\vec{p},-h)e^{ip\cdot x}\sqrt{\frac{E_p + hp}{E_p - hp}}(-i\sigma_2)u^*(\vec{p},h)$$

Unique signature of Majorana = interference of identical fermions

$$\sum_{h_1 h_2} |j_M \cdot j^e|^2 = \sum_{h_1 h_2} |j_D \cdot j^e|^2 + \delta_{ij} \frac{m_i m_j}{2E_1 E_2} \left(j_0^e (j_0^e)^\dagger - \vec{j}^e \cdot (\vec{j}^e)^\dagger \right)$$

- Effective only for pair emission
- Appear only (ii) threshold; proportional to m_i^2

  $(\nu_i \nu_j)$ $i \neq j$ pair
- Can be positive or negative
- Direct test of Majorana nature cf LV in $(0\nu)\beta\beta$

Dependence and sensitivity on Majorana phases

Matrix element for two neutrino emission of definite mass species $\nu_i \nu_j$, momentum p_1, p_2 and helicity h_1, h_2,

$$\langle (ip_1 h_1 \,, jp_2 h_2)|j_\nu|0\rangle = \xi_i^* \xi_j e^{i(p_1+p_2)\cdot x} v_1^\dagger \sigma u_2 - \xi_i \xi_j^* e^{i(p_1+p_2)\cdot x} v_2^\dagger \sigma u_1$$
$$= e^{i(p_1+p_2)\cdot x} \Big(i\Im \xi_i^* \xi_j (v_1^\dagger \sigma u_2 + v_2^\dagger \sigma u_1) + \Re \xi_i^* \xi_j (v_1^\dagger \sigma u_2 - v_2^\dagger \sigma u_1) \Big)$$
$$\xi_i^* \xi_j = U_{ei}^* U_{ej} = c_{ij}^{(0)} \,, \quad U_{e1} = c_{12} c_{13} \,, \; U_{e2} = s_{12} c_{13} e^{i\alpha} \,, \; U_{e3} = s_{13} e^{i\beta}$$

using the standard mass matrix parametrization.

The neutrino current product becomes

$$\langle (ip_1 h_2 \,, jp_2 h_2)|j_\nu^\alpha|0\rangle \langle 0|j_\nu^\beta|(ip_1 h_2 \,, jp_2 h_2)\rangle$$
$$= 2|\Im c_{ij}^{(0)}|^2 (v_1^\dagger \sigma^\alpha u_2 + v_2^\dagger \sigma^\alpha u_1) u_2^\dagger \sigma^\beta v_1 + 2|\Re c_{ij}^{(0)}|^2 (v_1^\dagger \sigma^\alpha u_2 - v_2^\dagger \sigma^\alpha u_1) u_2^\dagger \sigma^\beta v_1$$
$$-\Im c_{ij}^{(0)} \Re c_{ij}^{(0)} \Im \Big((v_1^\dagger \sigma^\alpha u_2 + v_2^\dagger \sigma^\alpha u_1) u_2^\dagger \sigma^\beta v_1 - (1 \leftrightarrow 2) \Big) + (\text{c.c})$$

(symmetry property under $1 \leftrightarrow 2$ is used)

Dropping CP-odd terms, 1st term is common in Dirac and Majorana cases, while 2nd ia Majorana interference term;

$$|c_{ij}^{(0)}|^2 (v_1^\dagger \sigma^\alpha u_2 u_2^\dagger \sigma^\beta v_1 + (1 \leftrightarrow 2)\,) \,, \quad (\text{common})$$
$$+(|\Im c_{ij}^{(0)}|^2 - |\Re c_{ij}^{(0)}|^2)(v_2^\dagger \sigma^\alpha u_1 u_2^\dagger \sigma^\beta v_1 + (1 \leftrightarrow 2)\,) \,, \quad (\text{Majorana interference})$$

Cancellation of leading CP-odd terms

The most important term for CP-odd quantities comes from GT terms squared, the last term. When multiplied by the coupling factor $2i\Im c_{ij}^{(0)}\Re c_{ij}^{(0)}$ which contains odd terms of Majorana phases,

$$
\begin{aligned}
&\Im c_{ij}^{(0)}\Re c_{ij}^{(0)} = \\
&c_{12}^2 s_{12}^2 c_{13}^4 \sin\alpha\cos\alpha\,, \text{ for } (ij)=(12) \\
&c_{12}^2 s_{13}^2 c_{13}^2 \sin\beta\cos\beta\,, \text{ for } (ij)=(13) \\
&s_{12}^2 s_{13}^2 c_{13}^2 \sin(\alpha-\beta)\cos(\alpha-\beta)\,, \text{ for } (ij)=(23)
\end{aligned}
$$

at three thresholds, it gives rise to T-reversal non-invariant pieces. Other terms such as $|\Im c_{ij}^{(0)}|^2$ are even in Majorana phases.

With neutrino helicity summation,

$$
\sum_h v_1^\dagger \sigma^k u_2 u_2^\dagger \sigma^l v_1 =
$$

$$
-\delta_{kl}\frac{1}{2}(1-\frac{\vec{p}_1\cdot\vec{p}_2}{E_1E_2}) - \frac{p_{1k}p_{2l}+p_{1l}p_{2k}}{2E_1E_2} - \frac{i}{2}\epsilon_{klm}(\frac{\vec{p}_1}{E_1}-\frac{\vec{p}_2}{E_2})_m
$$

$$
\sum_h v_2^\dagger \sigma^k u_1 u_2^\dagger \sigma^l v_1 = -\frac{m_i m_j}{2E_1E_2}\delta_{kl}
$$

$$
\sum_h v_1^\dagger \sigma^0 u_2 u_2^\dagger \sigma^k v_1 = \frac{1}{2}\left(i(\frac{(\vec{p}_1\times\vec{p}_2)_k}{E_1E_2}+(\frac{\vec{p}_1}{E_1}+\frac{\vec{p}_2}{E_2})_k\right)
$$

$$
\sum_h v_1^\dagger \sigma^k u_2 u_2^\dagger \sigma^0 v_1 = \frac{1}{2}\left(i\frac{(\vec{p}_1\times\vec{p}_2)_k}{E_1E_2}-(\frac{\vec{p}_1}{E_1}+\frac{\vec{p}_2}{E_2})_k\right)
$$

Cancellation of leading CP-odd quantity due to

$$
\int dP_\nu(\frac{\vec{p}_1}{E_1}-\frac{\vec{p}_2}{E_2}) = -\frac{\vec{k}}{2}\int dP_\nu\left(\frac{E_1-E_2}{E_1E_2}\frac{\Delta(\Delta-2\omega)}{\omega^2}-\frac{m_1^2-m_2^2}{\omega^2}\frac{\Delta-\omega}{E_1E_2}\right)=0
$$

$$
dP_\nu = d^3p_1 d^3p_2\,\delta(\vec{k}+\vec{p}_1+\vec{p}_2)\delta(\Delta-\omega-E_1-E_2)
$$

Enhanced RNPE by macro-coherence

- Single photon SR: coherence region limited by wavelength^2 x linear size of excited region
- When many photons or photon+neutrino pair are involved, coherence region may become macroscopic, due to

$$\left|\sum_{i=1}^{N}\exp\left\{i\left(\vec{k}_1+\vec{k}_2\right)\cdot\vec{r}_i\right\}\right|^2 \Rightarrow N^2 \text{ if } \vec{k}_1+\vec{k}_2=0$$

1. Xe etc implanted in nano-space such as solid matrix
2. N encapsulated in fullerene
3. Pair annihilation in p-n junction

C_60

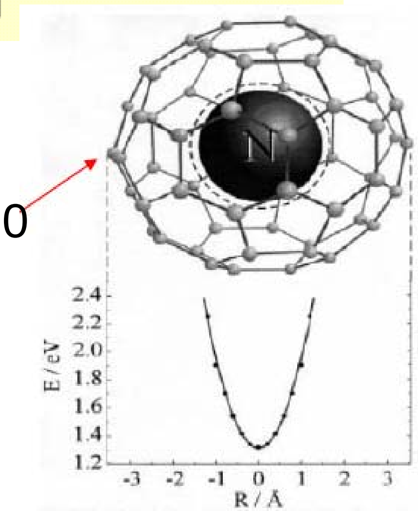
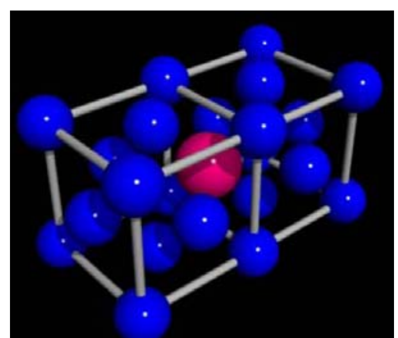


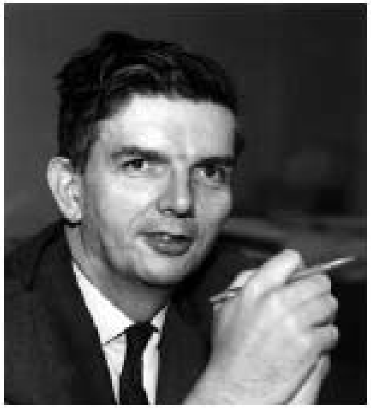
Fig. 6. Schematic view of nitrogen inside C_{60}. The size of the sphere corresponds to the van der Waals radius of nitrogen [12]. The dashed line marks the border of the inner cavity of the C_{60} shell if van der Waals radii are assumed for the carbon atoms [12]. In the lower part of the figure the calculated potential energy of nitrogen in C_{60} is shown as a function of the displacement from the center [4]. In the calculation, no relaxation of the cage atoms is assumed. The energy scale is relative to the energy of nitrogen at infinity

Energy, momentum both conserved, giving 6 pair threshold of photon energy

Rate ~ volume

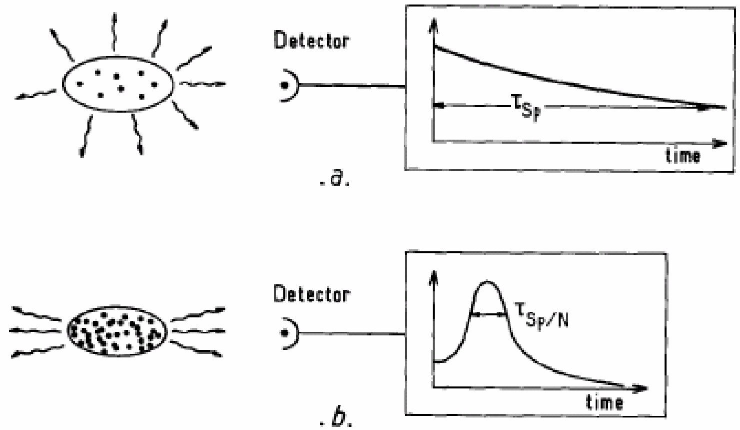


Superradiance: 2 level and 1 photon case



Bob Dicke

1916—1997



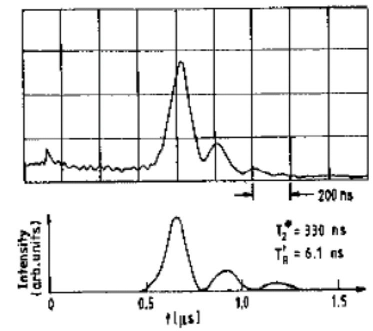
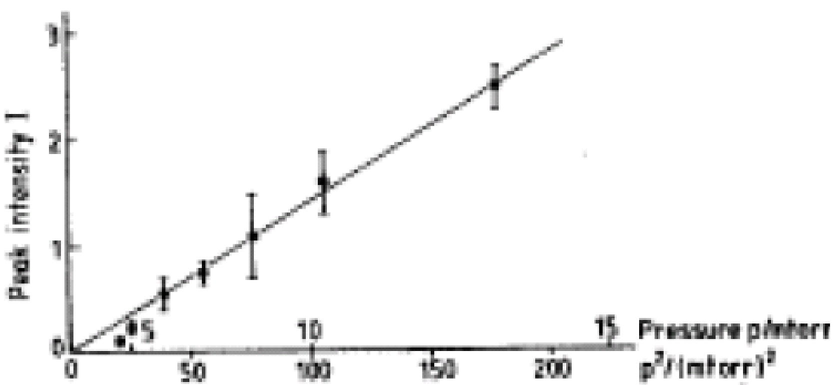
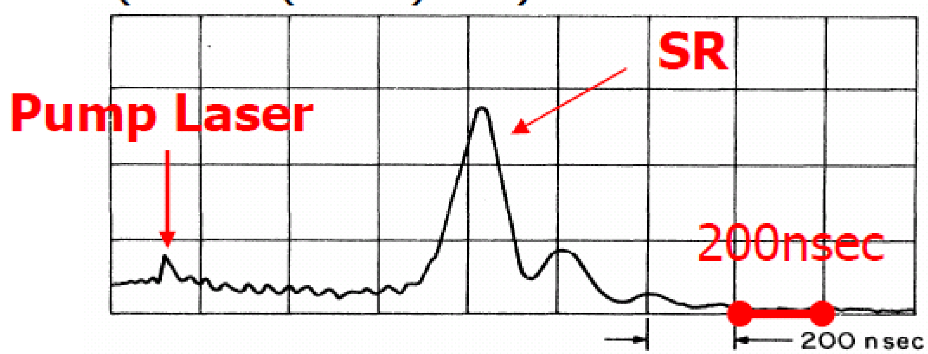


Figure 2.2. Oscilloscope trace of the super-radiance pulse observed by Skribanowitz *et al* [SHMF73] in HF gas at 84 μm ($J = 3 \rightarrow 2$), pumped by the $R_1(2)$ laser line, and the theoretical fit. The parameters are: pump intensity $I = 1$ kW cm^{-2}, $p = 1.3$ mTorr, $L = 100$ cm. The small peak on the oscilloscope trace at $t = 0$ is the 3 μm pump pulse, highly attenuated.



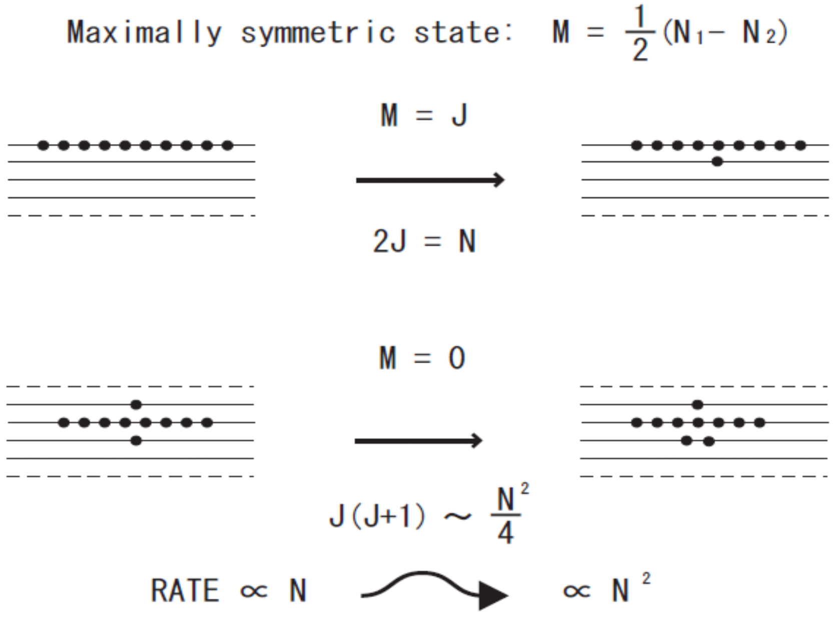
(PRL30(1973)309)



Rate enhanced by N

Delayed enhanced signal accompanied by ringing

Theoretical understanding

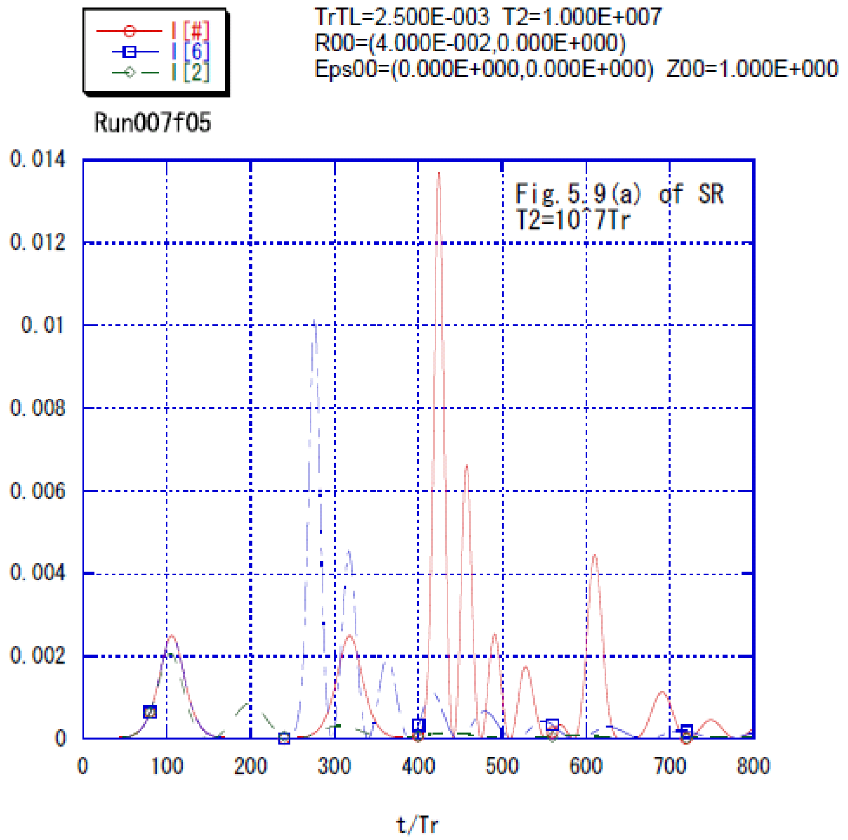


Maxwell-Bloch equation

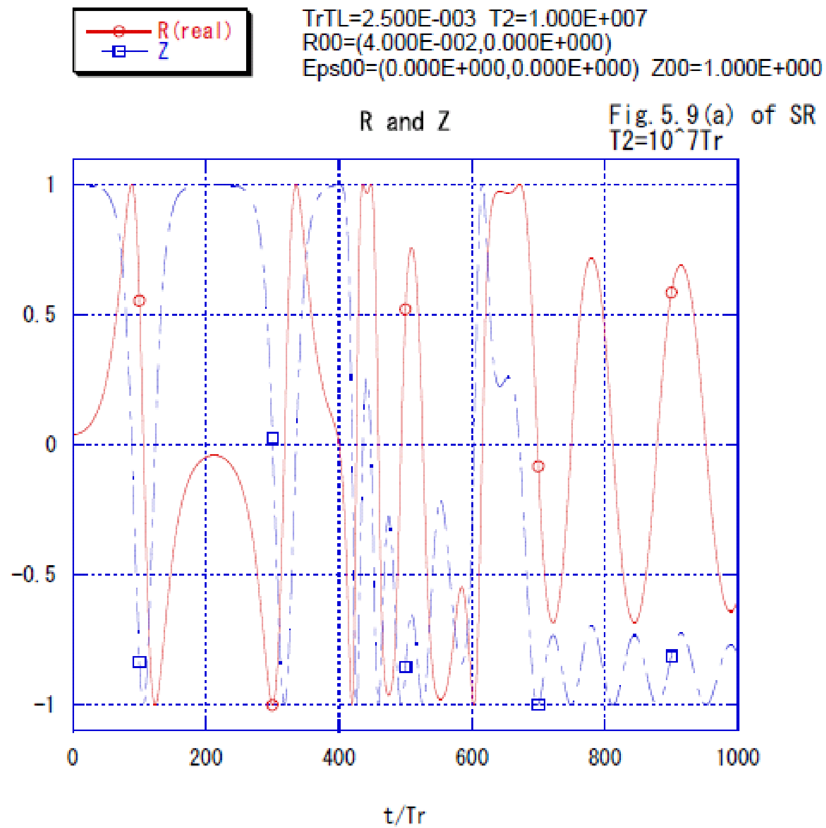
$$\frac{\partial \rho_{ee}}{\partial t} = \frac{id}{\hbar}\mathcal{E}(\rho_{ge} - \rho_{eg})$$
$$\frac{\partial \rho_{gg}}{\partial t} = -\frac{id}{\hbar}\mathcal{E}(\rho_{ge} - \rho_{eg})$$
$$\frac{\partial \rho_{eg}}{\partial t} = -i\omega_0 \rho_{eg} + \frac{id}{\hbar}\mathcal{E}(\rho_{gg} - \rho_{ee})$$
$$\frac{\partial^2 \mathcal{E}}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 \mathcal{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 \mathcal{P}}{\partial t^2}$$

Numerical solution of MB equations：1+1 dim.

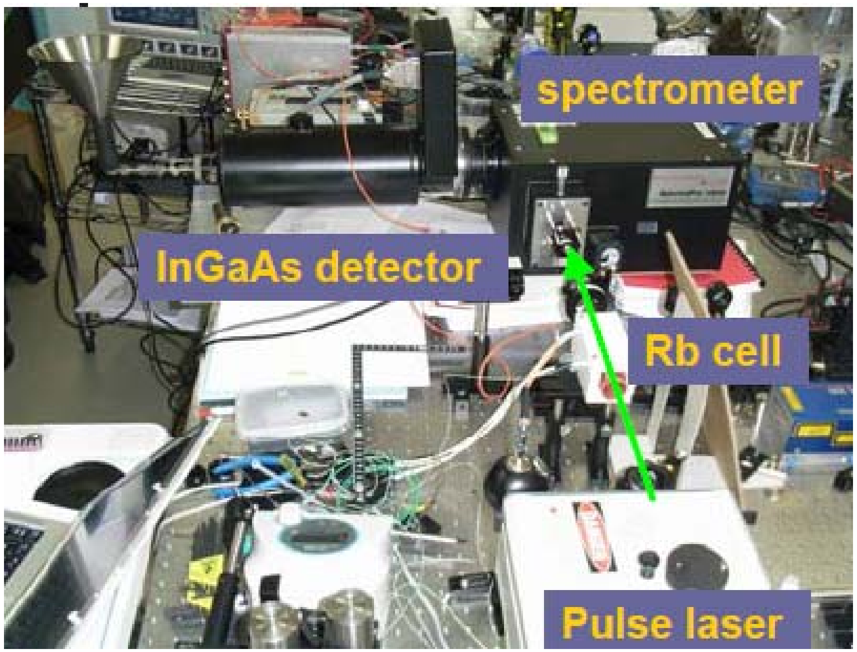
Field intensity at each location

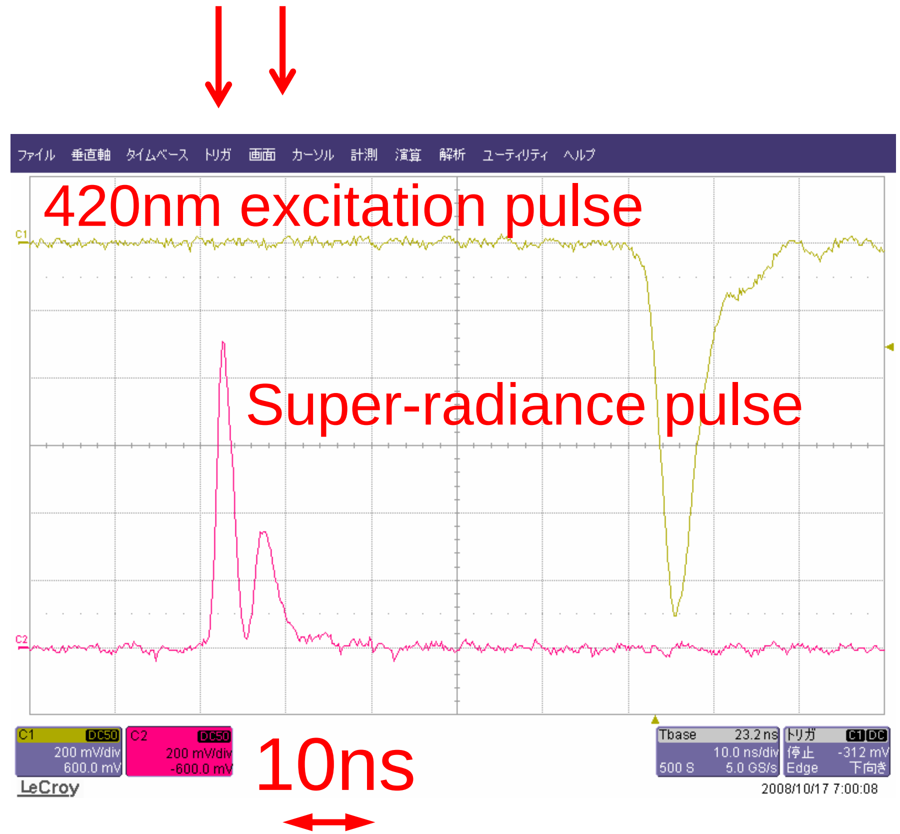


State occupancy and coherence

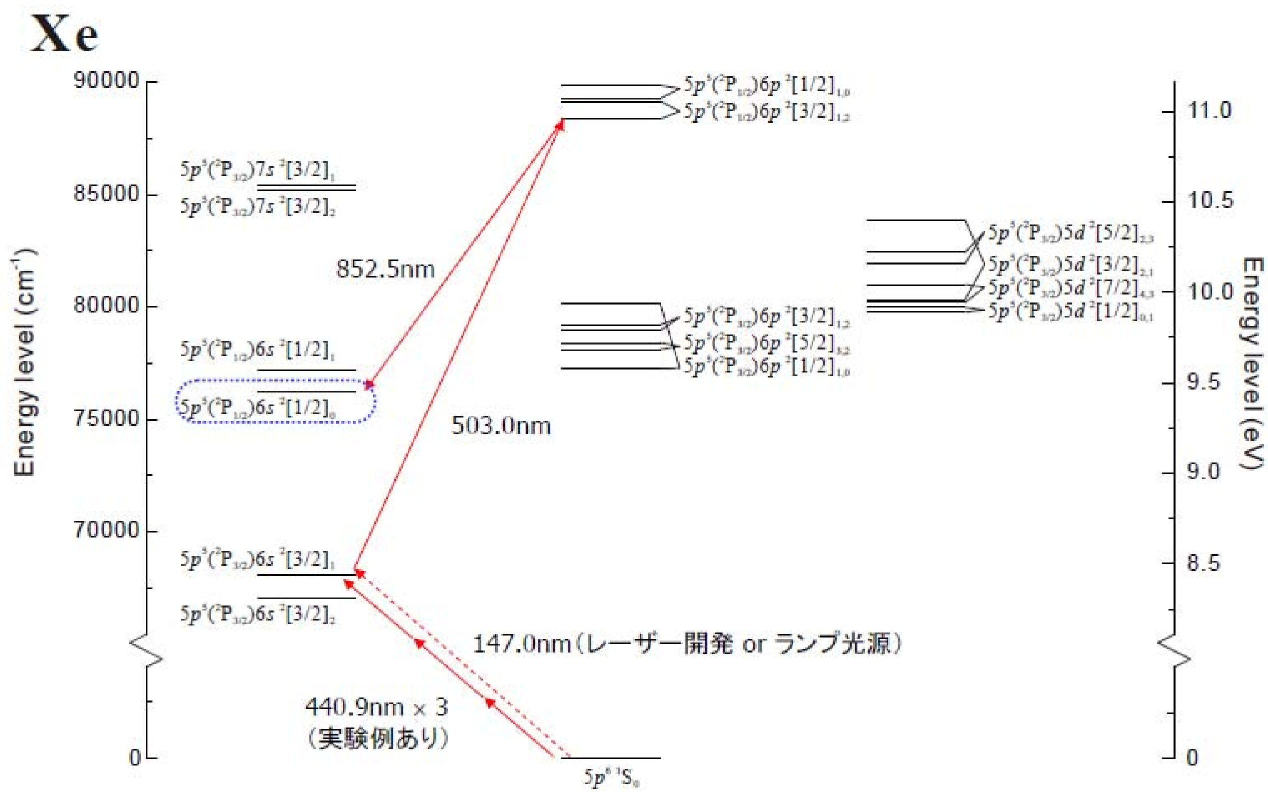


Our observation of SR in Rb gas





Target atom for RNPE of large rate



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

0.1 eV

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

rate scales like $\propto \Delta^6/\Delta_{ni}^2$

8.4 eV

$$|f\rangle_A = 5p^{6\,1}S_0$$

Rates and energy spectrum

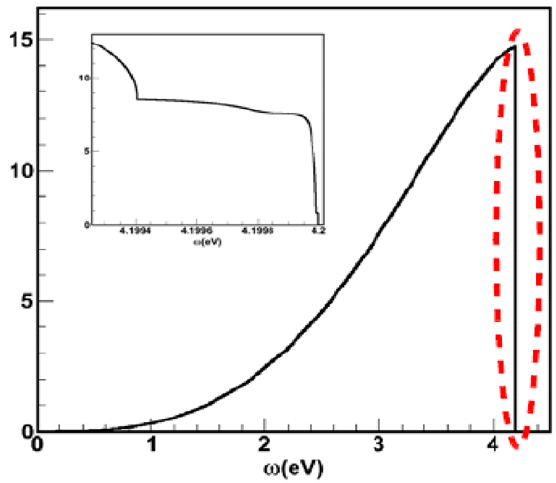
With soliton formation,

$$\Gamma = \frac{13\alpha G_F^2 \langle x\rangle^2 \Delta^4}{54\pi^2} nN \times O[10^4] \sim 6\times 10^{-4}\,\mathrm{Hz}\,(\frac{\Delta}{10\mathrm{eV}})^4(\frac{\langle x\rangle}{10^{-8}\mathrm{cm}})^2(\frac{n}{10^{22}\mathrm{cm}^{-3}})^2\frac{V}{\mathrm{cm}^3}$$

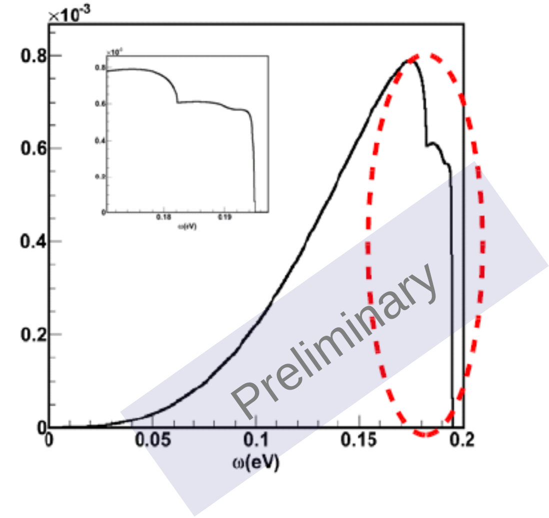
Xe implanted with a fraction 10^{-3} in 100 gr para-H_2 (lattice constant 3.8×10^{-8} cm) gives $nN = 1.1\times 10^{45}\mathrm{cm}^{-3}$, which then implies rate of $0.15\,\mathrm{Hz}$.

10^-4- 1 Hz for Xe including CG's

Fe-doped Si

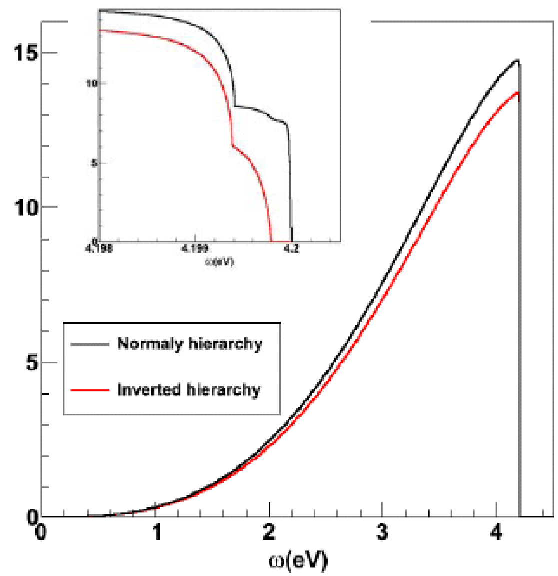


Xe



The closer of level energy to the neutrino mass sum, the better

Normal vs inverted hierarchy



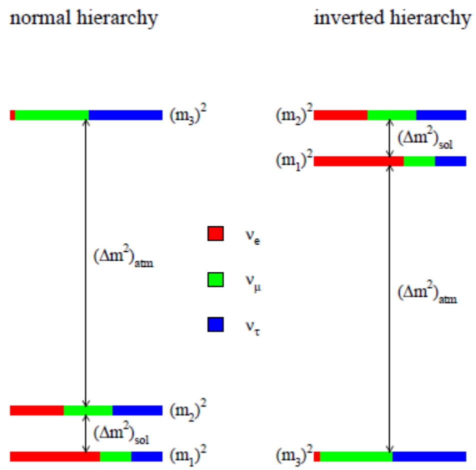


Figure 1: Assumed neutrino masses are 50, 10, 1 meV for the normal hierarchy, and 51, 50, 10 meV for the inverted hierarchy, with mixing angles, $\sin^2\theta_{12} = 0.3$, $\sin^2\theta_{13} = 0.039$, and $\eta = \pi/4$.

We can equally well investigate both.

Angle dependence

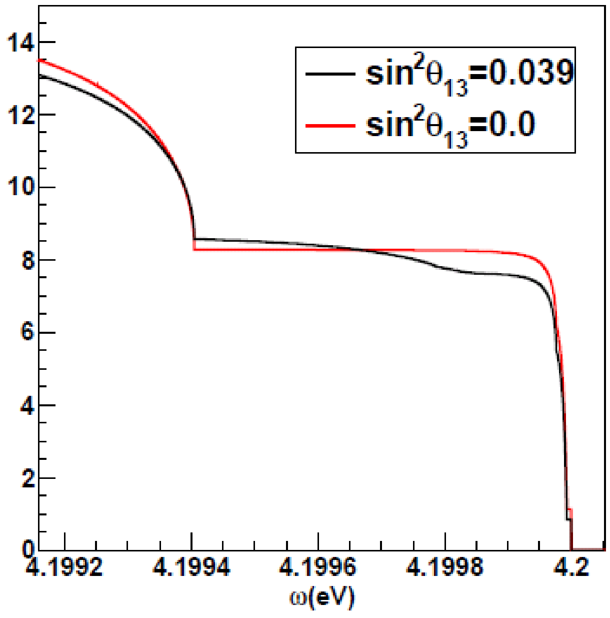
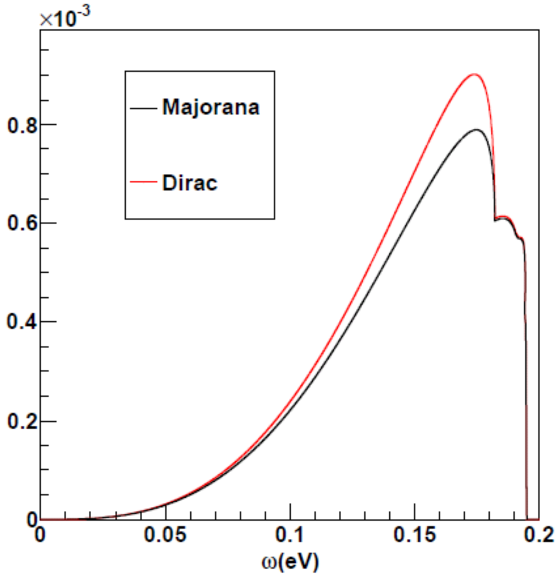


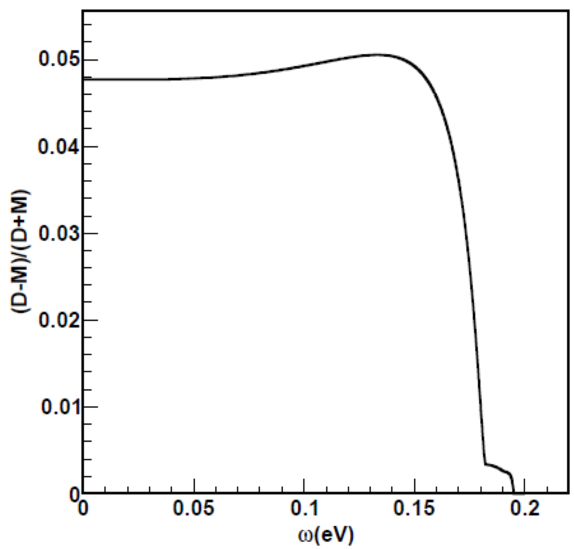
Figure 2: Xe spectral rate; θ_{13} dependence. Figure 1 expanded. Assumed neutrino masses are 1meV, 10 meV, 50meV, with mixing angles, $\sin^2\theta_{12} = 0.3$.

- (33) threshold insensitive to ¥theta_13

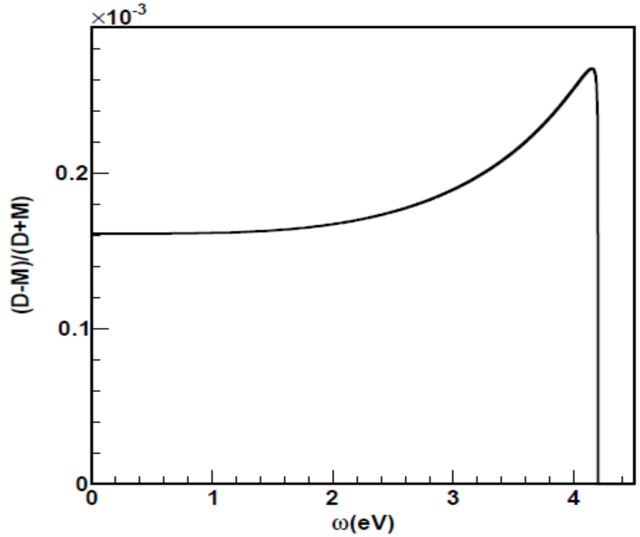
M/D distinction



Si-Fe



Si-Fe



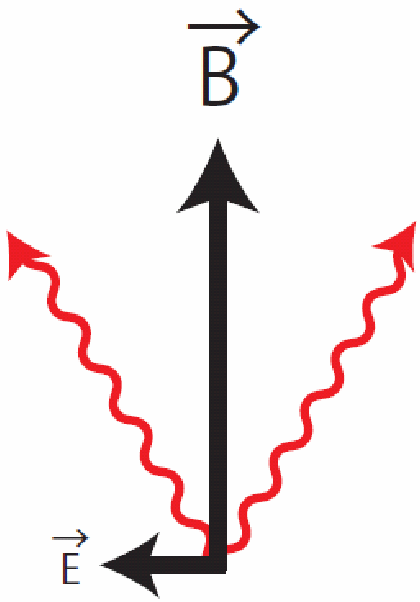
Xe

5% effect for atomic energy difference < 1 eV

Parity non-conservation: evidence for weak process

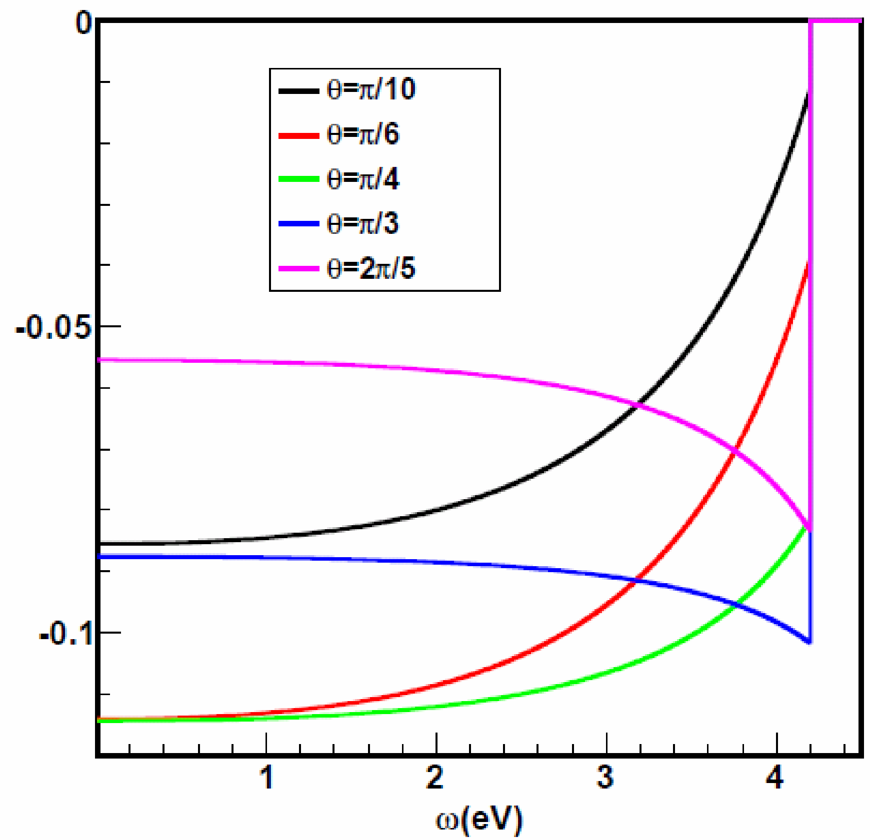
observables：

1. photon energy (with good resolution)
2. photon circular polarization

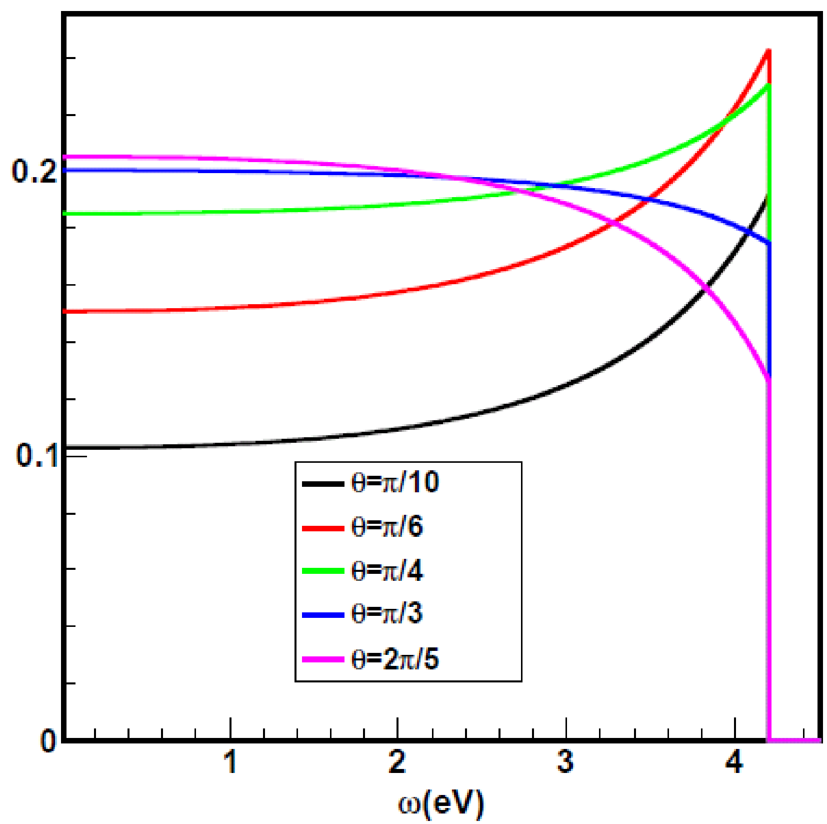


E-direction to be tilted from perpendicular direction

Angular asymmetry and circular polarization for Xe



Angular asymmetry



Circular polarization

1meV, 10 meV, 50meV, with mixing angles, $\sin^2\theta_{12} = 0.3$, $\sin^2\theta_{13} = 0.039$ in the normal hierarchy case

PV > 0.1 effect

Further enhancement and background rejection; Photonic soliton formation

- Topological objects classified by winding number, condensed field + atomic polarization
- Macro-coherence by 10^4 x N^2
- Suppress 2 gamma mode, but may lead to RNPE

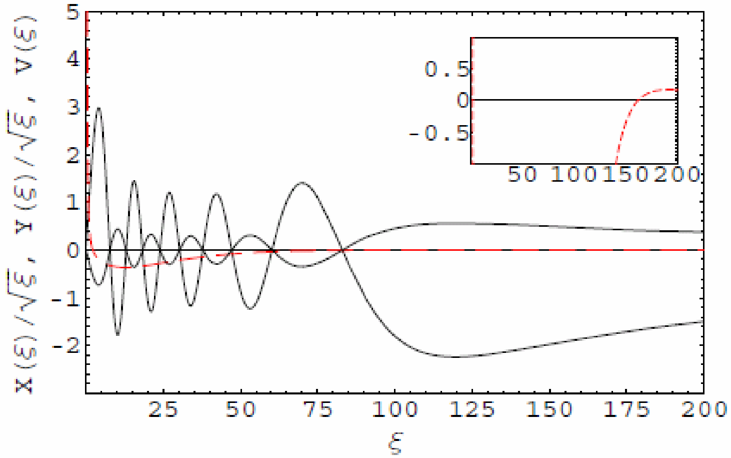
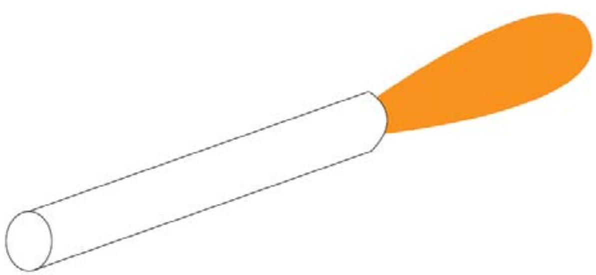
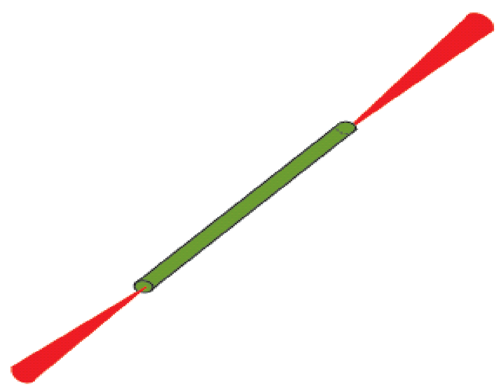


FIG. 1: Soliton profile. Stokes and pump fields (black) (assumed real) and the potential (dashed red) both in arbitrary units vs $\xi = \mathcal{M}\rho$ are shown for the refractive index $\nu = \sqrt{2}$, the field ratio at the origin $r(0) = -0.25$ (essentially fixed at all ξ), and $\xi_0 = 12.43\cdots$. The barrier region of the potential is expanded by 10^4 in the inset.





Summary: small scale particle physics experiments using atoms; new principles involved

- Decay from metastable atoms emitting neutrino pair

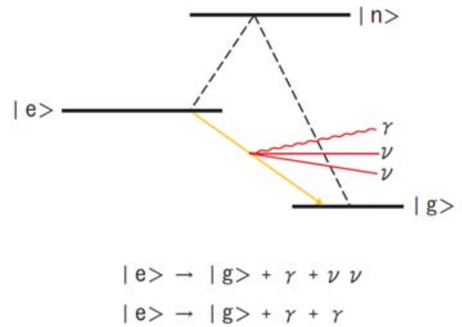
$$|e\rangle \rightarrow |g\rangle + \gamma + \nu_i \nu_j$$

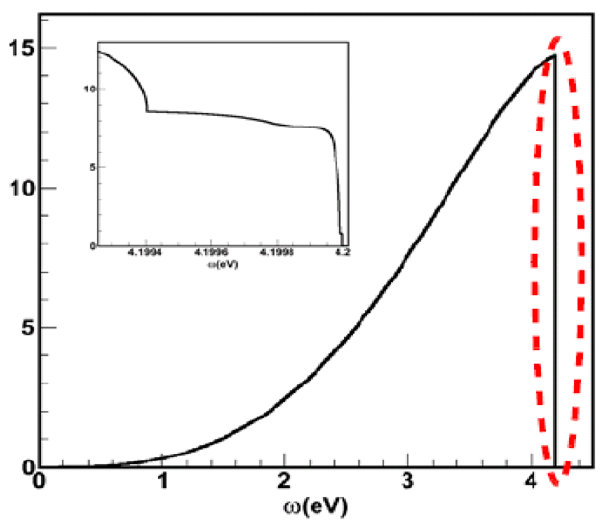
- Measurable quantities
  1. Photon energy spectrum
     6 threholds; mass and angle dependent

$$\theta_{13}$$

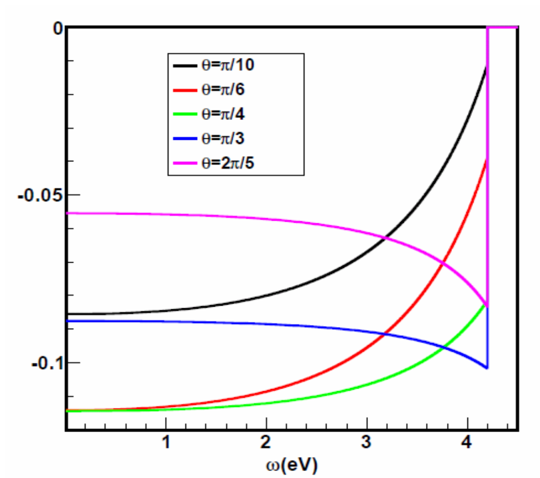
$$\omega_{ij} = \frac{\Delta}{2} - \frac{(m_i + m_j)^2}{2\Delta}$$

  2. Parity violation：
     angular asymmetry from oriented atoms
     circular polarization

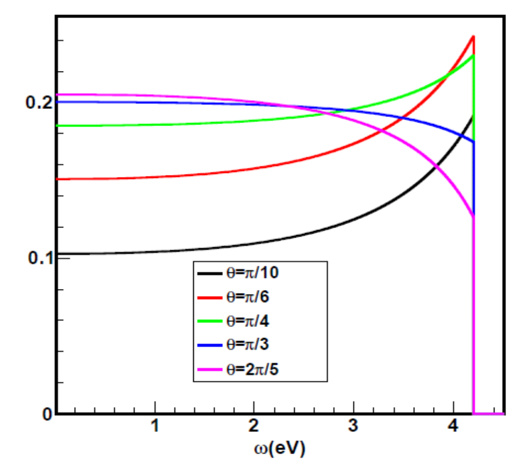




Xe



Angular asymmetry



Circular polarization

Observability of relic neutrino w. T. Takahashi

hep-ph/0703019

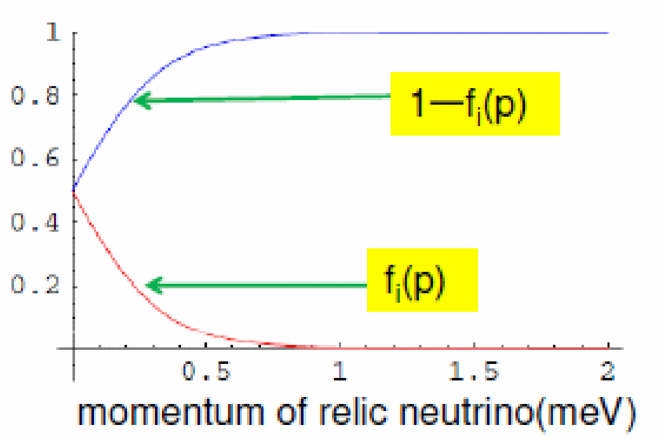
- Pauli blocking effect

$$\Gamma^M(\omega\,;T_\nu) = \frac{4G_F^2 F_0}{\pi\omega^2\Delta\omega}\frac{\gamma_r}{\gamma}\sum_{ij}\theta(\omega-\Delta_{fi}-m_i-m_j)\times$$

$$\int_{m_i}^{\omega-\Delta_{fi}-m_j} dE_1 I(E_1)\ \ (1-f_i(E_1))\left(1-f_j(\omega-\Delta_{fi}-E_1)\right)$$

$$I(E_1) = k_0^{ij}E_1(\omega-\Delta_{fi}-E_1)\sqrt{(E_1^2-m_i^2)\{(\omega-\Delta_{fi}-E_1)^2-m_j^2\}}$$

$$+k_M^{ij}\delta_{ij}m_im_j\sqrt{(E_1^2-m_i^2)\{(\omega-\Delta_{fi}-E_1)^2-m_j^2\}}$$



Distribution function near p=0

- **Relic neutrino distribution**

After the freeze-out at $\approx 1MeV$, neutrinos obey shifted thermal distribution with finite masses;

$$\left(\frac{\partial}{\partial t} - \frac{\dot{a}}{a} p \frac{\partial}{\partial p}\right) f(\vec{p}) = 0$$

$$f(\vec{p}) = \frac{1}{e^{\sqrt{\vec{p}^2 + (m/(z+1))^2}/T_0} + 1}\,, \quad z + 1 = \frac{T_d}{T_0}$$

$$k_B T_\nu \approx (\frac{11}{4})^{1/3} T_\gamma \approx 1.9K \approx 0.17meV$$

$$(1 - f_i)(1 - f_j) = \frac{1}{(1 + e^{-m_i/T_d})(1 + e^{-m_j/T_d})} \sim \frac{1}{4} + \frac{m_i + m_j}{8T_d}\,.$$

Here

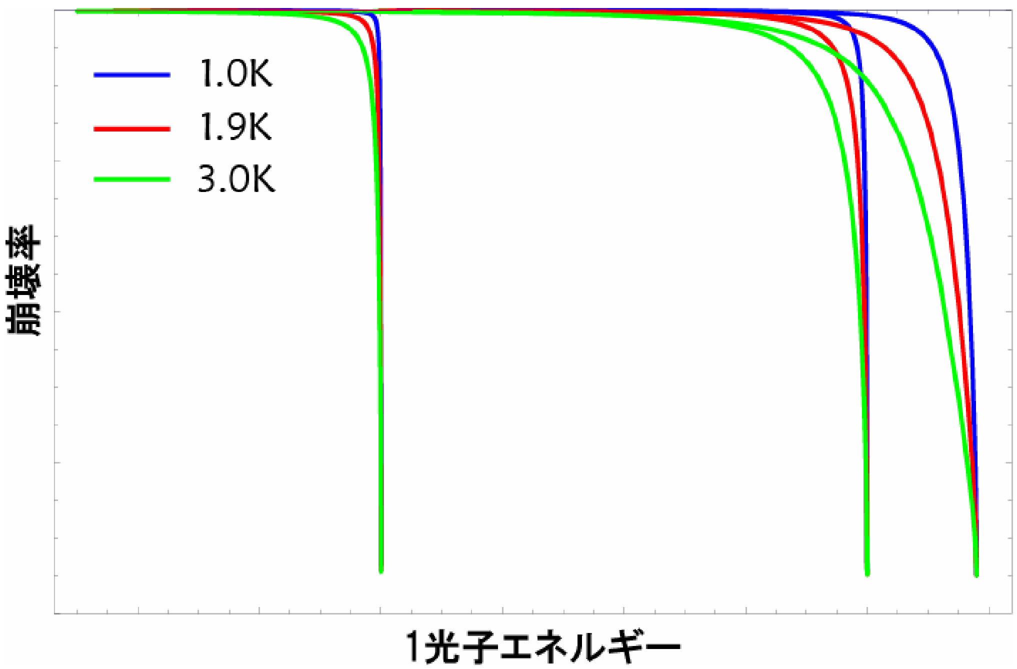
$$\frac{m_i}{T_d} \approx 5 \times 10^{-10} \frac{m_i}{1meV} \frac{2MeV}{T_d}\,,$$

$p = \sqrt{E^2 - m^2}$ to be used

Essentially m/T_0 is sensitivity on mass

Threshold reduction 1/2x1/2 = 1/4
Temperature measurement possible ?
Case of laser irradiated pair emission

Relative rate



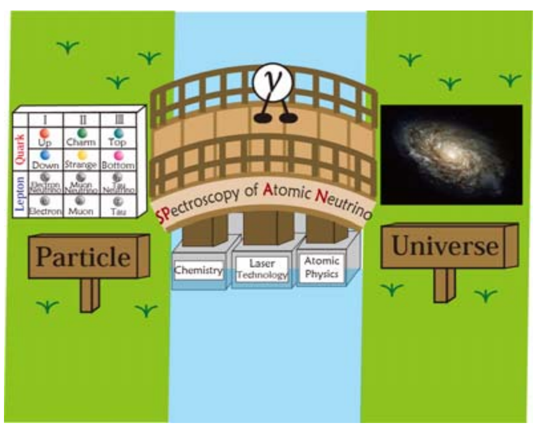
Photon energy

$$m_1 = 0.1\,,\ 1\,,\ 5\,meV$$

For m_1 < 1meV, temperature measurement is not difficult

Experimental strategy

- Verification of superradiance enhancement in 2 gamma EM transition
- Discovery of neutrino pair emission far away from threshold region, with large rates
- Approach to threshold region for neutrino spectroscopy
- Detection of relic neutrino at lightest threshold



SPAN collaboration

Present status of experiments

- Detection of SR
- @okayama Ar-matrix

@ kinki Ne/ Ar-matrix Xe implanted

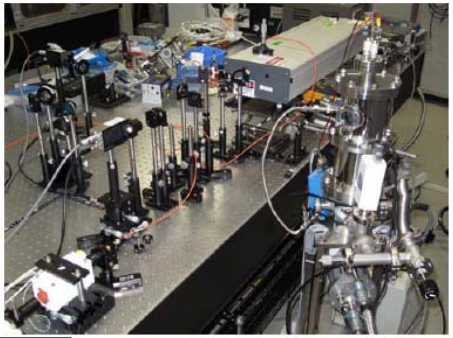


図 5: マトリックス実験

Para-H_2 converter

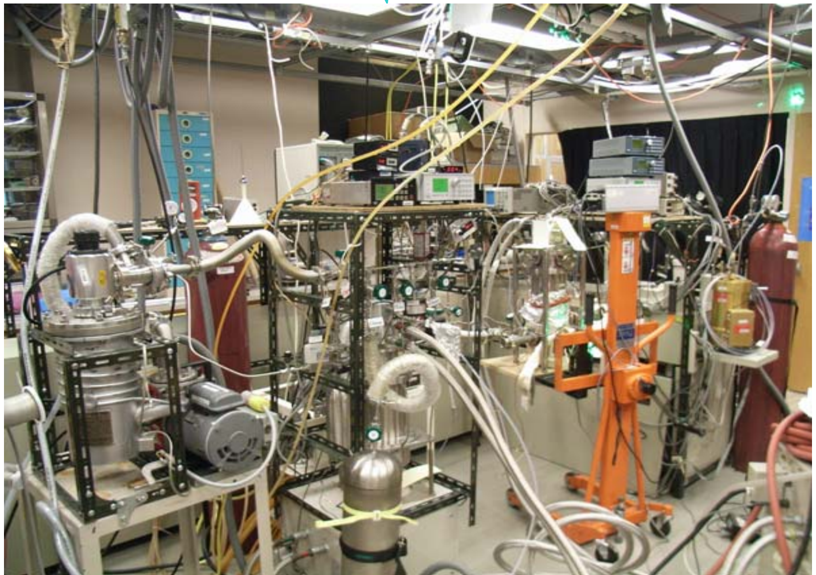
Cryostat

n-H_2

FT-IR

Pump

Para-H_2 matrix @UBC



Evidence for Xe implantation in para-H_2

In literature

P. L. Raston and D. T. Anderson, Journal of Molecular Spectroscopy 244, 138 (2007).

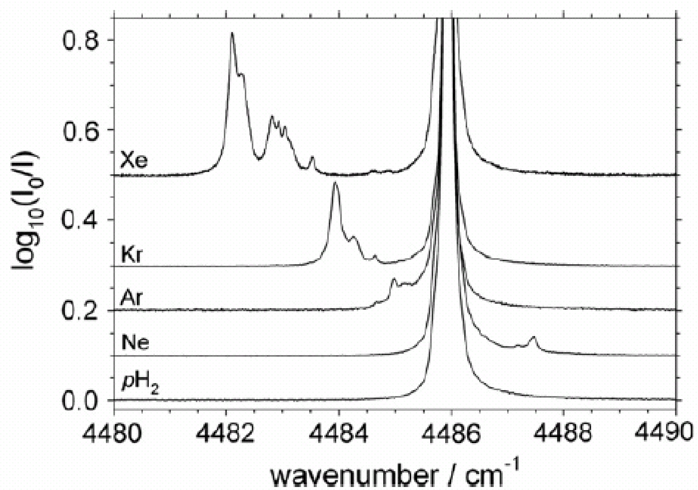
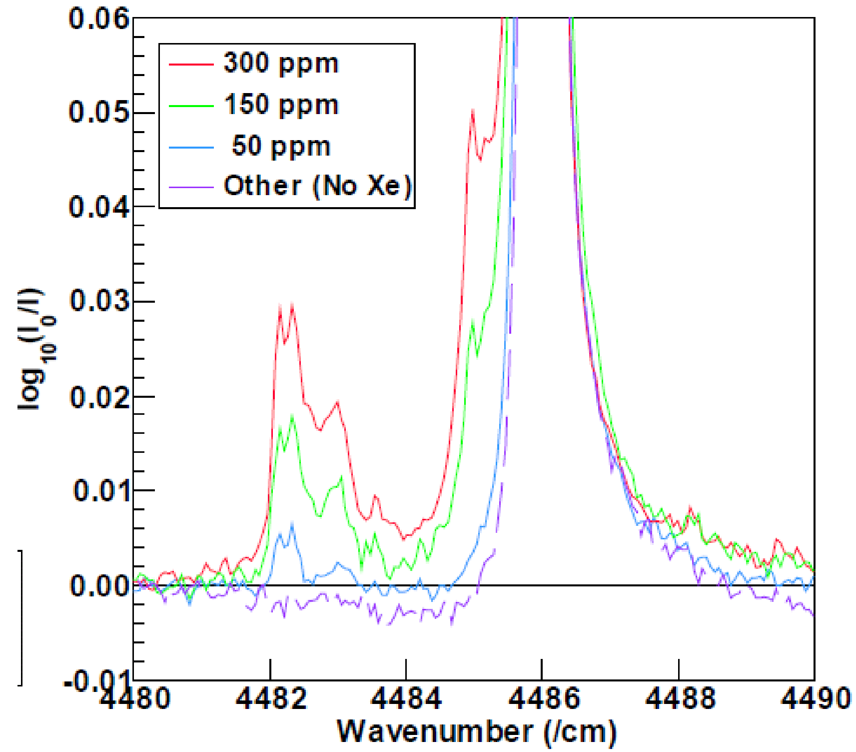


Fig. 2. Infrared absorption spectra in the 4480–4490 cm^{-1} region recorded at 2.0 K for as-deposited samples. Trace ($p\mathrm{H}_2$) is for a 2.8(1) mm thick neat $p\mathrm{H}_2$ solid containing 100 ppm of $o\mathrm{H}_2$. The other spectra are Rg atom doped samples with thicknesses and Rg atom concentrations as follows (Ne) 2.8(1) mm, 1000 ppm, (Ar) 1.8(1) mm, 1300 ppm, (Kr) 1.6(1) mm, 440 ppm, and (Xe) 2.5(1) mm, 260 ppm.

Our result

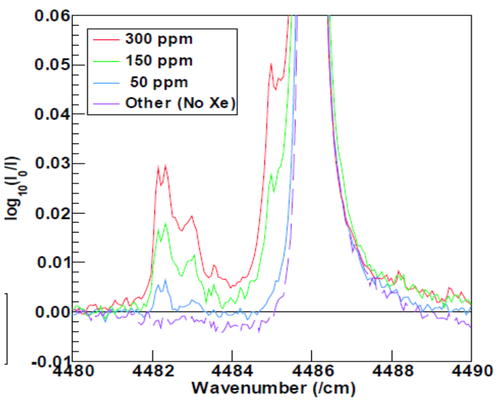


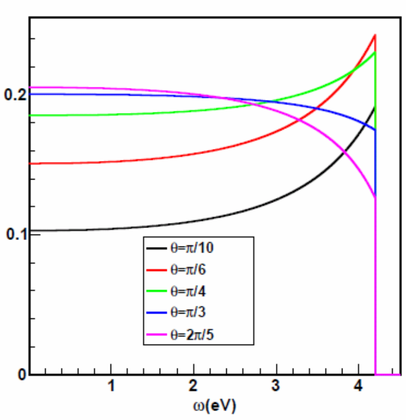
Different impurity can be detected by different satelite sturucture

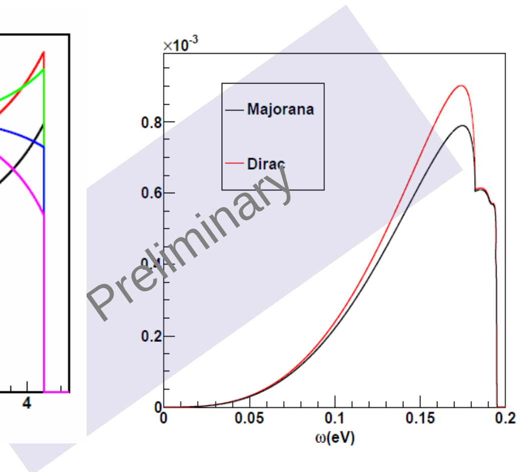
Summary

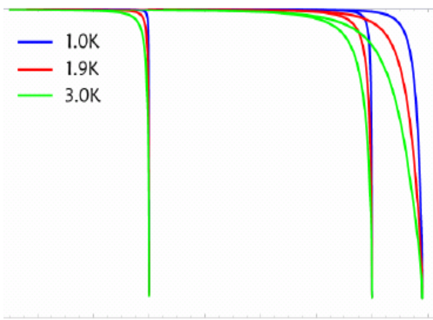
- Discussed a new possibility of using macro-coherent atomic targets of large density
- Excellent for neutrino mass spectroscopy giving 3 masses and 3 angles, along with M/D distinction
- Soliton formation gives extra enhancement
- PV quantity measurable
- If works ideally, a long path towards relic detection

Our result









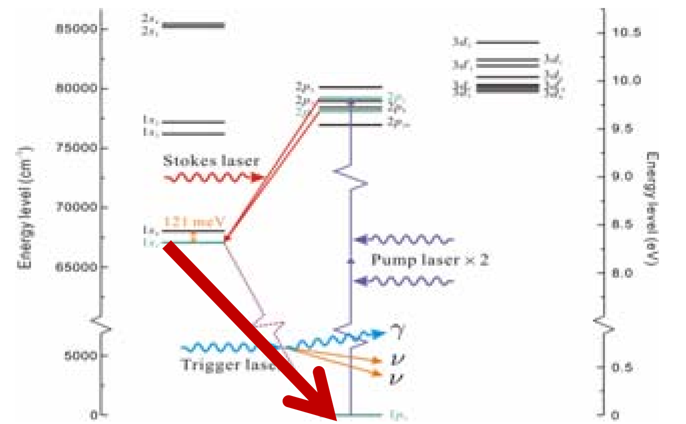
Si-Fe

Back up

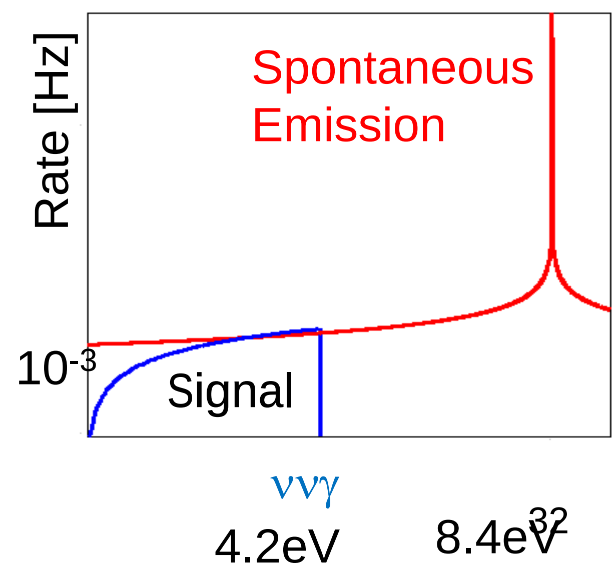
Backgrounds
(in case of Xe in p-H2)

- Spontaneous emission (1)
  - The excited level would emit 8.4eV photons.
  - Then they might be converted to 4.2eV photons via inelastic scattering with detector materials.
  - ➢ Detector's angular acceptance (10^{-3}), and spectrometer band pass $(\Delta\lambda=0.1\text{nm})$
- Spontaneous emission (2)
  - …ssion of 4.2eV photons due to Breit-…gner tail.
  - ➢ Detector's angular acceptance (10^{-3})
  - ➢ BG rate would be similar to signal rate for 300cc p-H2 target.

Severe Physics BG



Spontaneous Emission



Concrete ^131 Xe calculation

Xe: F = 7/2, M = -1/2

$$
\left\{ \begin{array}{l} \cos\eta |F, M\rangle \\ \\ \\ +\sin\eta |F-1, M+1\rangle \end{array} \right\} \underset{\vec{S}_e \cdot \vec{j}_\nu}{\longrightarrow} \left\{ \begin{array}{l} |F-1, M-1\rangle \\ |F-1, M\rangle \\ |F-1, M+1\rangle \\ |F-1, M+2\rangle \end{array} \right\} \underset{\vec{d} \cdot \vec{E}}{\longrightarrow} \left\{ \begin{array}{l} |F-2, M-1\rangle \\ |F-2, M\rangle \\ |F-2, M+1\rangle \\ |F-2, M+2\rangle \end{array} \right\}
$$

131Xe 5p6(2P3/2)6s 2[3/2]2

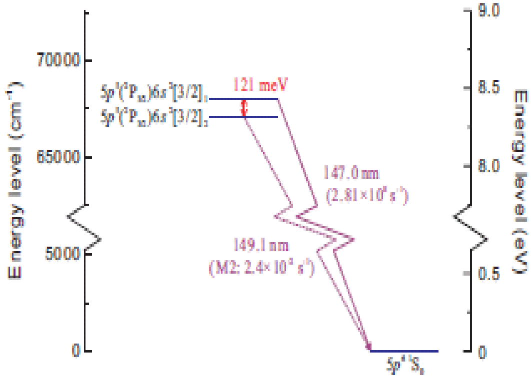
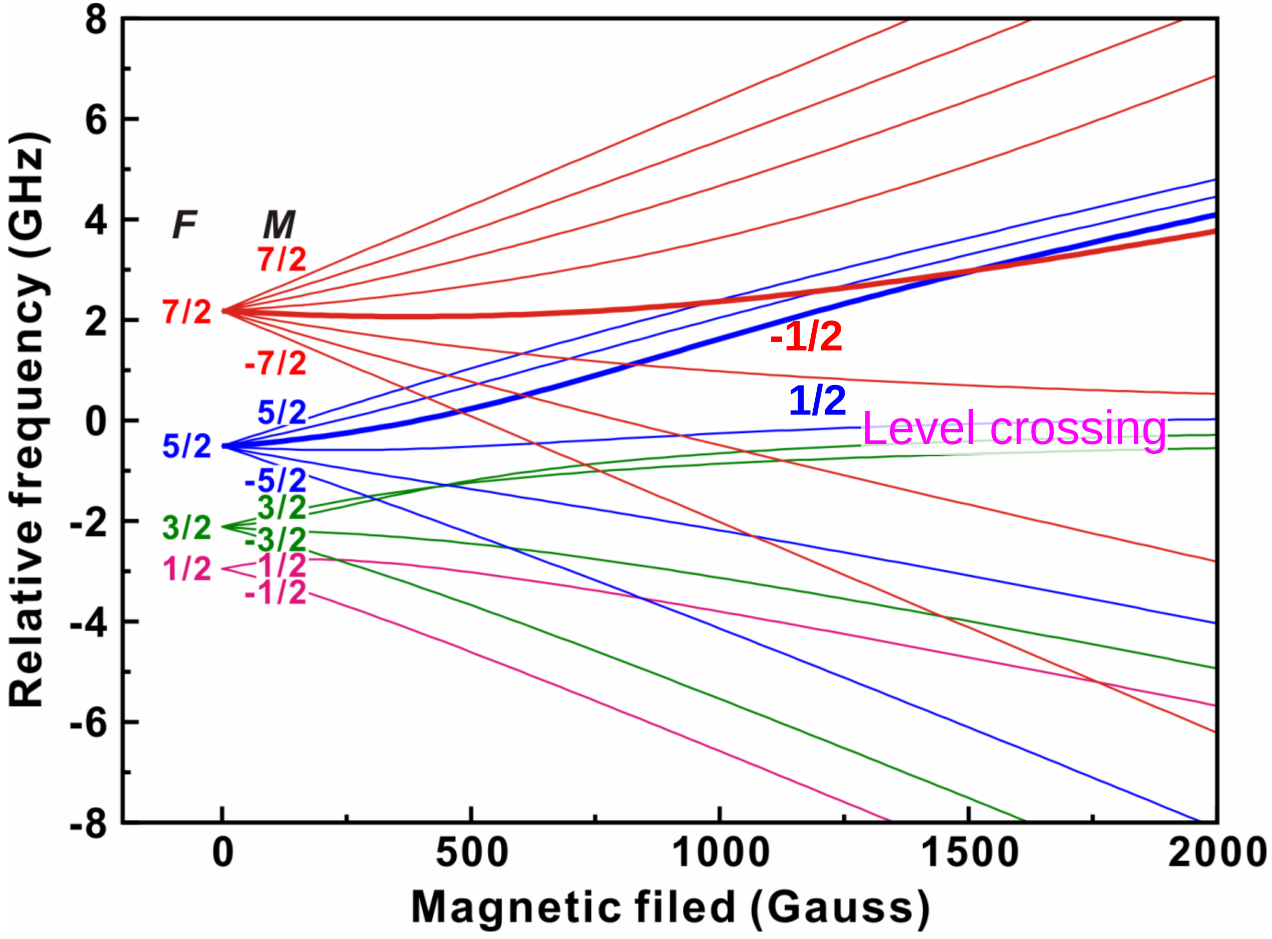


図 1: Xe energy level for radiative neutrino pair emission

Odd Xe for PV

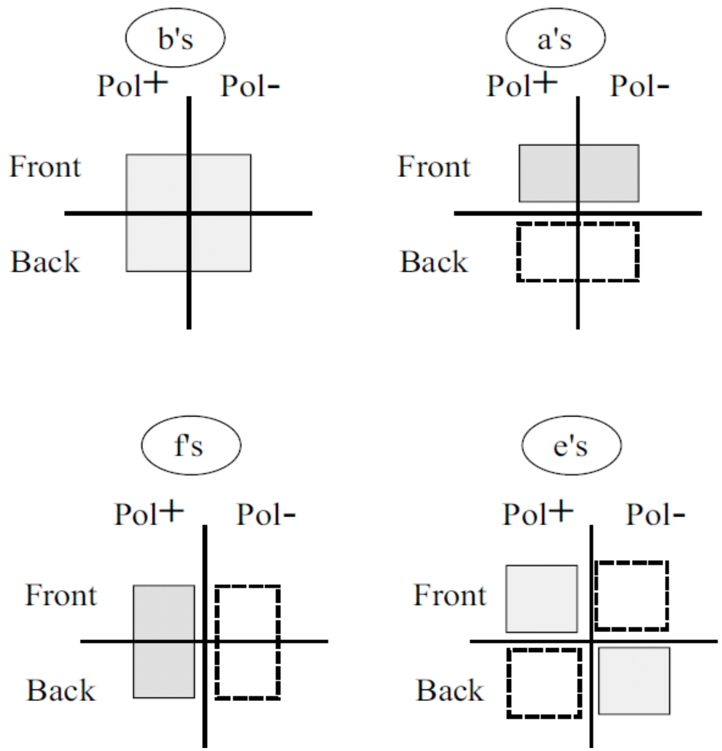
^{131}Xe $5p^6(^2P_{3/2})6s\ ^2[3/2]_2$ level hyperfine structure in an external magnetic field

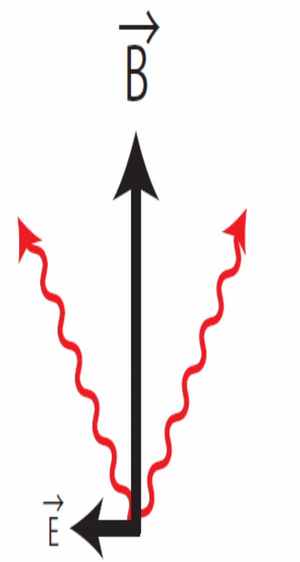


State mixture at 1.5 kG

Angular distribution of specific circular polarization

$$\frac{d^2\Gamma}{d\omega d\cos\theta}(\omega, h_\gamma) = \frac{G_F^2 d^2 n N \omega^3}{3\pi^3(\Delta-\omega)^2}\sum_{ij}|c_{ij}|^2\Big(b_4 c^4 + b_2 c^2 + b_0 + s(a_3 c^3 + a_1 c)$$
$$+ h_\gamma(e_3 c^3 + e_1 c + s(f_2 c^2 + f_0))\Big)\,,$$





E-direction tilted from pependicular

Angular asymmetry $0 \le \theta \le \pi/2$

$$A(\theta) = \frac{s(a_3 c^3 + a_1 c)}{b_4 c^4 + b_2 c^2 + b_0}$$

Circular polarization

$$P(\theta) = \frac{s(f_2 c^2 + f_0)}{b_4 c^4 + b_2 c^2 + b_0}$$

Numbers to memorize

$$\frac{G_F^2(10\text{eV})^4}{3\pi^3}\frac{d^2nN}{10^8cm^{-1}10^{22}} \sim 6.45\times 10^{-4}\text{sec}^{-1}$$

Xe atomic states

$$|i\rangle = 5p^5(^2P_{3/2})6s^2[3/2]_2\,, \quad \text{metastable with lifetime } O[40]\,\text{sec}$$

$$|n\rangle = 5p^5(^2P_{3/2})6s^2[3/2]_1\,, \quad \frac{1}{\tau}\sim 2.8\times 10^8\text{sec}^{-1}\,, \quad |f\rangle = 5p^6\,{}^1S_0$$

$$\Delta_{ni}\sim 0.12\text{eV}\,, \quad \Delta_{nf}\sim 8.4\text{eV}\,, \quad \text{Ionization energy} \sim 13.4\text{eV}$$