Anomalies and Sterile Neutrinos – Implications of New Theoretical Results

MEDEX′19

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Why should we revisit the reactor antineutrino and gallium anomalies?

- They have been long unexplained.
- It has been suggested that new physics such as the existence of one or more eV-scale *sterile neutrinos* could be behind these discrepancies.
- Disagreement between experiment and theory has been reported at the 2–3σ level
- The previous theoretical estimates use **very crude approximations** but are often treated as reliable.

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Short-baseline reactor neutrino experiments have two problems when compared to theory:

1) Total number of detected antineutrinos is 6 % lower
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Problem

Many of the contributing decays are forbidden but often treated as allowed or unique to simplify the calculations.

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The β spectrum shape is given by

$$\frac{dN}{dW} = pW(W - W_0)^2 F(Z,W) C(Z,W) K(Z,W), \qquad (1)$$

where

- $pW(W-W_0)^2$ Kinematics
- $F(Z,W)$ Fermi-function (interaction of beta particle with the nucleus)
- $C(Z,W)$ Shape factor $\Leftarrow$ Nuclear physics!
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- The nuclear matrix elements
- The effective value of g_A
- Kinematic factors

Uncertainty in the spectral shape can be estimated by varying the ratios of the matrix elements. Based on earlier research we consider $g_A = 0.7$-1.27 and enhance the axial-charge matrix element by a 40%–100%.

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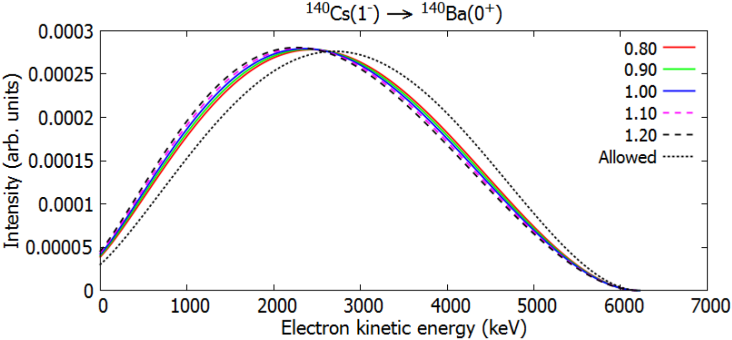
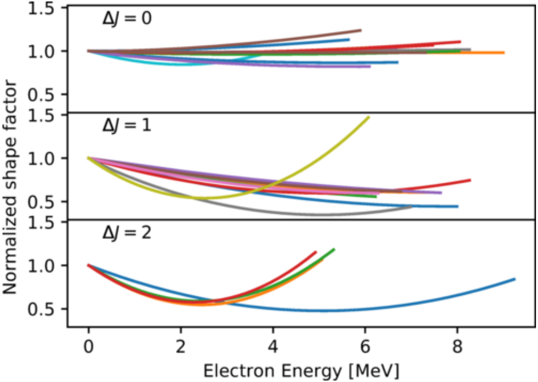
The allowed approximation is not always good:



J. K. and J. Suhonen, Int. J. Mod. Phys. A **33**, 1843008 (2018).

The shape factors of 29 most important forbidden decays:



L. Hayen, J. K., N. Severijns, J. Suhonen, Phys Rev. C **99**, 031301(R) (2019).

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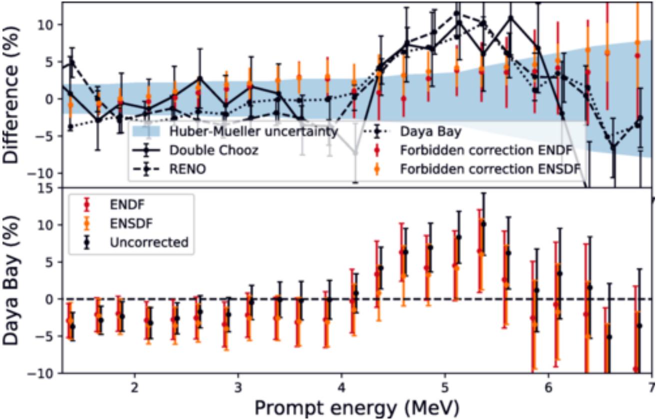

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Statistical analysis of Giunti and Laveder (2011) found a statistically significant difference between the experiments and the theoretical prediction of Bahcall at the 3.0σ level

Problem

The theoretical analysis assumes (p, n)-reaction BGTs and upper limits for BGTs are reliable estimates for weak BGTs

Solution?

Large-scale shell model calculation for the cross section. Tensor contributions in charge-exchange reactions.

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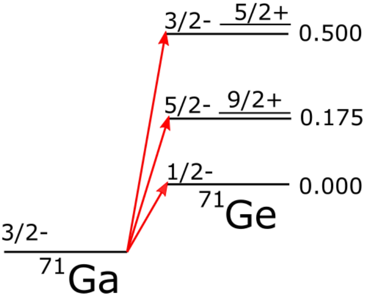
Evaluating the cross section:

- Gs-to-gs cross section can be deduced from beta decay of ^{71}Ge
- For the excited states other methods must be used (calculations, CERs)
- Bahcall used (p, n)-BGTs (more specifically half of the old upper limit <0.056 for $\mathrm{BGT}_{5/2-}/\mathrm{BGT}_{\mathrm{g.s.}}$)



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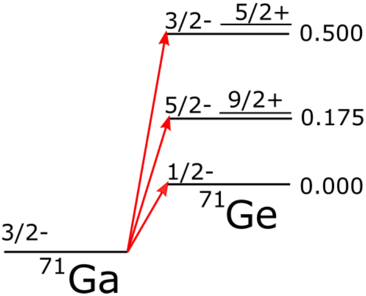

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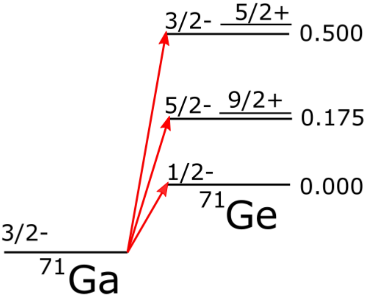

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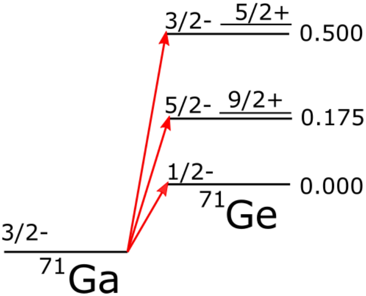

We ran new calculations using the nuclear shell model in the whole $0f_{5/2} - 1p - 0g9/2$ model space using several effective Hamiltonians of which the best turned out to be JUN45

- Reproduces the excitation spectrum relatively well
- Reproduces the ^{71}Ge half-life with $g_A = 0.955$
- Agreement with experimental dipole and quadrupole moments

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Table: Cross-section results for the ^{51}Cr neutrinos.

$1/2^-_{\mathrm{g.s.}}$	$5.53 \pm 0.07 \times 10^{-45}$
$5/2^-_1$	$1.21 \pm 0.61 \times 10^{-46}$
$9/2^+_1$	$\leq 10^{-56}$
$3/2^-_1$	$1.94 \pm 0.97 \times 10^{-47}$
total	$5.67 \pm 0.10 \times 10^{-45}$

Table: Cross-section results for the ^{37}Ar neutrinos.

$1/2^-_{\mathrm{g.s.}}$	$6.62 \pm 0.09 \times 10^{-45}$
$5/2^-_1$	$1.51 \pm 0.76 \times 10^{-46}$
$9/2^+_1$	$\leq 10^{-56}$
$3/2^-_1$	$2.79 \pm 1.40 \times 10^{-47}$
$5/2^+_1$	$5.91 \pm 2.96 \times 10^{-51}$
total	$6.80 \pm 0.12 \times 10^{-45}$

Shell model cross sections:

$$5.67 \pm 0.10 \times 10^{-45}\ \text{cm}^2 \quad (^{51}\text{Cr})$$

$$6.80 \pm 0.12 \times 10^{-45}\ \text{cm}^2 \quad (^{37}\text{Ar})$$

Bahcall cross sections:

$$5.81^{+0.21}_{-0.16} \times 10^{-45}\ \text{cm}^2 \quad (^{51}\text{Cr})$$

$$7.00^{+0.49}_{-0.21} \times 10^{-45}\ \text{cm}^2 \quad (^{37}\text{Ar})$$

Statistical significance of the gallium anomaly using the shell model cross sections with one-way t-test:

$$P = 0.09,$$

i.e. not statistically significant.

Problem

Charge-exchange reactions predict higher cross sections for the excited states. Why?

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Cross section can be expressed as

$$\sigma = \sigma_{\mathrm{gs}}\left(1 + \xi_{5/2^-}\frac{\mathrm{BGT}_{5/2^-}}{\mathrm{BGT}_{\mathrm{gs}}} + \xi_{3/2^-}\frac{\mathrm{BGT}_{3/2^-}}{\mathrm{BGT}_{\mathrm{gs}}}\right)$$

Study	Method	$\frac{\mathrm{BGT}_{5/2^-}}{\mathrm{BGT}_{\mathrm{gs}}}$	$\frac{\mathrm{BGT}_{3/2^-}}{\mathrm{BGT}_{\mathrm{gs}}}$
Krofcheck et al.	(p,n)	<0.057	0.126 ± 0.023
Bahcall		0.028	0.146
Frekers et al.	$(^3\mathrm{He},\mathrm{t})$	0.039 ± 0.030	0.202 ± 0.016
Present	ISM	0.033 ± 0.017	0.016 ± 0.008

Possible problems in extracting the BGT value:

- Extraction of the $[J_{pro}\ J_{tar}\ J_{rel}] = [110]$ component at 0°. Is the nuclear structure input valid and what are the uncertainties related to this?
- Relating the $[J_{pro}\ J_{tar}\ J_{rel}] = [110]$ component at 0° to the GT strength: possible significant contributions from $L = 2$ matrix element.

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Angular distribution analysis

"One-body transition densities (OBTDs) were calculated in the shell-model code NuShellX using the GXPF1a interaction in the full fp-model space"

Frekers et al. (2011)

Excitation spectrum of ^{71}Ge using this Hamiltonian:

$5/2^-$ 0.000 MeV
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$\mathrm{BGT}_{1/2-}$ 0.390
$\mathrm{BGT}_{5/2-}$ 0.001
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Requires $g_A \approx 0.6$ to reproduce the experimental half life of ^{71}Ge.

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With these the ground-state transition is 92%, transition to $5/2^-$ state is 40%, and the transition to $3/2^-$ state is 87 % [110]. How accurate are these?

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In (p,n)-reactions the interference between the Gamow-Teller (GT) and tensor (T) NMEs is described by the effective linear combination

$$\langle f||O_{(p,n)}||i\rangle = \langle f||O_{\mathrm{GT}}||i\rangle + \delta\langle f||O_{L=2}||i\rangle\,, \tag{2}$$

where i (f) is the initial (final) nuclear state and $\delta \approx 0.1$ is the mixing parameter.

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Table: Results for ^{71}Ga with $\delta = 0.097$.

State	$\langle f \| O_{\mathrm{GT}} \| i \rangle$	$\langle f \| O_{L=2} \| i \rangle$	$\mathrm{BGT}_{\beta}^{\mathrm{SM}}$	$\mathrm{BGT}_{(\mathrm{p,n})}^{\mathrm{SM}}$
$1/2^-_{\mathrm{g.s.}}$	-0.795	0.465	0.158	0.141
$5/2^-_1$	0.144	-1.902	0.0052	0.0004
$3/2^-_1$	0.100	0.0482	0.0025	0.0027

- There is a known large destructive interference for the $5/2^-$ state (Haxton 1998)
- New calculations show that there is a smaller destructive interference for the ground state
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- New calculations show that there is a smaller destructive interference for the ground state
- There is a constructive interference for the $3/2^-$ state
- The ratio $\mathrm{BGT}_{3/2^-}/\mathrm{BGT}_{\mathrm{gs}}$ is over estimated in CER

$L = 2$ matrix element

Suggests that the ratio $\mathrm{BGT}_{3/2^-}/\mathrm{BGT}_{\mathrm{gs}}$ is over estimated by at least 30 % in CERs.

Problem

There is still a factor 8 difference between the shell model results and the CER. Is the problem in theory or experiment?

Solution 1

Uncertainties in the mixing parameter: $L = 2$ contribution is actually larger. Also the [1 1 0] component at 0° might be smaller/larger for one of these transitions. No new particles.

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The shell model wave functions are not accurate. New physics.

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- New calculations for the reactor neutrino anomaly:
  1) Decrease the difference between experiment and theory
  2) Mitigate the spectral shoulder
- New calculations for the gallium anomaly:
  1) Decrease the difference between experimental and theoretical neutrino-nucleus scattering cross-sections
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- Conclusion: forbidden spectral shapes and tensor contributions in CERs must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

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