Towards Neutrino Spectroscopy and Measuring Relic Neutrino

- Why neutrino pair emission from excited atoms is interesting and useful towards neutrino spectroscopy ?
- Laser irradiated pair emission from low-lying, metastable states
- Possibility of detecting relic neutrino of 1.9K

hep-ph/0611362 and PRD, hep-ph/0703019

Merits and demerits of atomic process

- Infinitely many small energies

$$\Delta E(n_1 , n_2) = 13.6eV(\frac{1}{n_2^2} - \frac{1}{n_1^2}) = 27meV(\frac{10}{n})^3 \Delta n$$

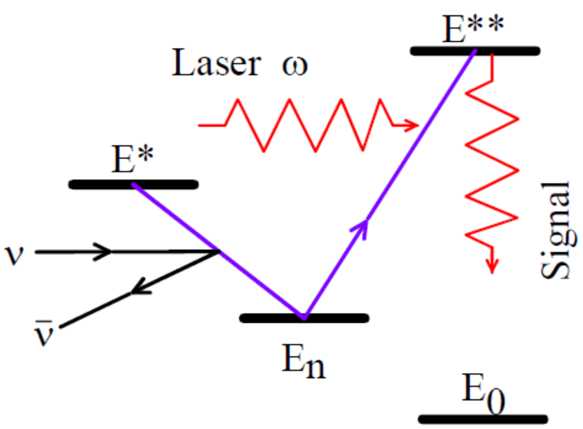
for Rydberg states

- Small decay rate of pair emission

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

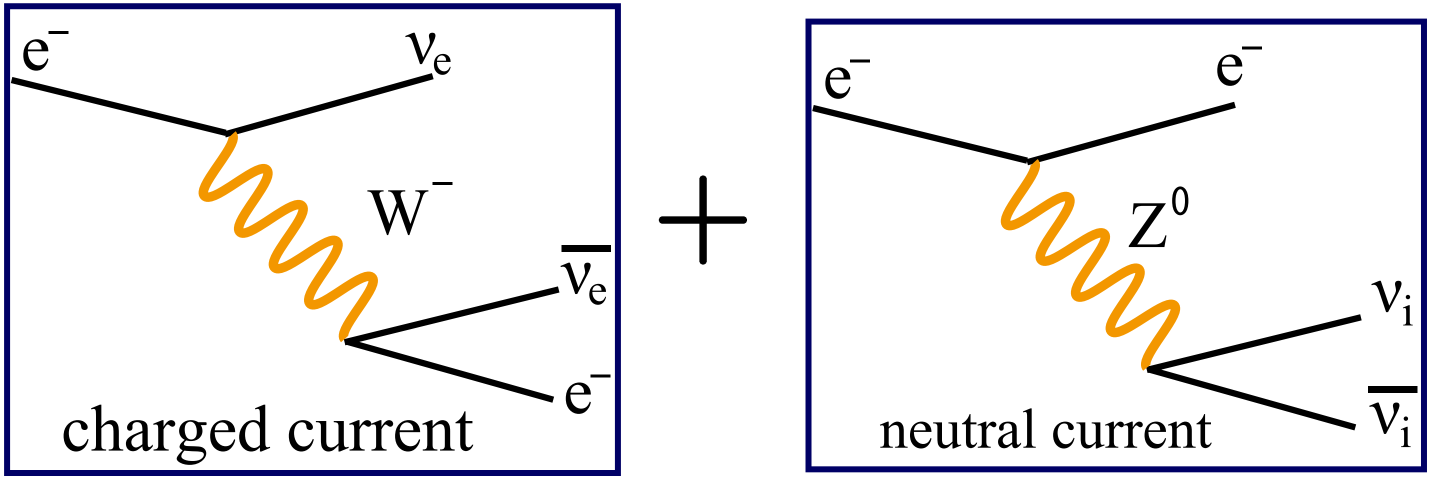
- How to obtain a large rate

From decay to laser-initiated reaction (activation)



M. Yoshimura @ B-L
September 22 2007

Neutrino interaction with atomic electron



4 Fermi interaction (after Fierz transformation) $\propto j_{M,D} \cdot j^e$

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**

M vs D

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

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

Majorana vs Dirac equations: chirally projected solutions

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

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

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

Majorana vs Dirac equations: chirally projected solutions

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

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

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

Where to look for M/D distinction

- Interference terms of anti-symmetric wave functions -> neutrino-antineutrino pair emission from excited atoms

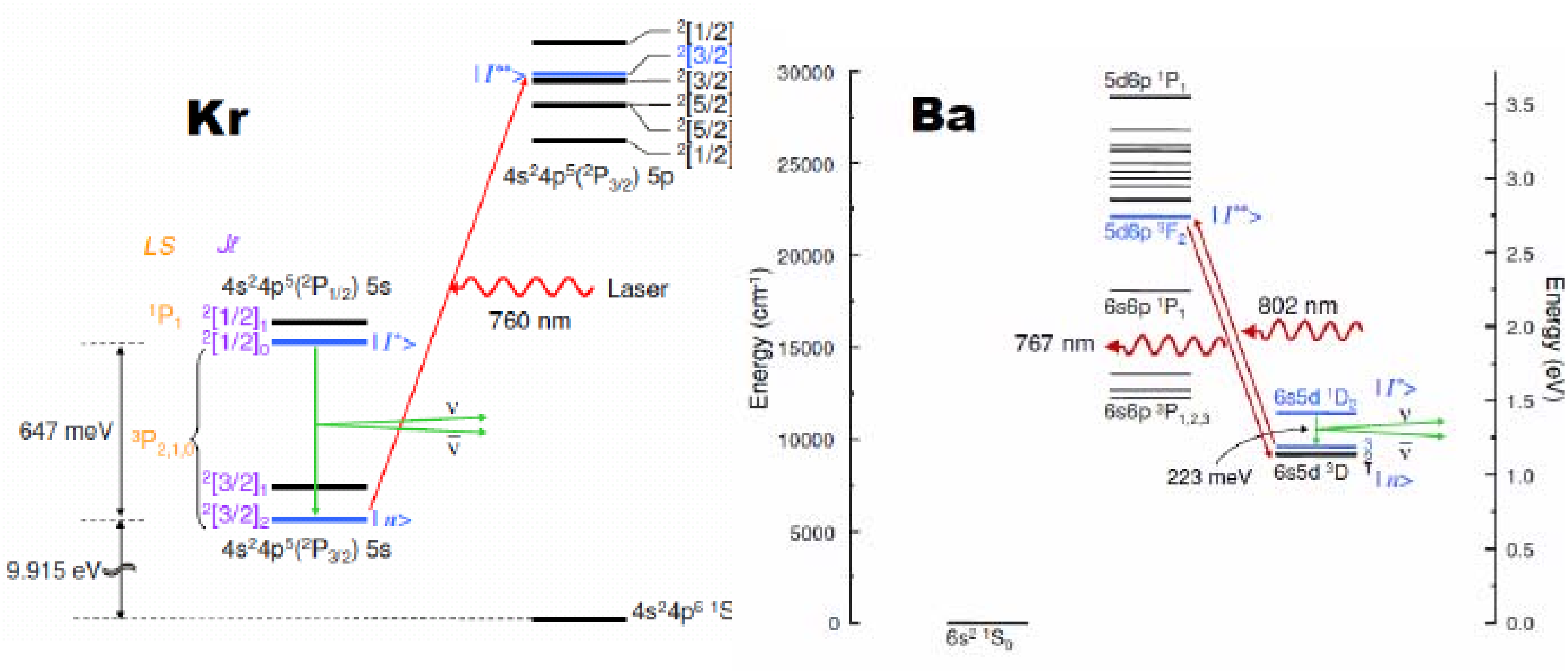
- Only near the threshold of pair production M/D distinction in emission rate is large

Unique signature of Majorana = interference of identical fermions

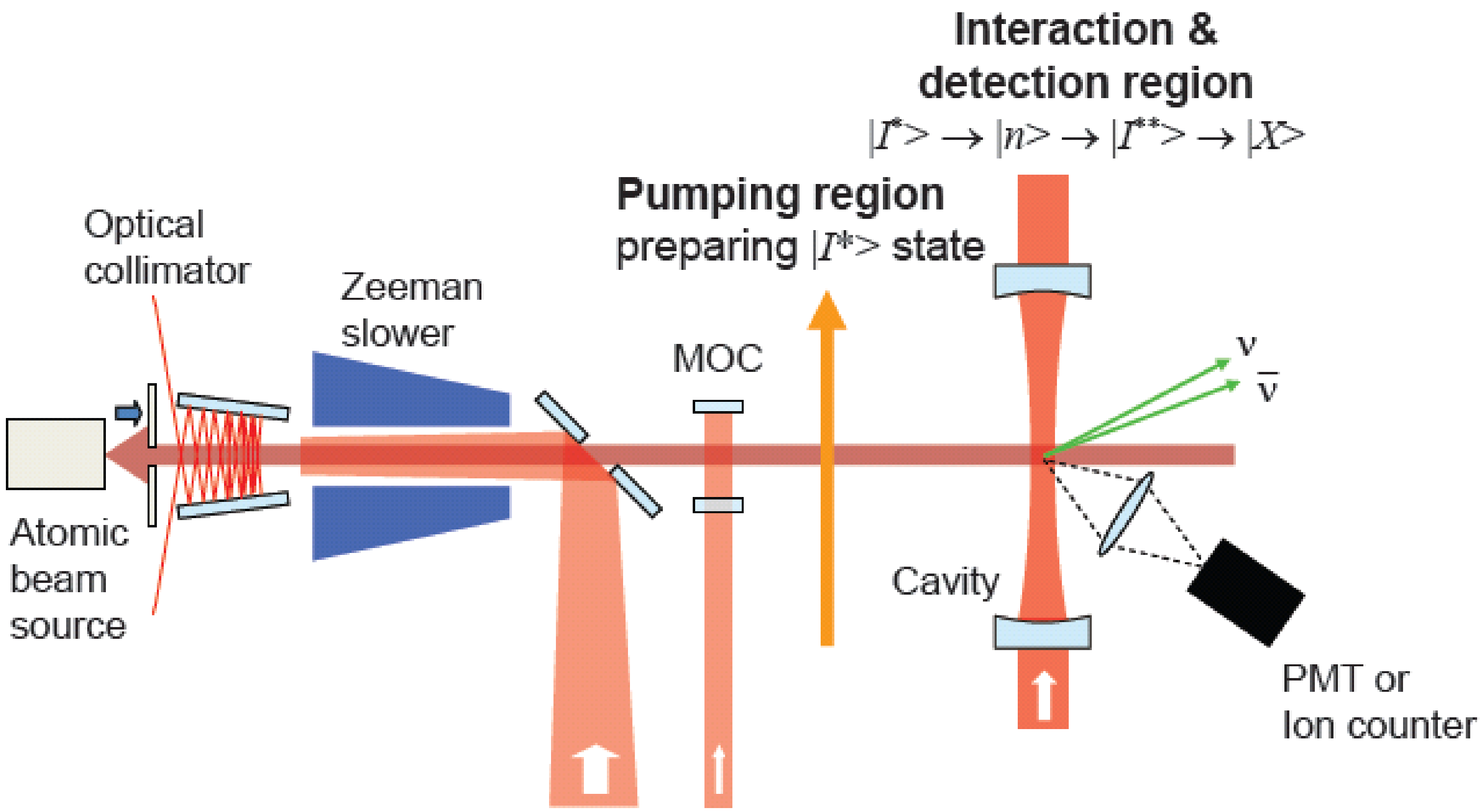
$$\sum_{h_1 h_2} |j_M \cdot j^e|^2 = \sum_{h_1 h_2} |j_D \cdot j^e|^2 + \delta_{ij} \frac{m_i m_j}{2E_1 E_2} \left(j_0^e (j_0^e)^\dagger - \vec{j}^e \cdot (\vec{j}^e)^\dagger \right)$$

- 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: unlike indirect LV in $(0\nu)\beta\beta$

Examples of atoms:
case of low lying metastable states



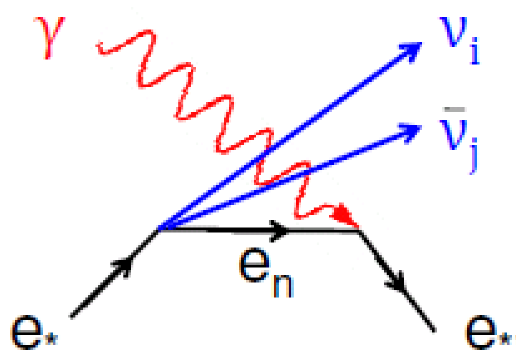
Example of experimental setup



Rate formula

$$\Gamma^M(\omega_0) = \frac{2G_F^2}{\pi^2}\frac{\gamma_r}{\omega_0^2}\int d\omega \sum_{ij}\theta(\omega - \Delta_{fi} - m_i - m_j)$$
$$\times \frac{F(\omega\,;\omega_0\,,\Delta\omega)}{(\omega - \Delta_{f0})^2 + \gamma^2/4}$$

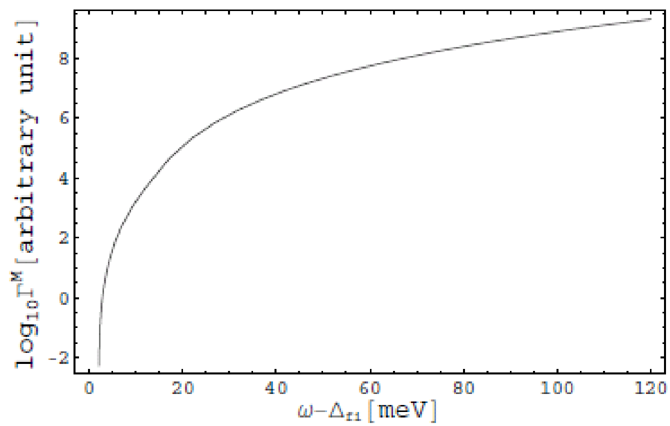
$$\times\Big[(|c_{ij}^{(0)}|^2 + 3|c_{ij}^{(s)}|^2)(\omega - \Delta_{fi})^5 Y_{ij}\left(\frac{m_i}{\omega - \Delta_{fi}}\,,\frac{m_j}{\omega - \Delta_{fi}}\right)$$
$$+\delta_{ij}(|c_{ij}^{(0)}|^2 - 3|c_{ij}^{(s)}|^2)m_i m_j(\omega - \Delta_{fi})^3 Z_{ij}\left(\frac{m_i}{\omega - \Delta_{fi}}\,,\frac{m_j}{\omega - \Delta_{fi}}\right)$$
$$Y_{ij}(\epsilon_i\,,\epsilon_j) = \int_{\epsilon_i}^{1-\epsilon_j} dx\,x(1-x)\sqrt{(x^2-\epsilon_i^2)\left((1-x)^2-\epsilon_j^2\right)}\,,$$
$$Z_{ij}(\epsilon_i\,,\epsilon_j) = \int_{\epsilon_i}^{1-\epsilon_j} dx\sqrt{(x^2-\epsilon_i^2)\left((1-x)^2-\epsilon_j^2\right)}\,.$$



$$\gamma + |I^*\rangle \to |I^{**}\rangle + \nu_i\bar{\nu}_j$$

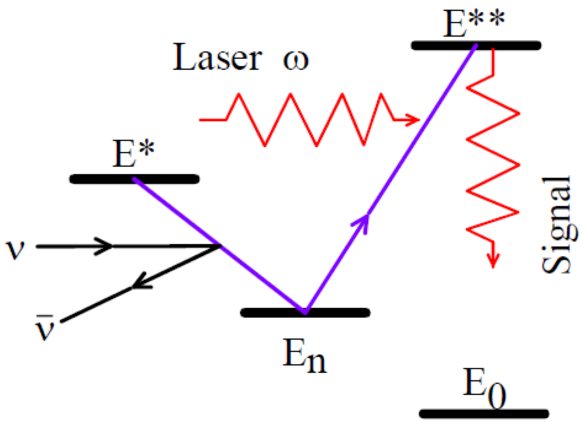
Coefficient depending on angle factors,

$$c_{ij}^{(s)} = U_{ei}^* U_{ej} - \frac{\delta_{ij}}{2}\ (\mathrm{F})\,,\quad c_{ij}^{(0)} = U_{ei}^* U_{ej}\ (\mathrm{NF})$$
$$\sum_{ij}|c_{ij}^{(s)}|^2 = \frac{3}{4}\,,\quad \sum_{ij}|c_{ij}^{(0)}|^2 = 1$$

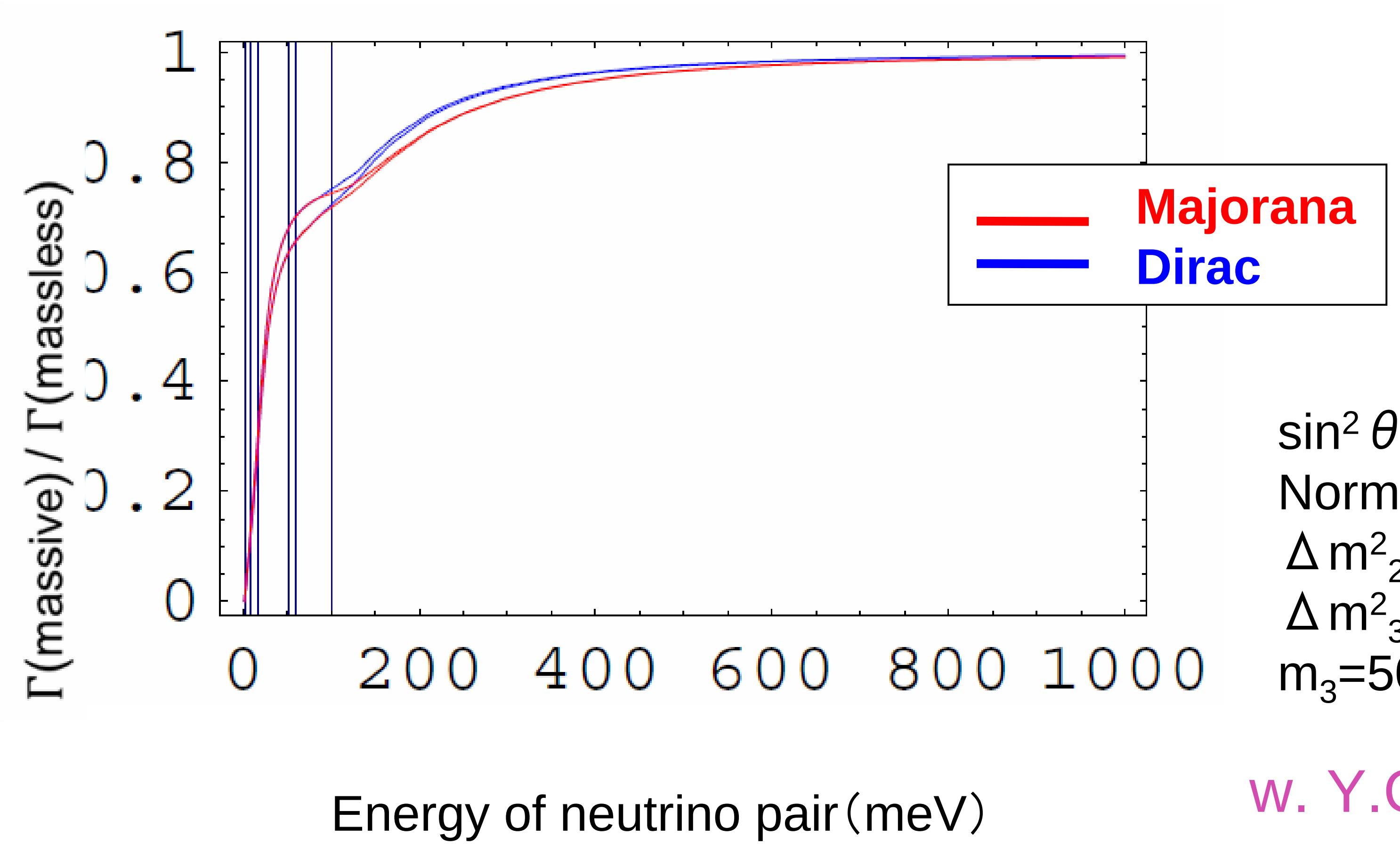


Rough rate numbers

$$\frac{13}{64\pi^2}\frac{G_F^2 F_0 \gamma_r}{\omega^2 \Delta\omega \gamma}(eV)^5 = 5.0 \times 10^{-19} s^{-1} \frac{P}{W mm^{-2}}(\frac{eV}{\omega})^4 \frac{10^{-9}\omega}{\Delta\omega}\frac{10^{-9}\gamma_r}{\gamma}$$

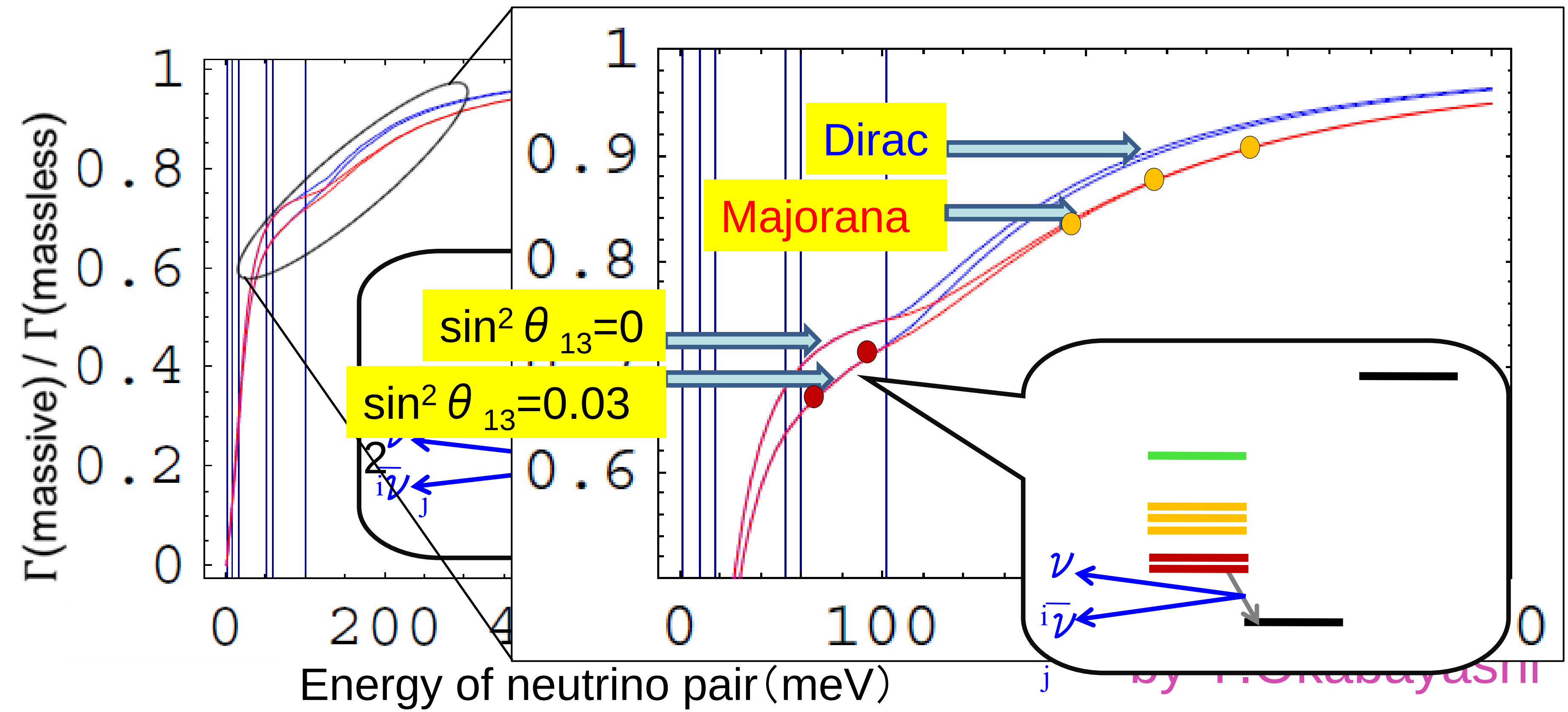


How to perform spectroscopy and M/D distinction



$\sin^2\theta_{12}$=0.35
Normal hierarchy
$\Delta m^2_{21}=8\times10^{-5}$eV
$\Delta m^2_{32}=2.0\times10^{-3}$eV
m_3=50.8meV

w. Y.Okabayashi

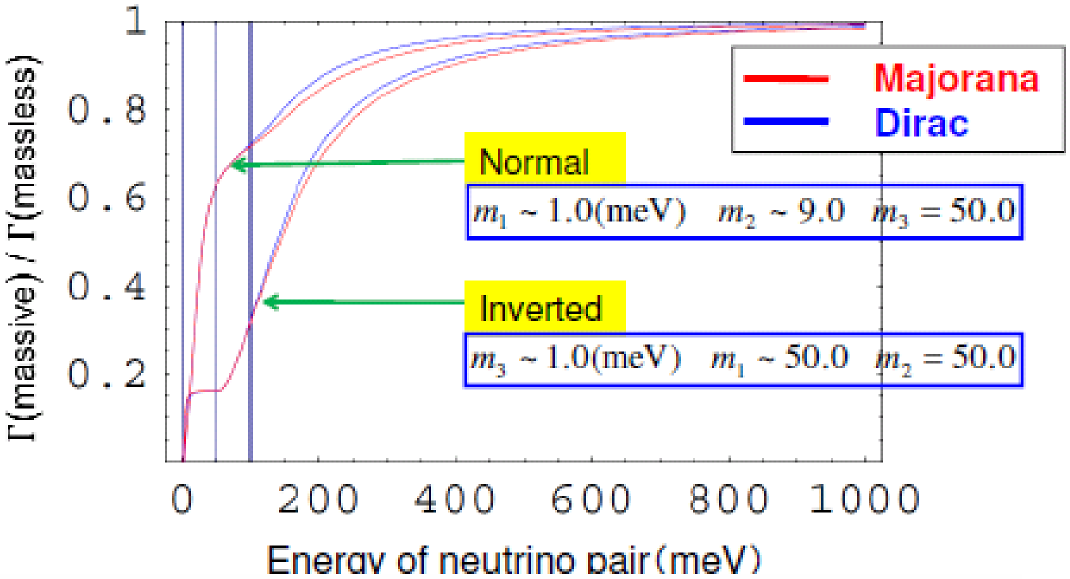


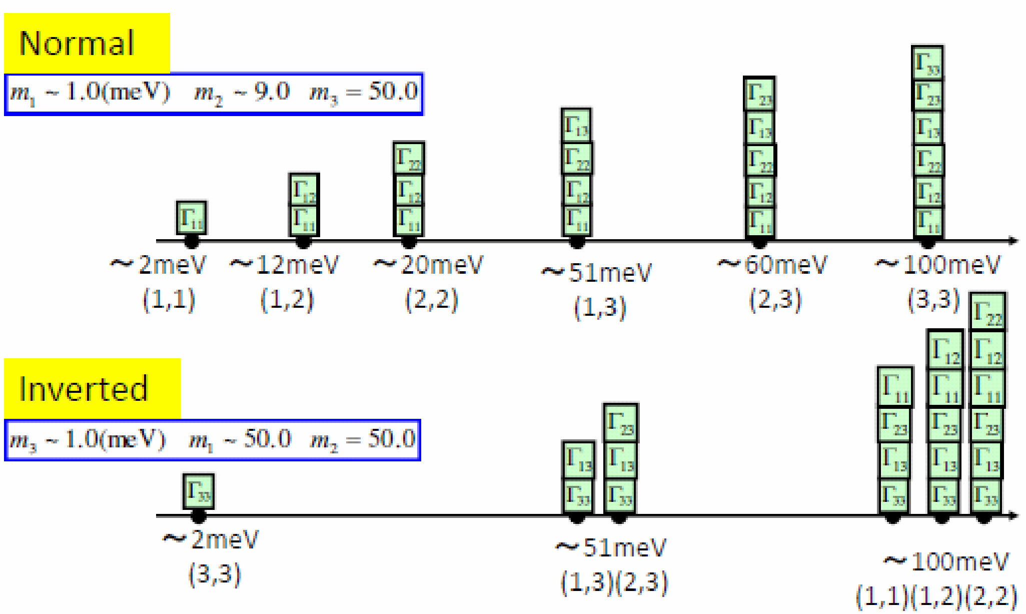
M3 determination where M/D distinction disappears

M/D distinction a little away from (33)-threshold

θ13 Determination near (23)-threshold

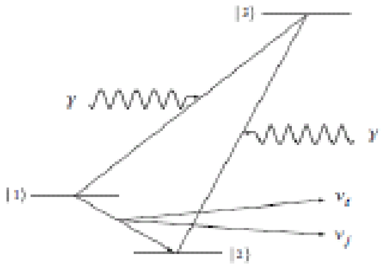
Normal vs inverted hierarchy

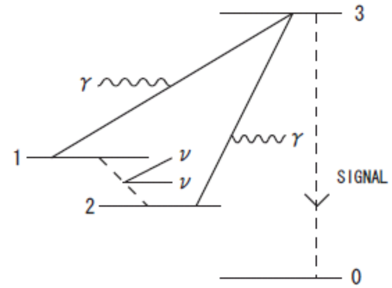


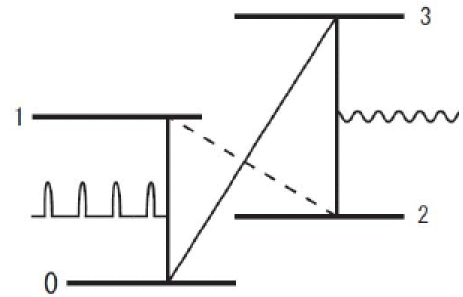


Works on-going and to be done

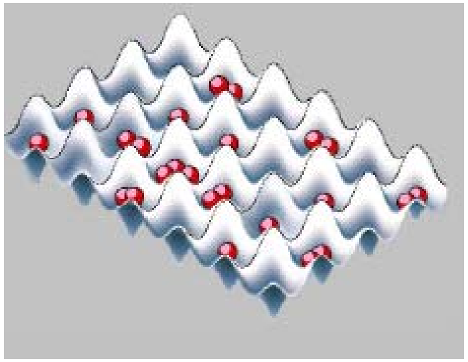
- Time dependent enhancement factor being systematically computed for semi-realistic (cyclic, recycling, modulation, relaxation) cases, using Optical Bloch Equation







- BEC (in optical lattice ?): N^2 target effect



- Search for large matrix element ratio of neutrino pair/radiative beyond long wave approximation

- Search for accumulated PV quantity to ultimately prove the weak process

Observability of relic neutrino w. T. Takahashi

hep-ph/0703019

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

$$\int_{m_i}^{\omega-\Delta_{fi}-m_j} dE_1 I(E_1)$$

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

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

Observability of relic neutrino w. T. Takahashi

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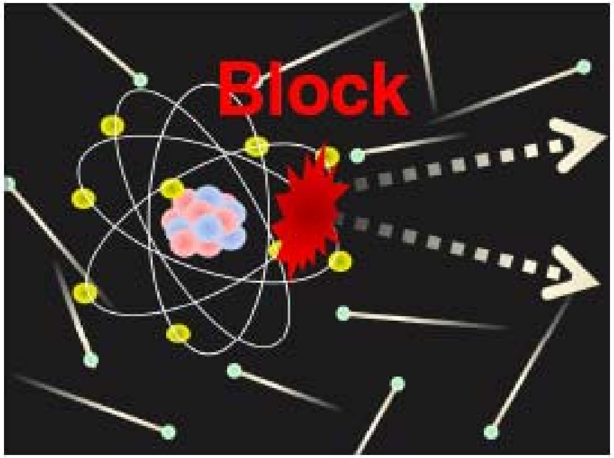
- Pauli blocking effect

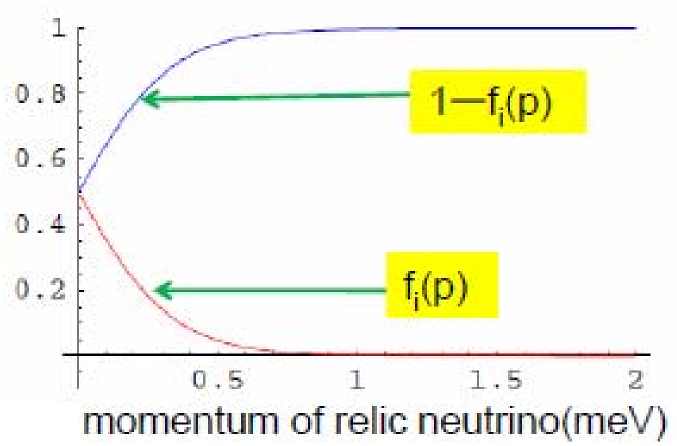
$$\Gamma^M(\omega\,;T_\nu) = \frac{4G_F^2 F_0}{\pi\omega^2\Delta\omega}\frac{\gamma_r}{\gamma}\sum_{ij}\theta(\omega-\Delta_{fi}-m_i-m_j)\times$$

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

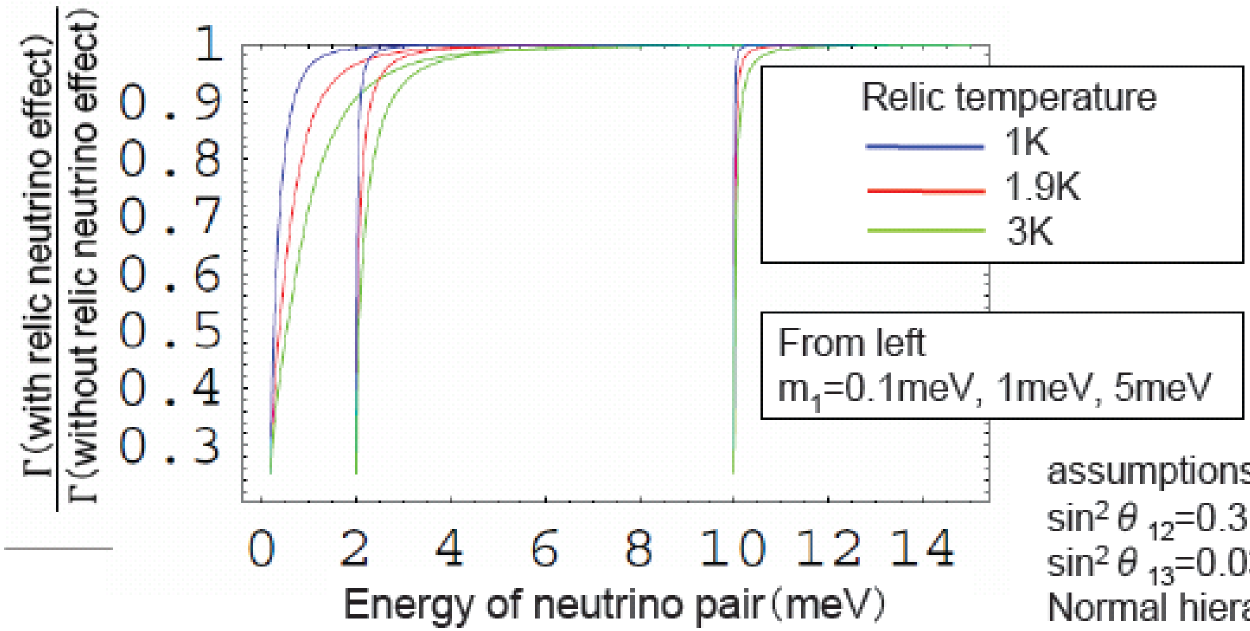
$$I(E_1) = k_0^{ij}E_1(\omega-\Delta_{fi}-E_1)\sqrt{(E_1^2-m_i^2)\{(\omega-\Delta_{fi}-E_1)^2-m_j^2\}}$$

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





Temperature measurement possible ?



At the threshold $(1-f_i)(1-f_j) \sim \frac{1}{4}$

assumptions
$\sin^2\theta_{12}=0.311$
$\sin^2\theta_{13}=0.032$
Normal hierarchy
$\Delta m^2_{21}=8\times10^{-5}$eV
$\Delta m^2_{32}=2.0\times10^{-3}$eV

For m_1 < a few meV, temperature difference is visible

SPectroscopy of Atomic Neutrino (SPAN collaboration)

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Summary

- Proposed a new experimental method for determination of both the type (M/D) and the magnitude, the mixing of neutrino masses
- Use of excited atoms most appropriate for systematic spectroscopy if large enhancement is feasible
- A possibility of detecting 1.9K relic neutrino