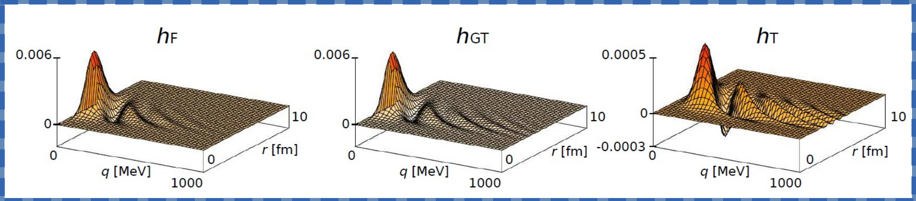
Supported by HPCI

# Determination Of Effective Neutrino Mass using Double Beta Decay Experiments


Institute of Innovative Research, Tokyo Institute of Technology
Department of Mathematics, Shibaura Institute of Technology

Yoritaka Iwata

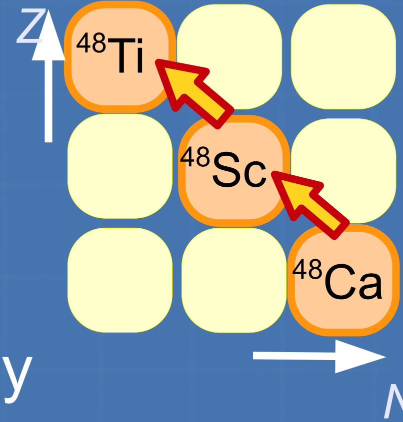
Collaboration with
J. Menendez, N. Shimizu, T. Otsuka, Y. Utsuno, M. Honma, T. Abe

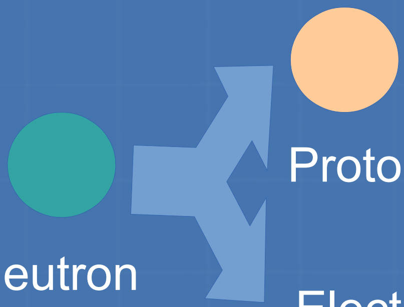

← Detail investigation on neutrino potential, now available on the arXiv

Y.I., “Neutrino potential for neutrinoless double beta decay”

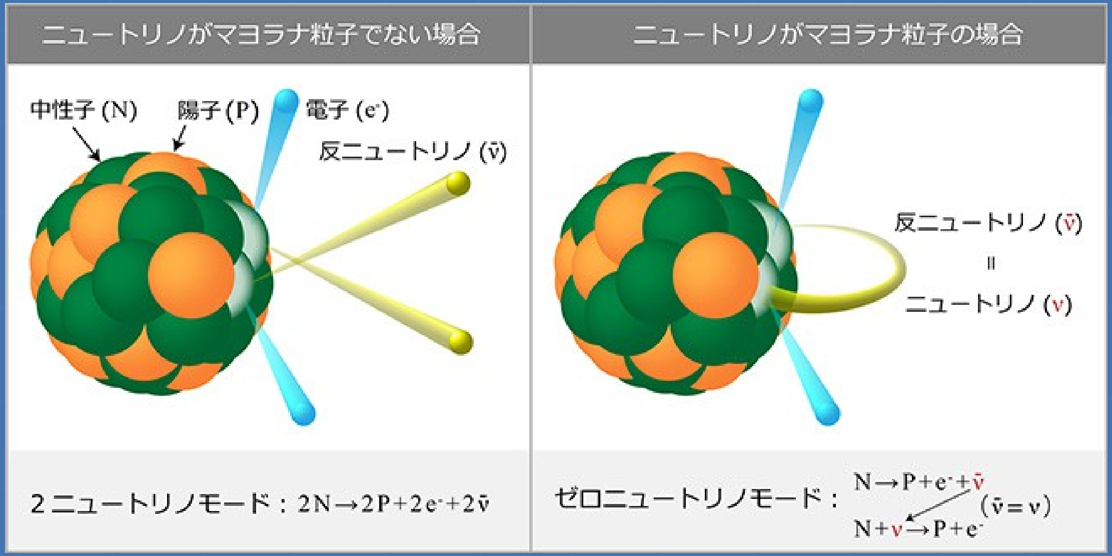
# Double beta decay of $^{48}Ca$




## Beta decay




## Double Beta Decay




From “Monthly JICFuS” on the web

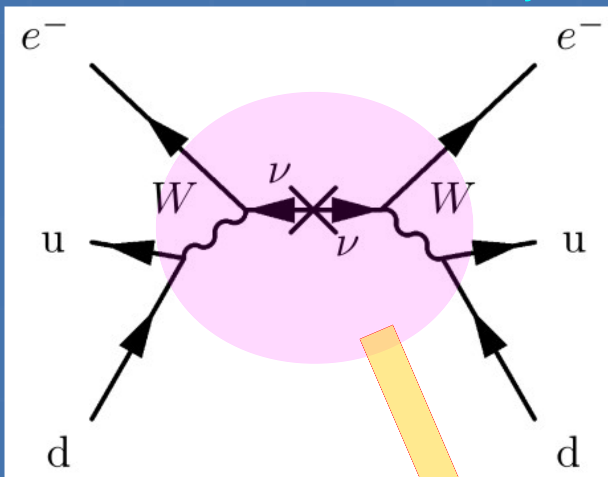
**Two modes associated with double beta decay**

- **Neutrino emission mode**
- **Neutrinoless mode (only if $\nu_e = \bar{\nu}_e$ )**

# Nuclear matrix element (NME)

## Majorana particle or not？

Neutrinoless double beta decay




lepton number violation
(beyond the standard model)

## Effective neutrino mass？

Relation between neutrino mass and decay half life:

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}_1 |M^{0\nu}|^2 \left(\frac{<m_{\beta\beta}>}{m_e}\right)^2$$

Half life — NME — Effective neutrino mass

In the standard model,
it is equal to zero

## Nuclear Matrix element under the closure approx.

$$M^{0\nu} = \left\langle f \left| \sum_{a,b} \tau_a^+ \tau_b^+ \left\{ -(g_V/g_A)^2 H_F(r) + \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b H_{GT}(r) - (3(\boldsymbol{\sigma}_a \cdot \boldsymbol{r})(\boldsymbol{\sigma}_a \cdot \boldsymbol{r}) - \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) H_T(r) \right\} \right| i \right\rangle$$

Fermi — Gamow-Teller — Tensor

$= H\alpha$ ($\alpha$: F, GT, T)

# NME component: Neutrino potential

Neutrino potential under closure approx. is calculated within the precision of “0.0010 [MeV fm].

Precise calculation provided by “MAXIMA”

$$H_\alpha(r) = \frac{2R}{\pi} \int_0^\infty f_\alpha(qr) \frac{h_\alpha(q)}{q + \langle E \rangle} q \, dq$$

<E> = averaged energy of virtual intermediate state

q: momentum of virtual neutrino

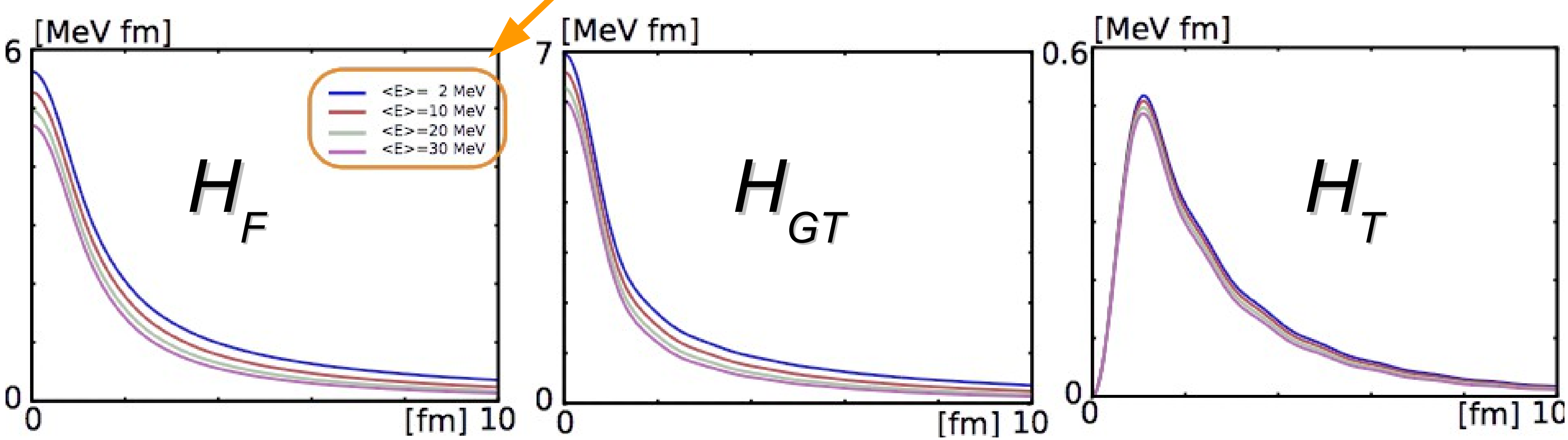
$f_\alpha$: spherical Bessel function ($\alpha$=0,2)

$\alpha$ = *F*, *GT*, *T* (Fermi, Gamow-Teller, Tensor parts)

## <*E*> dependence

<*E*> = 2 ~ 30 MeV

<*E*> : closure parameter = average energy



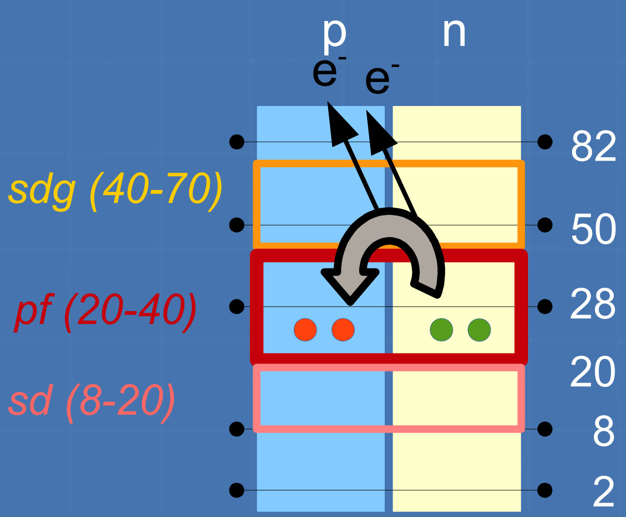

In the following <*E*> = 0.50 MeV, suggested by calc. w/o the closure approximation.

Senkov-Horoi-Brown PRC (2013)

# NME component: Initial/final state

Y.I.-Shimizu-Otsuka-Utsuno-Menendez-Honma-Abe, Phys. Rev. Lett. 116 (2016) 112502
Large-scale shell model analysis on nuclear matrix element

$$M^{0\nu} = \left\langle f \left| \sum_{a,b} \tau_a^+ \tau_b^+ \left\{ -(g_V/g_A)^2 H_F(r) + \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b H_{GT}(r) - (3(\boldsymbol{\sigma}_a \cdot \boldsymbol{r})(\boldsymbol{\sigma}_a \cdot \boldsymbol{r}) - \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) H_T(r) \right\} \right| i \right\rangle$$




Inclusion rate of 2nd major shell components :

$^{48}$Ca (22%), $^{48}$Ti (33%) — ***sd* + *pf***

$^{48}$Ca (~2%), $^{48}$Ti(~2%) — ***pf* + *sdg***

This result shows that
It should be necessary to take into account *sd* shell

In case of *sd* + *pf* ...

## $^{48}$Ca → $^{48}$Ti

$^{48}$Ca (p,n) = (20, 28) = (20+0, 20+8) = (8+12, 8+20)

$^{48}$Ti (p,n) = (22, 26) = (20+2, 20+6) = (8+14, 8+18)

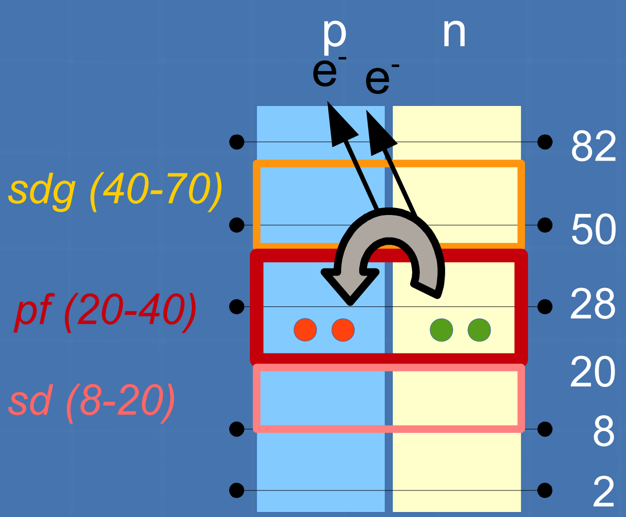
1shell — $<10^6$ dim

+1 shell — ~ $10^9$ dim

# Neutrinos of ordinary type

Y.I.-Shimizu-Otsuka-Utsuno-Menendez-Honma-Abe, Phys. Rev. Lett. 116 (2016) 112502
Large-scale shell model analysis on nuclear matrix element

$$M^{0\nu} = \left\langle f \left| \sum_{a,b} \tau_a^+ \tau_b^+ \left\{ -(g_V/g_A)^2 H_F(r) + \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b H_{GT}(r) - (3(\boldsymbol{\sigma}_a \cdot \boldsymbol{r})(\boldsymbol{\sigma}_a \cdot \boldsymbol{r}) - \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) H_T(r) \right\} \right| i \right\rangle$$




Inclusion rate of 2nd major shell components :

$^{48}$Ca (22%), $^{48}$Ti (33%) ***sd + pf***

$^{48}$Ca (~2%), $^{48}$Ti(~2%) ***pf + sdg***

This result shows that
It should be necessary to take into account *sd* shell

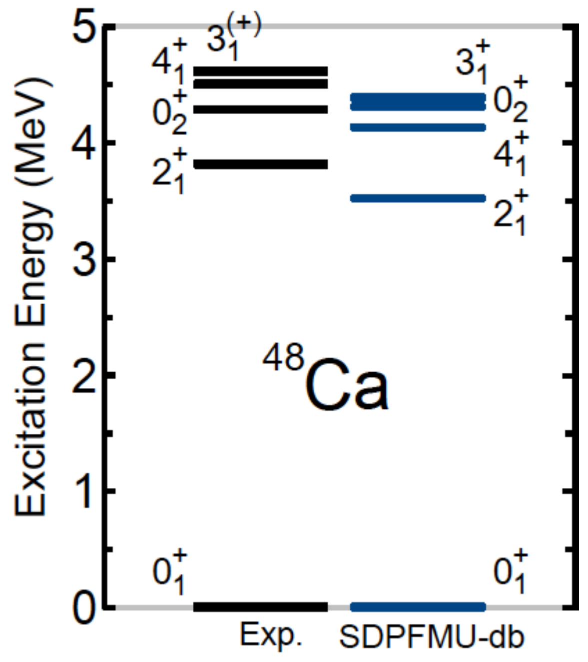
| | | |
|---|---|---|
| $M^{0\nu}$ | (1 shell) | 0.833 |
| $M^{0\nu}$ | (2 shells) | 1.118 |

34.2 % increased

Due to $(1/1.34)^2 \sim 0.56$,
it means that
**the half-life is almost halved**
for the same neutrino mass.

# Energy spectra, as a test of the nuclear structure calculation

As an evidence of good description,
the energy spectra made by SDPFMU-db is compared to the experiment;
SDPFMU-db is an effective interaction made for 2 major shell description.



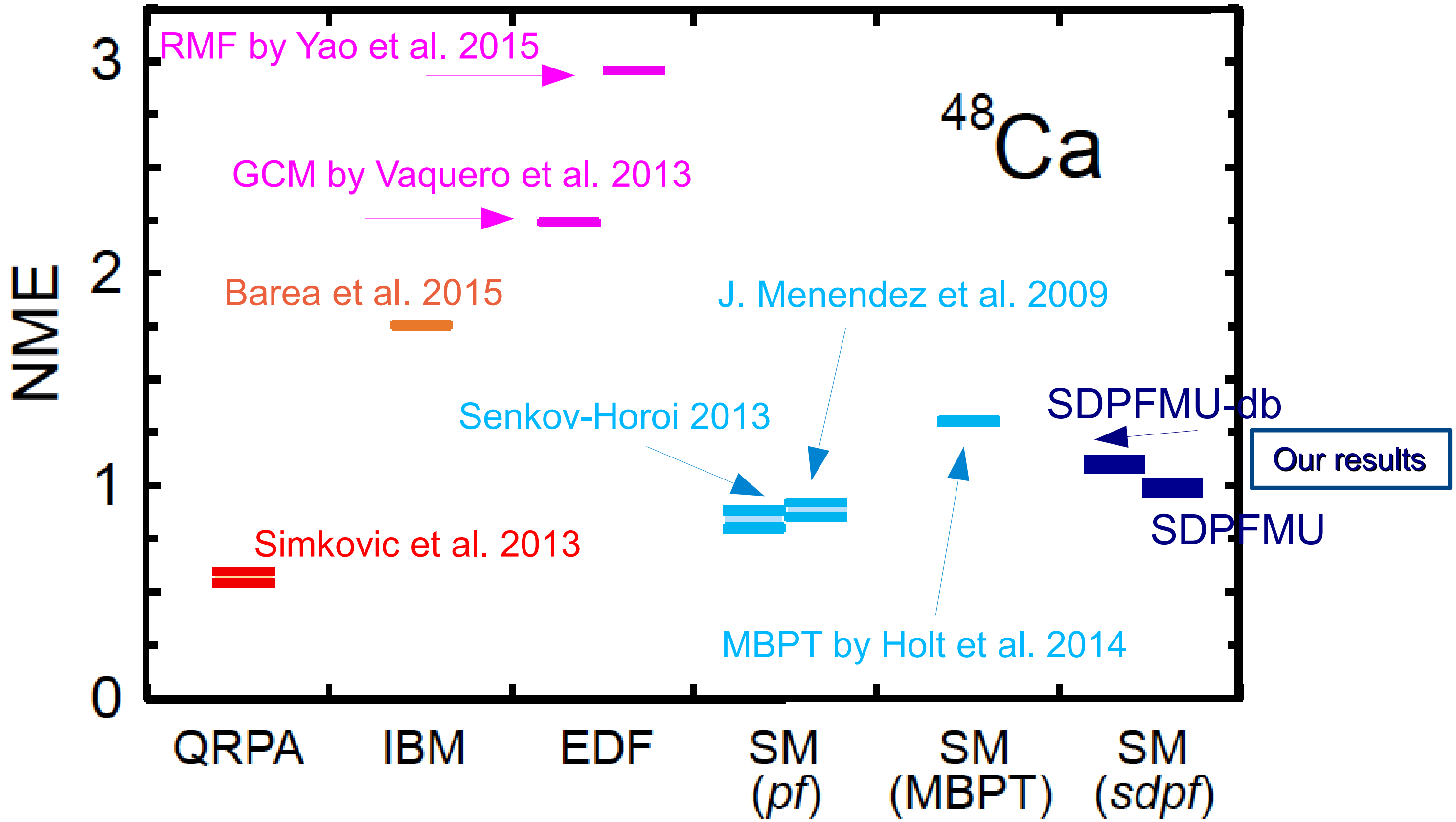

2nd $0^+$ state

2hw component ratio

SDPFMU-db
Ca48 (g.s.) , Ti48 (g.s.): 22%, 33%

# Summary: NME for 0νββ of $^{48}Ca$

Comparison of neutrinoless double beta decay NME (with ranges)




Y.I.-Shimizu-Otsuka-Utsuno-Menendez-Honma-Abe, Phys. Rev. Lett. 116 (2016) 112502
Large-scale shell model analysis on nuclear matrix element

# Constraint on the neutrino mass

$$\langle m_\nu \rangle = \sqrt{\frac{m_e^2}{|M^{0\nu}|^2 G^{0\nu}} \left[ T_{1/2}^{0\nu} \left( 0_i^+ \to 0_f^+ \right) \right]^{-1}}$$

Constants:

$G^{0\nu} = 1.27^4 \times 0.2989 \times 10^{-15}\ y^{-1}$ (for Ca48, Kotila-Iachello, PRC 2012)
$m_e = 5.110 \times 10^5$ eV
$T^{0\nu} > 5.8 \times 10^{22}$ y (ELEGANT IV, 2008)

Increase of the nuclear matrix element (NME) makes the experiment **sensitive to**
smaller neutrino masses (for the same half-life).

# Constraint on the neutrino mass

$$\langle m_\nu \rangle = \sqrt{\frac{m_e^2}{|M^{0\nu}|^2 G^{0\nu}} \left[ T_{1/2}^{0\nu} \left( 0_i^+ \rightarrow 0_f^+ \right) \right]^{-1}}$$

Constants:

$G^{0\nu} = 1.27^4 \times 0.2989 \times 10^{-15}\ \mathrm{y}^{-1}$ (for Ca48, Kotila-Iachello, PRC 2012)

$m_e = 5.110 \times 10^5$ eV

$T^{0\nu} >\ 5.8 \times 10^{22}$ y (ELEGANT IV, 2008)

10.1 eV (old)

Upper limit for the effective mass :

$\langle m_\nu \rangle\ < 7.5$ eV (new)

**The latest value using $^{48}$Ca**

# Constraint on the neutrino mass

10.1 eV (old)

Upper limit for the effective mass :

$\langle m_\nu \rangle < 7.5$ eV
(new)

**The latest value using $^{48}Ca$**

$$\langle m_\nu \rangle = \sqrt{\frac{m_e^2}{|M^{0\nu}|^2 G^{0\nu}} \left[ T_{1/2}^{0\nu} \left( 0_i^+ \to 0_f^+ \right) \right]^{-1}}$$

$T^{0\nu} > 5.8 \times 10^{22}$ y (ELEGANT IV, 2008)

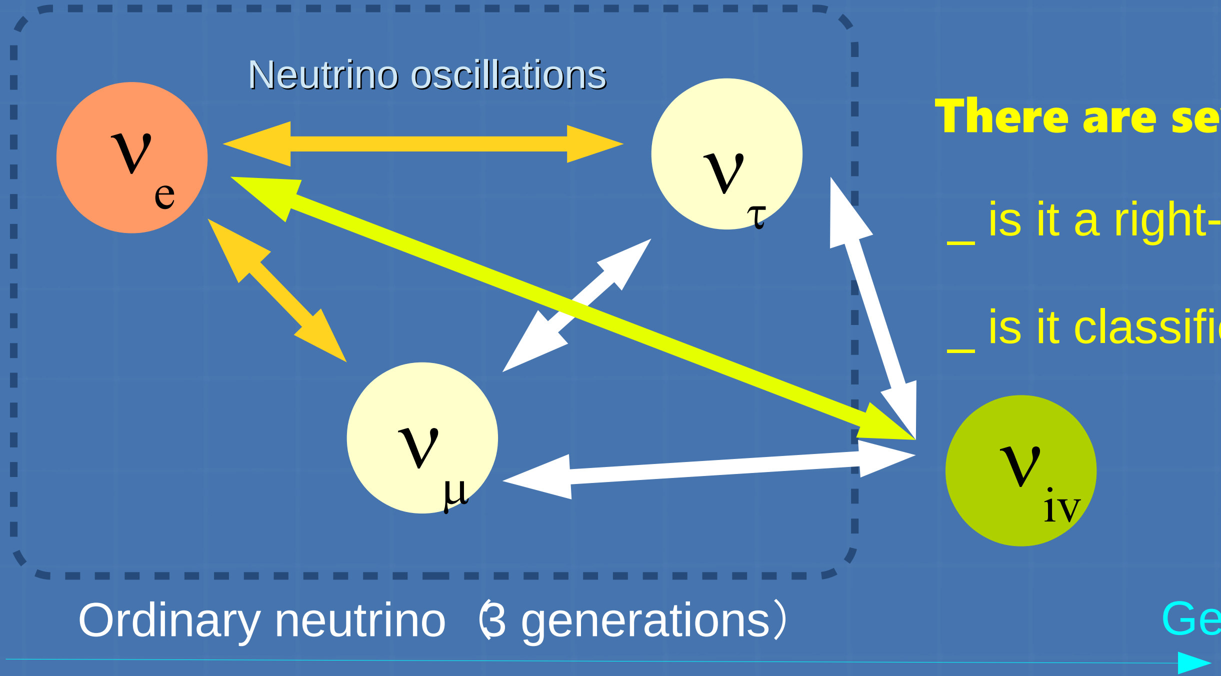
If this value becomes more precise, the predicted mass becomes smaller.

As a reference, in case of $^{136}Xe$

$T^{0\nu} > 1.9 \times 10^{25}$ y (Kamland-ZEN, 2013)

# Sterile neutrino

Mass range (at present) :
$10^{-10}$ to $10^{20}$ GeV/$c^2$




**There are several possibilities:**

_ is it a right-handed neutrino ?

_ is it classified to the 4th generation ?

Fact implying the existence of sterile neutrino :

_ LSND experiment (and also MiniBooNe experiment)

_ WMAP experiment … number of neutrino generation as 4.3.

# Sterile neutrino

Under assuming the following form ( assuming nonzero sterile neutrino mass), the NME value is calculated.

$$\left[T^{0\nu}_{1/2}\left(0^+_i \to 0^+_f\right)\right]^{-1} = G^{0\nu}\left\{|M^{0\nu}|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + |M^{0N}|^2\langle\eta_N\rangle^2\right\}$$

ordinary neutrino

Sterile neutrino

Refs. Vergados-Ejiri-Simikovic Rep Prog Phys (2012), Horoi PRC (2013)

View Points

1) The value of NME depends on the sterile neutrino mass.

2) Sterile neutrino mass appears in the representation.

These two effect can enhance or cancel with each other.

# Result: sterile neutrino

Neutrino potential (in general form)

$$H_\alpha(r) = \frac{2R}{\pi}\int_0^\infty \frac{f_\alpha(qr)\ h_\alpha(q)\ q^2}{\sqrt{q^2+m_\nu^2}(\sqrt{q^2+m_\nu^2}+\langle E\rangle)}\ dq$$

Massless limit

$$\frac{2R}{\pi}\int_0^\infty f_\alpha(qr)\frac{h_\alpha(q)}{q+<E>}q\ dq$$

Heavy mass limit

$M_{II}$

$$\frac{1}{m_\nu^2}\frac{2R}{\pi}\int_0^\infty f_\alpha(qr)h_\alpha(q)q^2\ dq$$

Ordinary neutrino (massless limit)

| | | |
|---|---|---|
| $M^{0\nu}$ | (1 major) | 0.833 |
| $M^{0\nu}$ | (2 major) | 1.118 |

34.2 % increased

Sterile neutrino (heavy mass limit)

| | | |
|---|---|---|
| $M^{0N}$ | (1 major) | 81.58 |
| $M^{0N}$ | (2 major) | 120.7 |

48.0 % increased

Consider "heavy mass limit" as an initialization of our research

**Simkovic unit**

$M_{II}$ / ( $m_e$ $m_p$ ) :

$m_e$ = 0.510999 MeV

$m_p$ = 938.2723 MeV

# Impact of sterile neutrino

Two unknown variables

$x$ $y$

$$\left[T^{0\nu}_{1/2}\left(0^+_i \rightarrow 0^+_f\right)\right]^{-1} = G^{0\nu}\left\{|M^{0\nu}|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + |M^{0N}|^2\langle\eta_N\rangle^2\right\}$$

$\eta_N$: effective mass of sterile neutrino (relative to electron mass)

[NME$^2$] 80 % increased

[NME$^2$] 119% increased

Square of mass ratio: $\langle\eta_N\rangle$ / $\langle m_\nu\rangle$ is decisive (to be studied).

If sterile neutrino exists,

The balance between 1st term and 2nd term of r.h.s. is dependent on the masses.

By means of precise NME values,
the possibility of the existence of heavy sterile neutrino is suggested to be determined by the half life measurement.

# Summary and Perspective

◆We have carried out large-scale shell model calculation
（up to 2 *$10^9$ dim diagonalization).

◆[Effect of the 2nd major shell]
→ More details are explained in
Y.I. *et al.*, Phys. Rev. Lett. 116 (2016) 112502
in terms of
"what causes the increase of NME; existence of cancellation".

...[Ordinary neutrino] **30%**↑,  [Sterile neutrino] **50%**↑

## Suggestion by "STERILE NEUTRINO" research:

◆Generally speaking, there is no prize for the 2nd experimental achievement, but this case will not ...

Indeed, measurement on one candidate cannot deny the existence of sterile neutrino, so that it is necessary to measure half life at least two candidates ...

In any case it is necessary to have precise NME values.