Neutrino Nuclear Responses for $\beta\beta-\nu$ & Charge Exchange Reactions

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Nuclear responses (matrix elements) for $\beta\beta-\nu$ and charge exchange reactions


H. Ejiri, Progress in Particle and Nuclear Physics, 64 (2010) 249-257
Nuclear matrix element for $\beta\beta$

Sensitivity of $m_\nu = k [M^{0\nu}]^{-1} [N_{\beta\beta}/B]^{-1/4}$ in case of $B>>1$

1. $M^{0\nu} = \langle \tau \tau \sigma \sigma \rangle$ is crucial for extracting $m_\nu$, CP phases, for designing exps. $M^{0\nu} 30\%$ leads to $N_{\beta\beta}$ detector 1/3

2. Sensitive to nuclear structures, $\tau \sigma$ corr., pp-correlation, effective $g_A$, short-range correlation.

3. Extremely small, $10^{-2} M^{SP}$, $10^{-4} M^{GR}$

4. $2\nu\beta\beta J^\pi=1$, $0\nu\beta\beta J^\pi=1+,2-,3+$, 6 for virtual $\nu q \sim 0.2$ GeV
A without shape change look good, but factor 2 in $M^{0\nu}$ gives 16 in detector volume.
$2\nu\beta \beta$ matrix element $1/m_e$

$E(2+ \text{ initial}) / E(2+ \text{ final})$

$\text{Ca, Nd, Nd', Cd, Zr, Mo, Mo'}$

$M^{2\nu}$ decrease as change of initial to final nuclear shapes near closed shell.

$M^{2\nu}$ with single lowest state is large due to the small denominator.

The ratio of the 1st excited state $E$ ~ deformation/shape/rigidity.

Xe predicted $>>$ observed
$M_{2\nu}^{\beta\beta} = \Sigma_k M_k^\beta M_k^b / \Delta_k$

$= \Sigma_k (g_{\text{eff}}^A)^2 (m_{ij})^2 V_n U_p V_p U_n / \Delta_k$

g_{\text{eff}}^A from \(\beta,\)EC exp. for \(M_k^\beta M_k^b\)


H. Ejiri Prog. Nuclear Particle Physics, 2009

\(136\text{Xe} \quad M=0.0185 \quad \text{FSQP} \quad T_{1/2}=6.3 \times 10^{20} \text{y} \quad T_{1/2}>8 \times 10^{21}\text{y}\)

\((g_{\text{eff}}^A)^2 \sim (0.25)^2 = 0.05\)

\(T^{0\nu} \sim (g_{\text{eff}}^A)^4 = 0.002\)
Nuclear $\tau\sigma$ responses for $\nu$ in $\beta$ & $\beta\beta$

Nuclear weak responses $\beta\beta-\nu$, solar-$\nu$, supernova $\nu$
Fermi- Isospin $\tau$
GT  Spin Isospin $\tau\sigma$

$\nu$-probe from J-PARC
$\gamma$-capture, $e$ scattering
$\nu$-probe from Spring-8, HIGS

CXR $^3\text{He}, t$ $t,^3\text{He}$ $d,^2\text{He}$
$N$ RCNP, MSU, KVI
2. Charge exchange reactions at RCNP for $\beta\beta-\nu$. 

A view from the Ejiri-Yokohama
CXR: Charge exchange reactions for $\tau\sigma\,\nu$-weak responses

RCNP ($^3\text{He}, t$) ($^7\text{Li}, ^7\text{Be}$), MSU ($t, ^3\text{He}$), KVI ($d, ^2\text{He}$)

I. Start 1995 for $\beta\beta$ & solar-$\nu$ (Akimune, Ejiri, Fujiwara et al)

II. 2007 $\Delta E \sim 10^{-4}$, Freckers Ejiri, Zegers et al. Ge, Se, Mo, Te, Xe

$V(\text{weak}) \neq V(\text{strong})$, non-central $V$, distortion, multi-step, etc.

CER q-dependence and EC/$\beta$ rates are used to get weak responses
Neutrino response Project

$\beta\beta$ and astro-neutrinos with $2^-$, weak $1^+$, CER, DCXR, $\nu^- e$, $\beta^- {^3}He, t$ RCNP $\Delta E/E = 0.03/450$

$e^- \nu, \beta^+ d, {^2}He$ RCNP LAS ($\Delta \phi = 240 \text{mr}$, $\Delta \theta = 125 \text{ mr}$, $\Delta p = \pm 15\%$ $\Delta E/E = x / 200$)
One state in FSQP, $^{100}$Mo

Ejiri et al (1997) $M_i = 0.56$


$M_i = 0.57$, agree with 1997 data

$M_i = 0.57$

$M_f = 0.55$

$\beta^-\text{decay}$

$M_1 = 0.11 \text{ me}^{-1}$, agree with

$M^{2\nu} = 0.09 \text{ (EL)} 0.12 \text{ (NEMO)}$
FSQP QP states at Fermi surface

Case I
Only one $1^+$ state
$^{96}$Zr, $^{100}$Mo, $^{116}$Cd .
($g7/2\ g9/2$)
$^{150}$Nd (h9/2,h11/2)

Case II
2-3 $1^+$ states
$^{76}$Ge, $^{82}$Se,
$^{128,130}$Te,
Fascination: With this 1 level only:

\[ T_{1/2}^{\text{calc.}} (2\nu\beta\beta) = (2.2 \pm 0.3) \cdot 10^{19} \text{ years} \]

\[ T_{1/2}^{\text{exp.}} (2\nu\beta\beta) = (2.2 \pm 0.4) \cdot 10^{19} \text{ years} \] (NEMO3-result)
Again!!

an anticorrelation
of strength
(very similar to $^{48}$Ca)

An effect of the
difference of
deformation ??

$^{76}$Se: oblate
($\beta_2 \sim -0.2$)

$^{76}$Ge: moderately
oblate/ prolate
($\beta_2 \sim 0.1$)
Correlate states within the experimental resolution

triplet of states: 0.044, 0.082, 0.12 MeV

76Se(d,²He)76As
\[ \Theta_{c.m.} \sim 0.4^\circ \]
\[ \Delta E = 120 \text{ keV} \]

76Ge(³He,t)76As
\[ \Theta_{c.m.} \sim 0.3^\circ \]
\[ \Delta E = 34 \text{ keV} \]
Effective $g_A$

$(g_A)^2 \sim 0.5$

$g_A \sim 0.7$

Nuclear medium effect

$g_A \sim 1$ (p,n)

g$^\text{eff}(1^+) = 0.24$, where 0.33 by GR shift and 0.7 by medium effect, likewise for 2-
One or several low-lying 1+ states of \([g7/2 \ g9/2]\) etc.
One or several low-lying 2- states of \([h11/2 \ g7/2]\) etc.
These contribute to \(2\nu\beta\beta\) and \(0\nu\beta\beta\) processes.
Nuclear Matrix elements from $0^+$ to $1^+$ and $2^-$

\[ M(1^+) \sim 0.4 \]
\[ g_{\text{eff}} = \frac{M(1^+)}{M(\text{SQP})} \sim 0.25 \]

\[ M(2^-) \sim 0.7 \times 10^{-3} \]
\[ g_{\text{eff}} = \frac{M(2^-)}{M(\text{SQP})} \sim 0.15 \]

\[ M^{0\nu} = <\tau \nu \sigma \bar{h}> \text{, with } h \sim \frac{R}{|r_1 - r_2|}, \]
\[ = \frac{R}{2<\sigma>^3} M_i M_f, \] Use exp. $M_i \sim g_{\text{eff}} M_{QP}, \ M_{QP} = <\tau> <\tau \sigma Y_1> U V$

$M^{0\nu} \sim 0.01$ for the lowest 2-state, sum $\sim 0.02$, while

QRPA $\sim 0.8$ with $g_{\text{eff}} \sim 1$ ($\sim 0.02$ with $g_{\text{eff}} \sim 0.15$) GR?
Takahisa Ejiri et al.,
Preliminary

$dE/TOF$

$^{11}$Li

$^{13}$C($^{11}$B, $^{11}$Li)$^{13}$O

881 MeV (80 MeV/A), 50 nA/electric, 7 mg/cm² (13C)
Photon $\gamma$


1. Neutral current responses
2. Isospin rotation for charged current responses via IAS

$\langle f \mid g M_\beta \mid i \rangle = g/e (2T)^{1/2} \langle f \mid e m_\gamma \mid I \rangle$

E1 and M1 $\gamma$

$P_\gamma(L)$ azimuthal distribution

HiGS Albert, Hiro, Mitzi,
Nuclear $\beta^+$ weak responses by $\mu$-capture and

H. Ejiri Proc. e-$\gamma$ conference Sendai 1972

Exp. $\sigma(\mu, Nn \gamma)$

MUSIC RCNP 10$^7$/s100nA

1. Large atomic cross section, capture probability $\sim 1$
2. E up to 100 MeV, $p \sim 100$ MeV/c, and $l \sim 1$-2

No of n and $\gamma$ & their $E$ give the strength distribution. Calibrate by $p/\alpha$ captures.

Remarks

The mountain log cottage at Tateshina
Mass sensitivities & nuclear sensitivity

\[ T^{0\nu} = |\langle m_\nu \rangle|^2 S_N \]
\[ <m_\nu> = S_N^{-1/2} (N_{\text{eff}})^{-1/2} \delta^{1/2} \]

\[ S_N = k [M^{0\nu}]^2 (G^{0\nu}/0.01A), \quad N_{\text{eff}} = \varepsilon^{0\nu} N \text{ t y}, \quad \delta \sim (BN)^{1/2} \]

\[ \beta\beta\text{-sources nuclear sensitivity} \]
\[ S_{N}^{-1/2} \sim 10 \text{ meV}, \quad M^{0\nu} \sim 3, \quad G^{0\nu} \sim 3 \times 10^{-14}/y, \quad Q_{\beta\beta} \sim 3 \text{MeV} \]
\[ A = 40\text{~to~}90\% \]
\[ \text{Production} \sim 0.1 \text{ t/y} \]
\[ \text{Note } N_0 = N/A^2 \]
\[ 100\text{~to}1.2 \text{ ton if } A=10\text{~to}90\% \]

\[ \text{Detector sensitivity} \]
\[ (N_{\text{eff}})^{-1/2} \delta^{1/2} \sim 2 \]
\[ \text{Detector} = \text{Source} \quad \varepsilon^{0\nu} \sim 0.7 \]
\[ N \sim 1.5 \text{ t y} \quad \delta \sim 3, \quad \Delta E \sim 5 \text{ keV}, \quad \text{BG: B} \sim 5 \text{ /t y} \]

\[ \text{Detector} \neq \text{Source} \quad \varepsilon^{0\nu} \sim 0.2 \]
\[ N \sim 5 \text{ t y} \quad \delta \sim 3, \quad \Delta E \sim 100 \text{ keV}, \quad \text{BG: B} \sim 5 \text{ /t y} \]
Nuclear sensitivity $S_N$ for $\beta\beta$-mass

$T^{0\nu} = |\langle m_\nu \rangle|^2 S_N$  $\langle m_\nu \rangle = S_N^{-1/2} (N_{\text{eff}})^{-1/2} \delta^{1/2}$

$S_N = [65 \text{ meV}]^{-2} [M^{0\nu}]^2 (G/0.01A) \quad G \text{ in } 10^{-14}/\text{y} \quad M^{0\nu}=3$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$G^{0\nu}$</th>
<th>$Q_{\beta\beta}$</th>
<th>$S_N$</th>
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<tbody>
<tr>
<td>136Xe</td>
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<tr>
<td>130Te</td>
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<td>100Mo*</td>
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<td>100Mo</td>
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<td>82Se</td>
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<td>76Ge</td>
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$G$ in $10^{-14}$, $Q_{\beta\beta}$ in MeV, $S$ in $10^{-3}/\text{meV}^2$
Neutrino mass sensitivities for $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{130}$Te

CUORE $B=33$), MOOM-PS($B=10$), MOOM-PL $B=7$), GERDA($B=20$)

$\varepsilon^{0\nu}=1$ $B=0$

$C m_\nu (N=1 \text{ t y})$ $D m_\nu (N=5 \text{ t y})$ $t \text{ y}=\text{ton year}$

$^{150}$Nd for the deformed excited state and less-deformed ground state if $\sim 40\%$
Concluding remarks

1. Neutrino nuclear responses ($M^{0\nu}$) are crucial for $0\nu\beta\beta$. Calculated values are very small and sensitive to nuclear parameters.

2. Experimental inputs such as $2\nu\beta\beta$, $\beta$–EC & charge exchange $1^+, 2^-$ and transfer reactions, etc are indispensable to get effective $g_A$, $\beta$-strengths for intermediate states, deformation effects, and p-h vacancy effects and others to help/verify calculations.

3. Charge exchange reactions (CER) with RCNP $^3$He, d and MSU t probes, the NewSUBARU/HIGS $\gamma$ probes, the RCNP $\mu$ probes and J- PARC $\nu$ probes in future are used for studying $\nu$ responses.

4. The $2\nu\beta\beta$ matrix elements are reproduced by FSQM. Extension to the $0\nu\beta\beta$ matrix elements is of great interest.

5. PS MOON(ZnMoO4) with 5keV, PSA/PS is most powerful for IH.

6. Coordinated/collaboration efforts for high-sensitivity $0\nu\beta\beta$ exps. and theoretical and experimental evaluations of $M^{0\nu}$ are of vital importance for QD- IH $\nu$-mass $0\nu\beta\beta$ studies.
A view from the mountain log cabin at Tateshina

Thanks for your attention