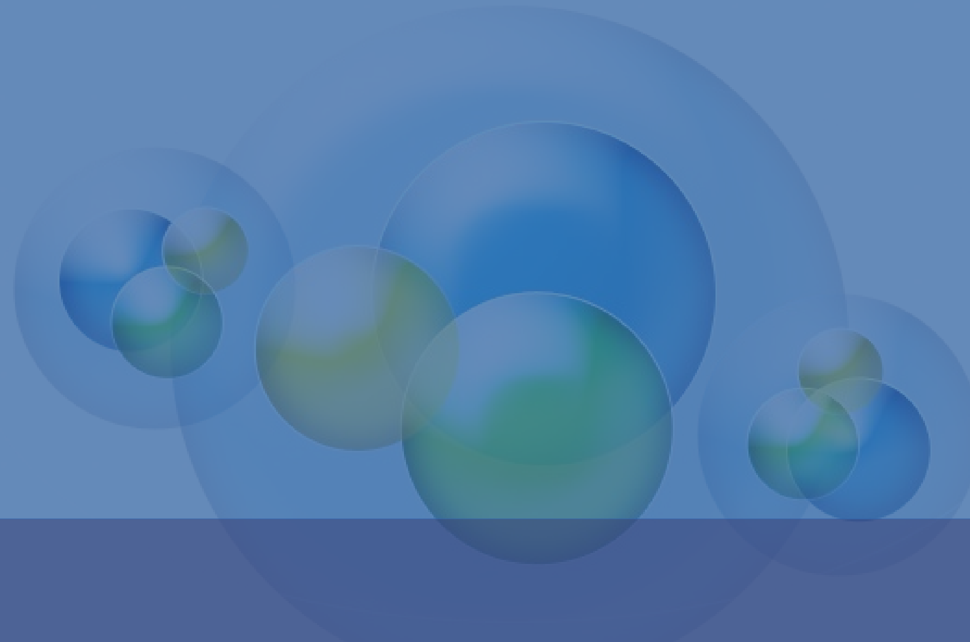


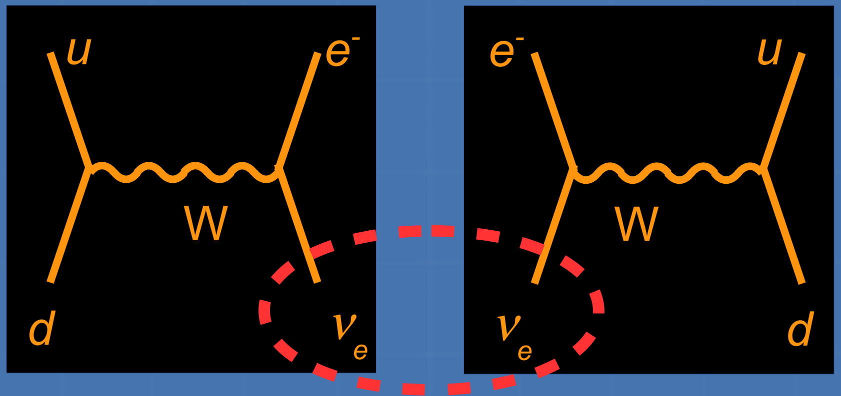
Constraining the neutrino mass with low-energy experiments on nuclei

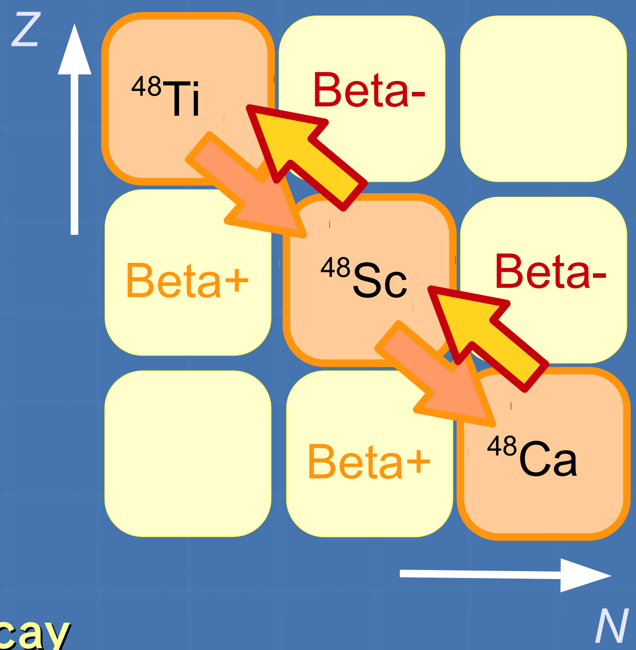
Institute for Innovative Research, Tokyo Institute of Technology

Yoritaka Iwata

Double beta decay of ^{48}Ca

$^{48}\mathrm{Ca} \rightarrow (^{48}\mathrm{Sc}) \rightarrow {}^{48}\mathrm{Ti}$





Two modes associated with double beta decay

2ν process (neutrino emission):
Take place when neutrinos is Majorana or Dirac particles:

$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}$$

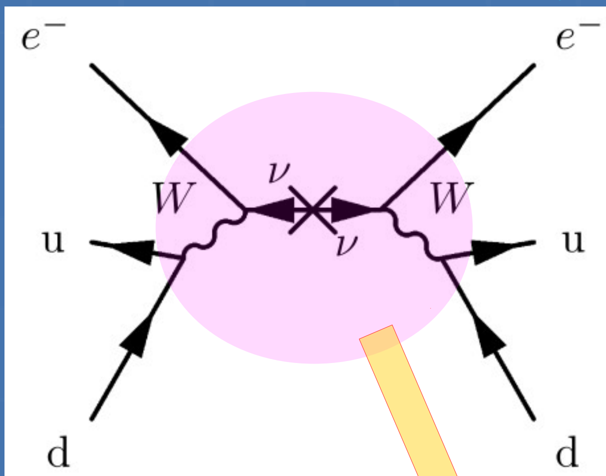
0ν process (neutrinoless):
Take place when neutrinos is Majorana particles:

$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

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

Nuclear Matrix element under the closure approx.

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

Fermi Gamow-Teller Tensor

$= H\alpha$ (α: 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

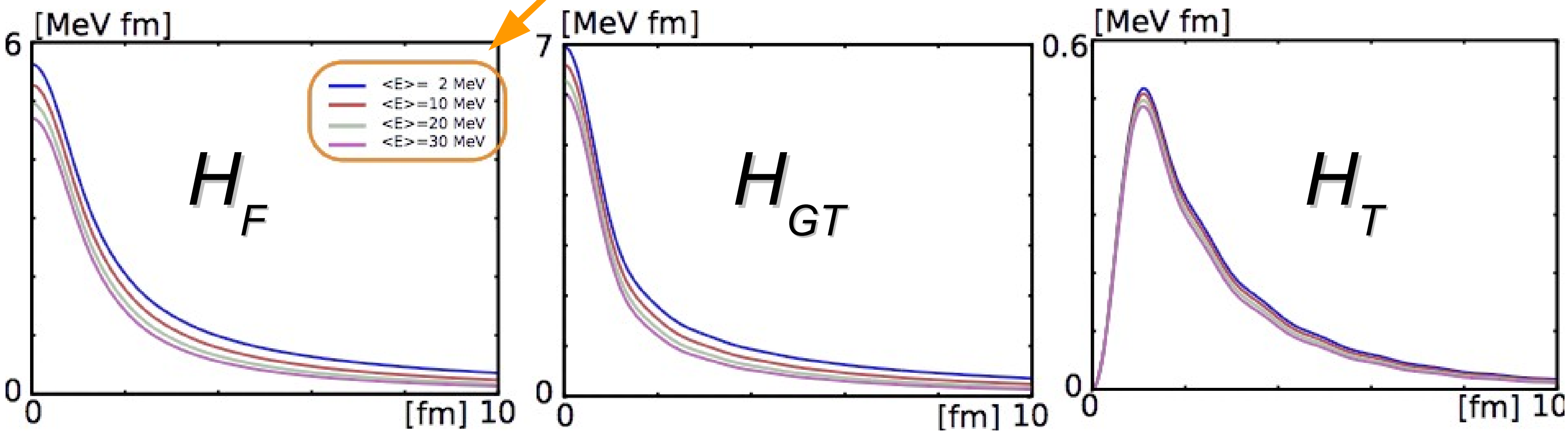
fα: spherical Bessel function (α=0,2)

α = *F*, *GT*, *T* (Fermi, Gamow-Teller, Tensor parts)

<*E*> dependence

<*E*> = 2 ~ 30 MeV

<*E*> : closure parameter
= average energy



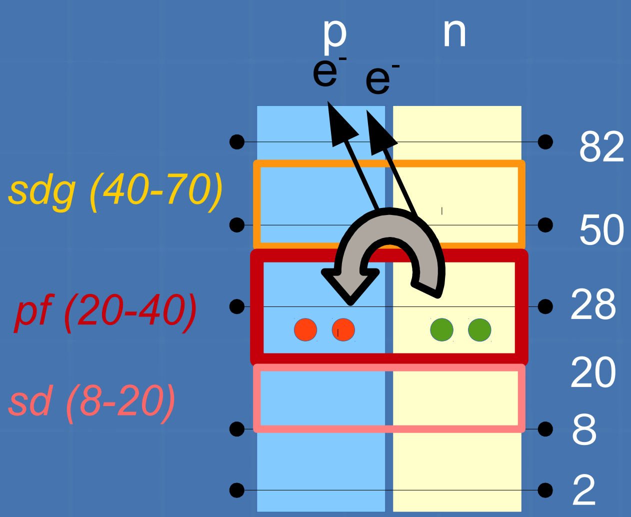
In the following <*E*> = 0.50 MeV, suggested by calc. w/o the closure approximation.
Senkov-Horoi-Brown PRC (2013)

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

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

$G^{0\nu}$: phase space factor
m_e: electron mass
These values are well known.



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 (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

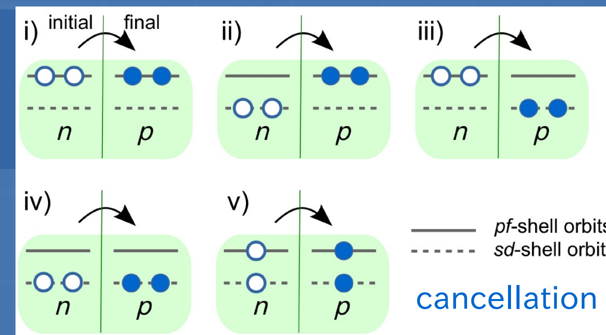
+1 shell — $\sim 10^9$ dim

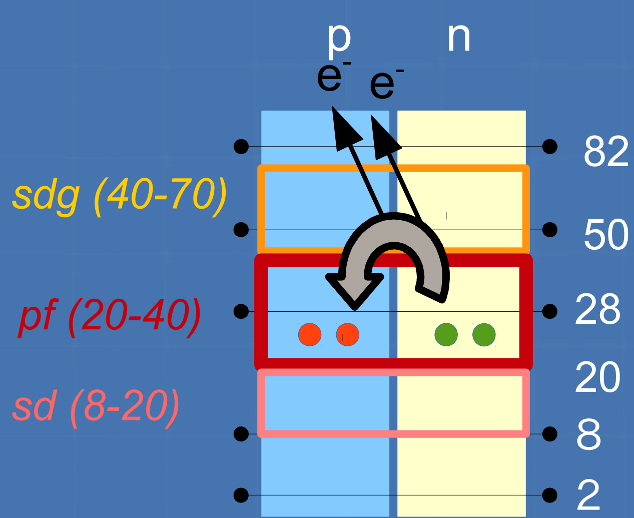
Neutrinos of ordinary type

Y.I.-Shimizu-Otsuka-Utsuno-Menendez-Honma-Abe, Phys. Rev. Lett. 116 (2016) 112502

Large-scale shell model analysis on nuclear matrix element

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





Inclusion rate of 2nd major shell components:

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

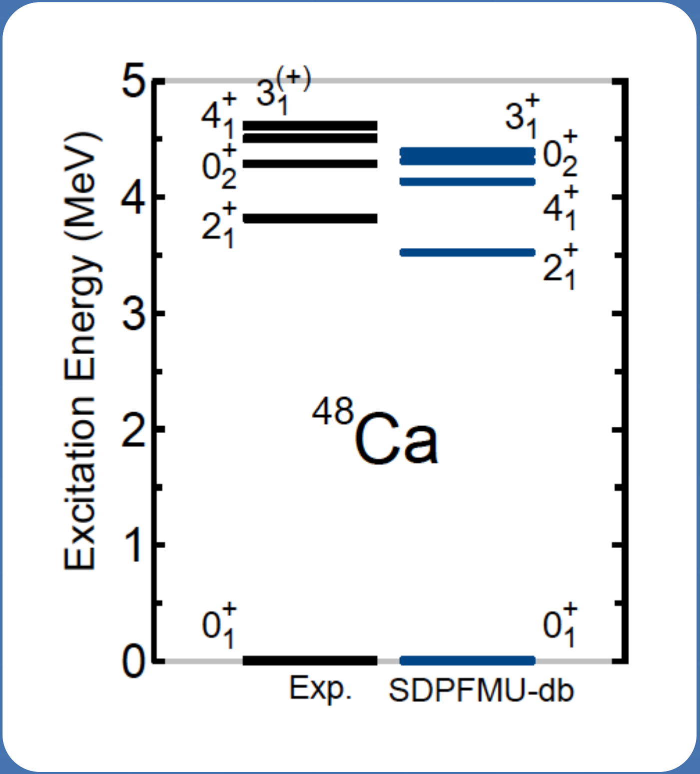
This result shows that
It should be necessary to take into account *sd* shell

$M^{0\nu}$ (1 shell)	0.833	34.2 % increased
$M^{0\nu}$ (2 shells)	1.118	

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 <u>SDPFMU-db</u> is compared to the experiment;
SDPFMU-db is an effective interaction made for 2 major shell description.



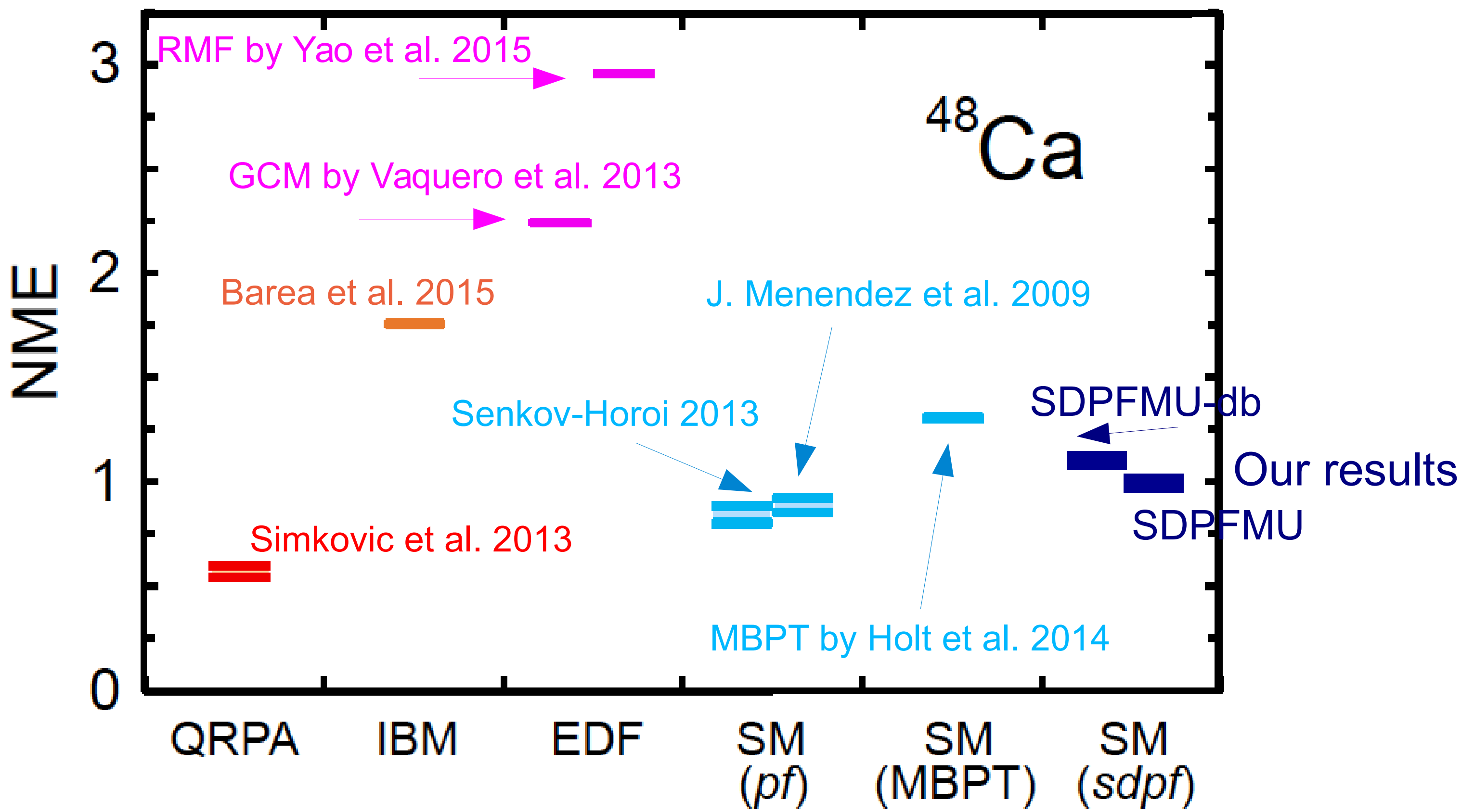
2nd 0^+ state

2hw component ratio

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

Summary: NME for $0\nu\beta\beta$ 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

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

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)

10.1 eV (old)

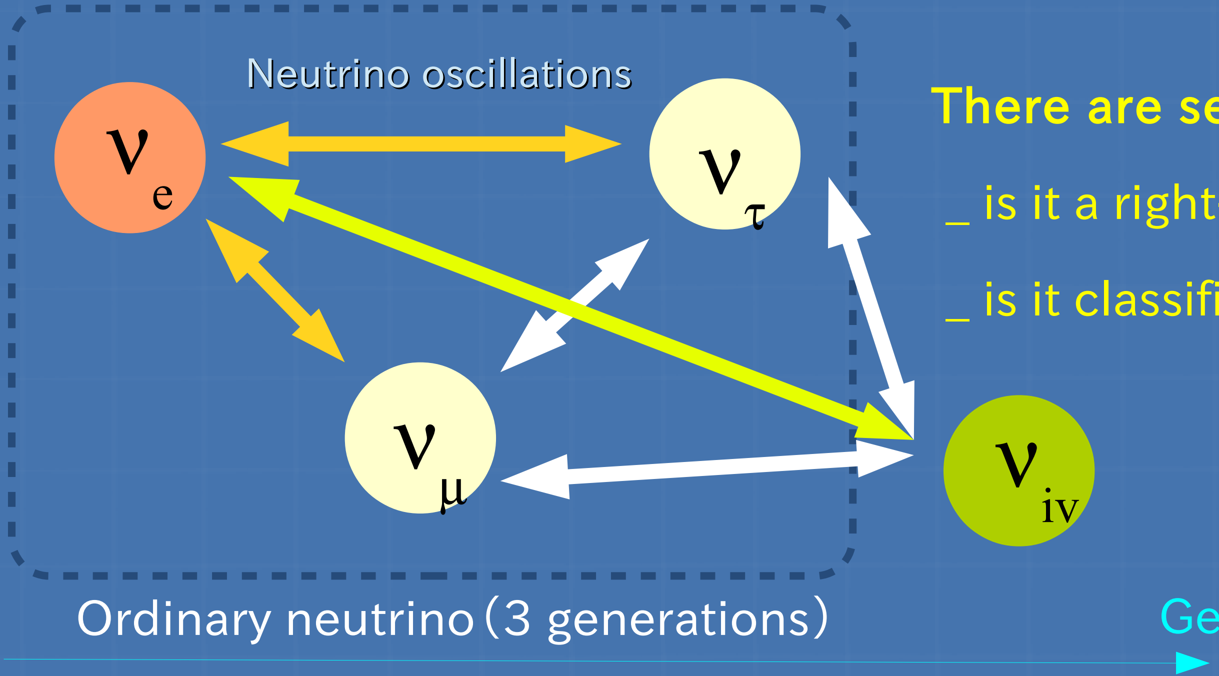
Upper limit for the effective mass:

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

The latest value using ^{48}Ca

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

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

η_N: effective mass of sterile neutrino
(relative to electron mass)

[NME²]

80 %
increased

[NME²]

119%
increased

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

Provided 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

Summary:

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

→ More details are explained in
Y.I. *et al.*, Phys. Rev. Lett. 116 (2016) 112502
in terms of
"how this calculation reproduce 2 neutrino processes "

◆[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", and "existence of cancellation".

…[Ordinary neutrino] 30%↑, [Sterile neutrino] 50%↑

Perspective:

◆ Constant on sterile neutrino mass (in preparation)

◆ The mechanism of double beta decay w.r.t. mass-dependence.