

Experimental Aspects of Nuclear Matrix Elements for Double Beta Decays and Astro Neutrinos

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Abstract. We report briefly recent experimental studies of nuclear responses (square of nuclear matrix element NME) for astro-neutrinos and double beta decays (DBDs) by single EC/ β decays, charge exchange reactions (CERs) and ordinary muon captures (OMCs). The NMEs are shown to be uniformly reduced with respect to quasi-particle and pnQRPA NMEs in wide multipole and momentum regions. The reduction is expressed by the quenching coefficient g_A^{eff}/g_A . Impact of the reduction on astro-neutrino and DBD studies is discussed.

1. Introduction

Double beta decay (DBD) is a sensitive and realistic probe to study neutrino properties such as the Majorana nature, the mass scale and spectrum, the CP phases and others beyond the standard model (SM). Astro-neutrino nuclear interactions are used to study astro-neutrino productions, neutrino oscillations and neutrino nucleo-syntheses. Neutrino nuclear responses (square of nuclear matrix element NME) for them are crucial for extracting neutrino properties of astro-particle interests, and even for designing DBD and astro-neutrino detectors.

NMEs are very sensitive to nuclear models and nuclear parameters to be used for calculating NMEs, and thus it is very hard to calculate theoretically accurate values for them. Therefore some experimental inputs for NMEs are important to help evaluate the NMEs. Recent works on the DBDs and the NMEs are given in reviews and references therein in [1, 2, 3, 4, 5, 6].

This is a brief report on experimental studies for the neutrino nuclear responses by using single EC/ β decays, charge exchange reactions (CERs) and ordinary muon captures (OMCs) [1, 2, 3, 5]. They are schematically shown in Fig. 1.

2. Axial-vector NMEs at low momentum region

Single β^\pm Gamow-Teller (GT) and spin dipole (SD) NMEs $M(\alpha)$ with α =GT and SD in the mass region of DBD nuclei are obtained from the observed $f_1 t$ values. The experimental NMEs $M_{EX}(\alpha)$ are reduced much with respect to simple quasi-particle NMEs $M_{QP}(\alpha)$ as shown in Fig. 2 [7, 8]. The NME is expressed as

$$M_{EX}(\alpha) = k(\alpha)M_{QP}(\alpha), \quad (1)$$

where $k(\alpha) \approx 0.20-0.25$ is the reduction coefficient.

M2 and M4 γ NMEs are mainly isovector ones and are analogous, respectively, to axial-vector β NMEs with $L=1, J=2$ and $L=3$ and $J=4$. They are also reduced with respect to the QP



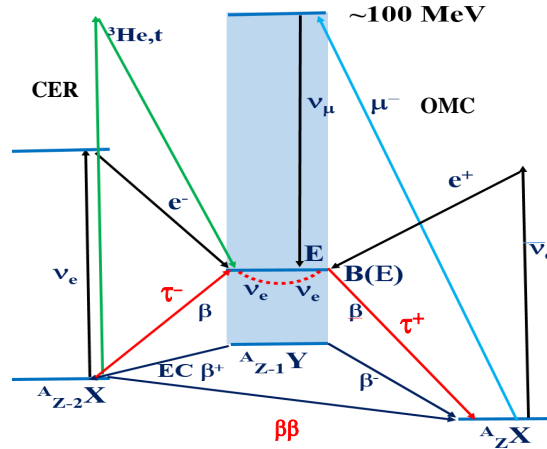


Figure 1. Schematic transition diagrams for EC/ β^+ and β^- decays, neutrino and anti-neutrino interactions, ordinary muon capture (OMC) reaction of (μ, ν_μ) , nuclear CER of $(^3\text{He}, t)$ and neutrino-less DBD via a light Majorana neutrino [2].

NMEs by a coefficient $k \approx 0.20-0.25$ as shown in Fig. 2. Here $k(\alpha)$ and k stand for all kinds of reduction effects, which are not included in the QP model. Among them, the nucleonic spin isospin correlations are included in pnQRPA (quasi particle random phase approximation) with adequate spin isospin interactions. Then the experimental NMEs are expressed as

$$M_{EX}(\alpha) = k_{NM}(\alpha)M_{QR}(\alpha), \quad (2)$$

where $k_{NM}(\alpha) \approx 0.4-0.6$ is the reduction coefficient due to non-nucleonic and nuclear medium effects that are not explicitly included in the pnQRPA model [7, 8]. It is expressed as the effective axial-vector coupling g_A^{eff} in units of the free one g_A as discussed in reviews [2, 5, 7, 8].

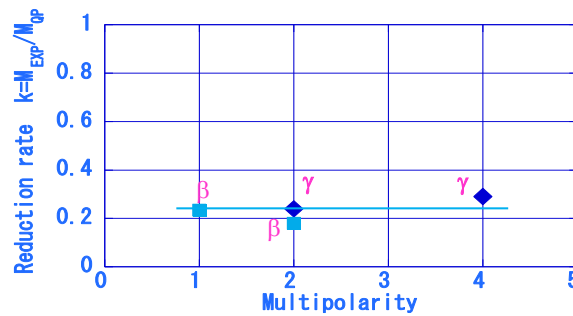


Figure 2. Average reduction coefficients for single GT, SD, M2 and M4 NMEs with respect to the QP NMEs are plotted against the multipolarity. Squares and diamonds are for β and γ decays.

3. Aaxial-vector NMEs by CERs and OMCs in the medium momentum

EC/ β^\pm NMEs discussed so far are associated with the low (0.3-3 MeV/c) momentum transfer, while supernova and neutrino-less DBD are associated with the medium momentum transfer of $q=30-100$ MeV/c.

High energy-resolution ($^3\text{He}, t$) CERs on DBD nuclei were used to study the q dependence of the τ^- -NMEs by observing the angular distribution of t over $\theta=0-4$ deg. [2, 9, 10, 11, 12, 13] The differential cross section is expressed as

$$\frac{d\sigma}{d\Omega} = K(\alpha)F(\alpha, q)J(\alpha)^2\kappa^{eff}(q)^2B(\alpha), \quad (3)$$

where $K(\alpha)$ and $J(\alpha)$ with $\alpha=\text{F, GT, and SD}$ are the kinematic factor and the volume integral of the interaction, respectively. The kinematic q -dependence is given by $F(\alpha, q)$. The q -dependent response is effectively expressed as $\kappa^{eff}(q)^2 B(\alpha)$ with $B(\alpha)$ being the nuclear response at $q=0$.

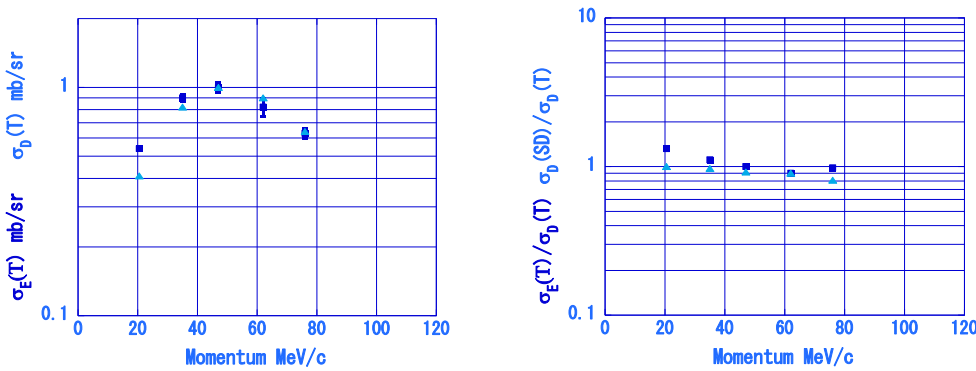


Figure 3. The ($^3\text{He}, t$) CER cross section for the lowest SD state in ^{130}Te as a function of the momentum transfer. Left panel: the experimental (squares) and DWBA (triangles) distributions. Right panel: the experimental to DWBA cross section ratios (squares) and the DWBA-SD to DWBA cross section ratios (triangles).

High energy-resolution ($^3\text{He}, t$) reactions on DBD nuclei were studied at RCNP. The differential cross sections for the F (IAS), GT and SD states show the momentum dependence as expected from the DWBA (Distorted Wave Born Approximation) kinematic distribution of $F(q, \alpha)$. Thus the nuclear responses are constant over the wide momentum transfer region. They are shown for the case of the SD state in ^{130}Te in Fig. 3 [10, 13]. It is interesting to note that the GT, and SD responses are reduced uniformly in the wide momentum region.

OMCs are used to study τ^+ -NMEs in the wide momentum and energy regions of $E \leq 60$ MeV and $P \leq 100$ MeV/c. The observed strength distribution shows a μ -capture giant resonance at around 10-15 MeV, and the observed OMC NME is reduced by a coefficient around $k \approx 0.4$ with respect to the pnQRPA NME. Thus the OMC NMEs with $J=1^\pm$ and 2^\pm are reduced as much as the τ^- NMEs in the medium momentum region [2, 14, 15, 16].

4. DBD NME and ν -mass sensitivity

The transition rate for the ν -mass mode DBD is proportional to $m_\nu \times M^{0\nu}$ with m_ν and $M^{0\nu}$ being the ν -mass and the DBD NME. Then an experimental limit on the DBD half-life gives a limit on $m_\nu \times M^{0\nu}$, and thus it gives a limit on m_ν only if one knows $M^{0\nu}$.

The limits on $m_\nu \times M^{0\nu}$ given by the lower limit of 10^{26} y for ^{76}Ge and ^{136}Xe are shown in Fig. 4. One needs to improve the experimental mass sensitivity by a factor 10-20 to access the IH (Inverted Hierarchy) ν -mass of around 20 meV, depending on the NME [2].

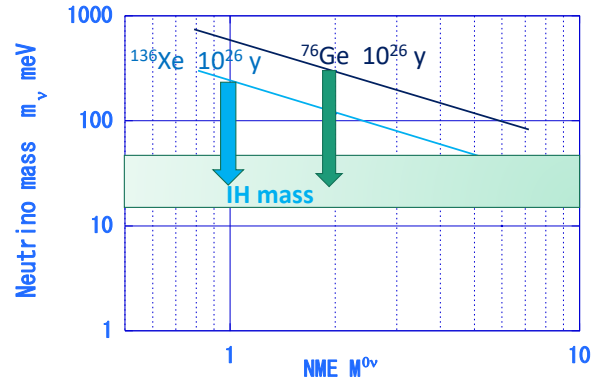


Figure 4. Limits on m_ν and $M^{0\nu}$. The lines show the upper limits in cases of $T_{1/2} \leq 10^{26}$ y for ^{76}Ge and that for ^{136}Xe . The green area: IH ν -mass region.

The ν -mass sensitivity for the DBD detector is defined as the minimum mass to be detected by the detector. It is given in case of the detection efficiency around 0.5 as

$$m_m \approx 2m_0(B/NT)^{1/4}, \quad m_0 = k/M^{0\nu}, \quad (4)$$

where m_0 is the unit mass to give the DBD rate =1 per ton year, NT is the isotope mass and exposure time in units of ton year and B is the BG rate per ton year. So a factor 2.5 in $M^{0\nu}$ corresponds to a factor 40 in NT or B . Then the factor 10-20 improvement in the ν mass from the present limits to the IH mass requires improvement by 4-5 orders of magnitude in the ratio of (B/NT) as shown in Fig. 4.

5. Concluding remarks

Experimental studies of weak NMEs by the high energy-resolution CERs and the OMCs are promising to provide data to help evaluate NMEs associated with astro-neutrinos and DBDs in the wide energy and momentum regions [2]. The axial-vector NMEs are reduced by the re-normalization coefficient $k_{NM} = g_A^{eff}/g_A \approx 0.3-0.5$ with respect to the pnQRPA NME. Accordingly the DBD NME may be reduced (quenched) by a coefficient around 0.2-0.4, depending on the vector DBD NME, with respect to the pnQRPA one with $g_A=1.27$ [2, 17].

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