Neutrinoless $\beta\beta$ Decay, Nuclear Matrix Elements and Weak Axial Coupling

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- Intro: DBD rates
- Effective value of $g_A$
- Impact on $0\nu\beta\beta$ NMEs
- OMC vs $0\nu\beta\beta$
- About reactor-$\bar{\nu}$ anomaly
INTRO: Rates of double beta decay

Two-neutrino $\beta\beta$ decay of $^{116}\text{Cd}$

$$t_{1/2}(2\nu\beta^-\beta^-) = (8.25 \pm 0.15) \times 10^{19} \text{ a}$$

$$2\nu\beta^-\beta^-$$

$$2\nu\beta\beta - \text{rate} \sim \left| M_{\text{GTGT}}^{(2\nu)} \right|^2 = (g_A)^4 \left| \sum_{m,n} \frac{M_L(1^+ M_R(1^+)}{D_m} \right|^2$$

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Neutrinoless $\beta\beta$ decay of $^{116}$Cd

\[
0^{+}_{\nu\beta\beta} \sim |M^{(0\nu)\text{GTGT}}|^2 = (g_{A,0\nu})^4 \sum_{J,\pi} |\mathcal{O}^{(0\nu)\text{GTGT}}(J,\pi)|^2 \left| 0^+_i \right|^2
\]
Motivation:

**Effective values of weak couplings** are involved in all weak processes, and thus have impact on

- **studies of rare $\beta$ decays**
- **processes in neutrino physics** ($\beta\beta$ decay, low-energy (anti)neutrino-nucleus scattering, nuclear muon capture, . . .)
- **processes in astrophysics** (allowed and forbidden $\beta$ decays, (anti)neutrino-nucleus scattering cross sections, . . .)
The free-nucleon value of $g_A$ is changed in nuclear-structure calculations by:

- Non-nucleonic degrees of freedom (e.g. $\Delta$ resonances)
- Effects beyond the impulse approximation (e.g. two-body meson-exchange currents)
- Deficiencies in nuclear many-body approaches (e.g. restricted valence spaces, lacking many-body configurations, omission of three-body nuclear forces)
Definitions


Nucleon weak current in a nucleus:

$$j^\mu_N = g_V \gamma^\mu - g_A \gamma^\mu \gamma^5$$

Quenching:

$$q = \frac{g_A}{g_A^{\text{free}}}$$

Free value of $g_A$ (Particle Data Group 2016) from the decay of free neutron:

$$g_A^{\text{free}} = 1.2723(23)$$

Effective value of $g_A$:

$$g_A^{\text{eff}} = q g_A^{\text{free}}$$
Gamow-Teller $\beta$ and $2\nu\beta\beta$ decays

There are data on:

**Gamow-Teller $\beta$ transitions and $2\nu\beta\beta$ transitions**

For these we have the low-momentum-exchange limit

$$g_{A,0\nu}(J^\pi) \xrightarrow{q \to 0} g_A(J^\pi),$$

where the usual convention is $g_A \equiv g_A(1^+)$

Nuclear models:

- ISM (Interacting Shell Model)
- pnQRPA (proton-neutron QRPA)
- IBM-2 (microscopic interacting boson model)
Typical Gamow-Teller $\beta$ and $2\nu\beta\beta$ transitions

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Results extracted from the GT $\beta+2\nu\beta\beta$ calculations


Faessler2007: pnQRPA A. Faessler et al., arXiv 0711.3996v1 [Nucl-th]


Forbidden $\beta$ decays and the value of $g_A$

Results from:

Quenching of $g_A(J^\pi)$

as derived from $\beta$ decays

of forbiddenness $K$
INCENTIVE: $0\nu\beta\beta$ decay through the higher angular-momentum states

$^{116}_{48}\text{Cd}_{68}\rightarrow 0^+_{gs}\rightarrow 1^+_{gs}^{116}_{49}\text{In}_{67}\rightarrow 0^+_{gs}$

$^{116}_{50}\text{Sn}_{66}\rightarrow$ stable $ightarrow 0^+_{gs}$
Novel approach: Spectrum-Shape Method (SSM)

Results for higher-multipole transitions:

Effective value of $g_A(J^\pi)$

as derived from electron spectra of

forbidden non-unique $\beta$ decays
Spectrum shape of higher-forbidden non-unique $\beta$ decays

Half-life:

$$t_{1/2} = \kappa / \tilde{C}.$$ 

Dimensionless integrated shape function:

$$\tilde{C} = \int_1^{w_0} C(w_e) p w_e (w_0 - w_e)^2 F_0(Z_f, w_e) \, dw_e.$$ 

Shape factor:

$$C(w_e) = \sum_{k_e,k_\nu,K} \lambda_{k_e} \left[ M_K(k_e, k_\nu)^2 + m_K(k_e, k_\nu)^2 - \frac{2\gamma_{k_e}}{k_e w_e} M_K(k_e, k_\nu) m_K(k_e, k_\nu) \right],$$

where

$$\lambda_{k_e} = \frac{F_{k_e-1}(Z, w_e)}{F_0(Z, w_e)}; \quad \gamma_{k_e} = \sqrt{k_e^2 - (\alpha Z_f)^2},$$

$F_{k-1}(Z, w_e)$ being the generalized Fermi function.

**Decomposition of the shape factor:**

$$C(w_e) = g_V^2 C_V(w_e) + g_A^2 C_A(w_e) + g_V g_A C_{VA}(w_e).$$
Normalized ISM-computed electron spectra for the 2nd-forbidden nonunique $\beta^-$ decays of $^{94}$Nb and $^{98}$Tc ($g_V = 1.0$).

From: J. Kostensalo, J. Suhonen, $g_A$-driven shapes of electron spectra of forbidden $\beta$ decays in the nuclear shell model, Phys. Rev. C 96 (2017) 024317
Example: Decay of $^{113}\text{Cd}$ – Comparison with data

Normalized electron spectra for the 4th-forbidden nonunique $\beta^-$ decay $^{113}\text{Cd}(1/2^+) \to ^{113}\text{In}(9/2^+)$ ($g_V = 1.0$).

Distribution of the best-match $g_A$ values from 44 detector units
Example: Decay of $^{113}$Cd – Comparison with data

$\bar{g}_A(\text{ISM}) = 0.915 \pm 0.007$

$\bar{g}_A(\text{MQPM}) = 0.911 \pm 0.013$

$\bar{g}_A(\text{IBFM-2}) = 0.955 \pm 0.022$
Example: Decay of $^{115}\text{In}$ – Comparison with data

Normalized electron spectra for the $4\text{th}$-forbidden nonunique $\beta^-$ decay

$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$

$(g_V = 1.0)$.

Result from The MIT-CSNSM-Jyväskylä collaboration: A. Leder et al., to be submitted.

\[ \bar{g}_A(\text{ISM}) = 0.83 \pm 0.03 \]

\[ \bar{g}_A(\text{IBFM-2}) = 0.88 \pm 0.06 \]

\[ \bar{g}_A(\text{MQPM}) = 0.94^{+0.03}_{-0.04} \]
Effects of quenched values of $g_A$

Results from:

Effects of a quenched $g_A$ on NMEs of $0\nu\beta\beta$ decays:

$$\left[T_{1/2}^{(0\nu)}\right]^{-1} = (g_{A,0\nu})^4 G^{(0\nu)} |M^{(0\nu)}|^2 \left(\frac{\langle m_{\nu}\rangle}{m_e}\right)^2$$

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_{V}}{g_{A,0\nu}}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$
Example: $0\nu\beta\beta$ NMEs of $^{76}\text{Ge}$, effect on the half-life

- **Menendez et al.**: Nucl. Phys. A 818 (2009) 139 (ISM)
- **Senkov et al.**: Phys. Rev. C 93 (2016) 044334 (ISM)
- **Suhonen**: Phys. Rev. C 96 (2017) 055501 (pnQRPA + isospin + data on $2\nu\beta\beta$)

\[ \langle m_\nu \rangle = 50 \text{ meV} \]
OMC as a probe of $0\nu\beta\beta$ NMEs

There are and will be more data on:

**CAPTURE RATES**

OF

**ORDINARY MUON CAPTURE (OMC)**

In particular:

**OMC STRENGTH FUNCTIONS**
Ordinary Muon Capture on $^{76}\text{Se}$

$^{76}\text{Se} + \mu^- \rightarrow ^{76}\text{As} + \nu_\mu$

$m_\mu c^2 \approx 105 \text{ MeV}$

- OMC and $0\nu\beta\beta$ operate in the $q \approx 100 \text{ MeV}$ momentum-exchange region $\Rightarrow g_{A,0\nu}(J^\pi)$
- Induced currents ($g_P$) are activated

Experiments:
- RCNP, Osaka
- J-PARC MLF, Japan
- PSI, Villigen, Switzerland

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Experimental and computed rates of OMC on $^{100}\text{Mo}$

**First evidence on OMC giant resonance:**

**Experiments:** MuSIC beam channel at RCNP (Research Center for Nuclear Physics), Osaka, Japan
D2 beam channel in J-PARC (Japan Proton Accelerator Research Complex) MLF, Ibaraki, Japan

**OMC giant resonance:**
L. Jokiniemi and J. Suhonen, Muon-capture strength functions in intermediate nuclei of $0\nu\beta\beta$ decays, Phys. Rev. C 100 (2019) 014619.
Novel application of electron spectra of forbidden decays

Investigating Reactor-$\bar{\nu}$ anomaly and the spectral shoulder
Neutrino-related anomalies could imply oscillations to sterile neutrinos

Sterile neutrinos:

- The gallium anomaly
- The reactor antineutrino anomaly

imply oscillations of the “ordinary” neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) to STERILE NEUTRINO in the mass range of a few eV

But what is the reactor antineutrino anomaly?

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The reactor antineutrino anomaly

The $\bar{\nu}_e$ flux from reactors has been measured in short-baseline neutrino-oscillation experiments$^1$: Daya Bay (in Daya Bay, China; 6 reactors, 8 detectors), RENO (South Korea; 2 detectors 294m and 1383 m from 6 reactors) and Double Chooz (Chooz, France, 2 detectors 400m and 1050 m from 2 reactors, schematic figure below).

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The neutrino-flux measurements find:

The reactor $\bar{\nu}_e$ anomaly:
The measured flux is some 5% smaller than that predicted from the $\beta$ decays of the fission yields of the reactor fuel.

#### Oscillations to STERILE NEUTRINOS

The bump anomaly:
There is an unexpected bump at 4 – 6 MeV (spectral shoulder) in the measured $\bar{\nu}_e$ spectrum.
Taking into account the (first-forbidden) decays of

\(^{86}\text{Br}(0^+)\), \(^{86}\text{Br}(2^+)\), \(^{87}\text{Se}\), \(^{88}\text{Rb}\), \(^{89}\text{Br}(3/2^-)\), \(^{89}\text{Br}(5/2^+)\), \(^{90}\text{Rb}\), \(^{91}\text{Kr}(5/2^-)\), \(^{91}\text{Kr}(3/2^-)\), \(^{92}\text{Rb}\), \(^{92}\text{Y}\), \(^{93}\text{Rb}\), \(^{94}\text{Y}(0^+)\), \(^{94}\text{Y}(0^+)\), \(^{95}\text{Rb}(7/2^+)\), \(^{95}\text{Rb}(3/2^+)\), \(^{95}\text{Sr}\), \(^{96}\text{Y}\), \(^{97}\text{Y}\), \(^{98}\text{Y}\), \(^{133}\text{Sn}\), \(^{134}\text{mSn}\), \(^{134}\text{Sb}(6^+)\), \(^{134}\text{mSb}(6^+)\), \(^{135}\text{Te}\), \(^{136}\text{mI}\), \(^{137}\text{I}\), \(^{138}\text{I}\), \(^{139}\text{Xe}\), \(^{140}\text{Cs}\), \(^{142}\text{Cs}\)

decreases the \(\bar{\nu}\) flux by a few %!

The spectral shoulder appears due to forbidden spectral corrections!

Conclusions and outlook

Conclusions:

- The effective value of $g_A$ is involved in all weak processes, and thus has impact on studies of rare $\beta$ decays, neutrino physics and astrophysics.
- The long chain of ISM calculations and the recent pnQRPA and IBM-2 calculations of Gamow-Teller $\beta$ decays and $2\nu\beta\beta$ decays are (surprisingly!) consistent with each other and clearly point to a $A$-dependent quenched $g_A$.
- The spectrum-shape method (SSM) for forbidden non-unique $\beta$ decays is a robust tool (largely independent of the nuclear model, the assumed Hamiltonian and mean field) to search for the effective value of $g_A$ and to try to solve other problems, like those related to the reactor-$\bar{\nu}$ spectra: Proper account of the spectral shapes of first-forbidden $\beta$ decays is instrumental in the quest for the solution to the anomaly.

- The OMC can test the weak axial couplings at the momentum-exchange region relevant for the $0\nu\beta\beta$ decay.

Outlook:

- Urge measurements of the $\beta$ spectra for the interesting decays amenable to the SSM.
- Measurements of the OMC rates for the $0\nu\beta\beta$-decay daughters will yield important information on the (induced) axial couplings relevant for $0\nu\beta\beta$ decay.
THANKS FOR PATIENCE!