Anomalies and Sterile Neutrinos – Implications of New Theoretical Results

MPIK

Joel Kostensalo

University of Jyväskylä

January 13, 2020

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.
- The frequentistic framework which has been used to analyze the gallium anomaly is not very flexible and thus crude approximations have been used here as well.

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.
- The frequentistic framework which has been used to analyze the gallium anomaly is not very flexible and thus crude approximations have been used here as well.

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.
- The frequentistic framework which has been used to analyze the gallium anomaly is not very flexible and thus crude approximations have been used here as well.

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.
- The frequentistic framework which has been used to analyze the gallium anomaly is not very flexible and thus crude approximations have been used here as well.

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.
- The frequentistic framework which has been used to analyze the gallium anomaly is not very flexible and thus crude approximations have been used here as well.

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.
- The frequentistic framework which has been used to analyze the gallium anomaly is not very flexible and thus crude approximations have been used here as well.


Reactor
antineutrino
anomaly

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

1) Total number of detected antineutrinos is 6 % lower
2) Detected energy spectrum has a bump

Problem

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

Solution

Calculate the shape factors without these approximations using the nuclear shell model.

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

1) Total number of detected antineutrinos is 6 % lower
2) Detected energy spectrum has a bump

Problem

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

Solution

Calculate the shape factors without these approximations using the nuclear shell model.

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

1) Total number of detected antineutrinos is 6 % lower
2) Detected energy spectrum has a bump

Problem

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

Solution

Calculate the shape factors without these approximations using the nuclear shell model.

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

1) Total number of detected antineutrinos is 6 % lower
2) Detected energy spectrum has a bump

Problem

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

Solution

Calculate the shape factors without these approximations using the nuclear shell model.

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

1) Total number of detected antineutrinos is 6 % lower
2) Detected energy spectrum has a bump

Problem

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

Solution

Calculate the shape factors without these approximations using the nuclear shell model.

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!
- $K(Z,W)$ Higher-order corrections

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!
- $K(Z,W)$ Higher-order corrections

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!
- $K(Z,W)$ Higher-order corrections

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!
- $K(Z,W)$ Higher-order corrections

The β spectrum shape is given by

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

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!
- $K(Z,W)$ Higher-order corrections

In the first-order the shape factor is simple for allowed and unique decays, complicated for non-unique decays. For non-unique decays the shape factor depends on

- 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%.

In the first-order the shape factor is simple for allowed and unique decays, complicated for non-unique decays. For non-unique decays the shape factor depends on

- 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%.

In the first-order the shape factor is simple for allowed and unique decays, complicated for non-unique decays. For non-unique decays the shape factor depends on

- 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 $g_A = 0.7\text{-}1.27$ and enhance the axial-charge matrix element by a 40%–100%.

In the first-order the shape factor is simple for allowed and unique decays, complicated for non-unique decays. For non-unique decays the shape factor depends on

- The nuclear matrix elements
- The effective value of g_A
- Kinematic factors

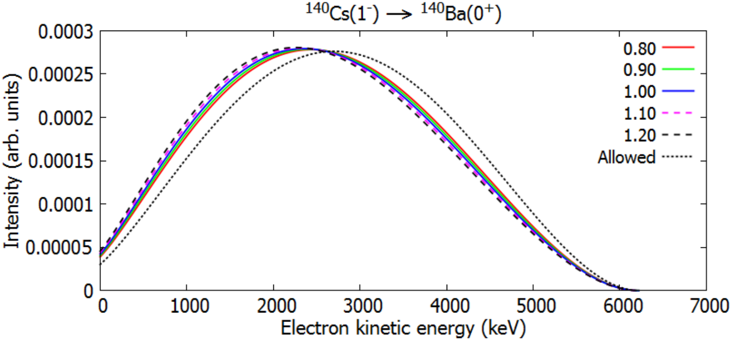
Uncertainty in the spectral shape can be estimated by varying the ratios of the matrix elements. Based on earlier research we consider $g_A = 0.7$-1.27 and enhance the axial-charge matrix element by a 40%–100%.

In the first-order the shape factor is simple for allowed and unique decays, complicated for non-unique decays. For non-unique decays the shape factor depends on

- 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 $g_A = 0.7\text{-}1.27$ and enhance the axial-charge matrix element by a 40%–100%.

The allowed approximation is not always good:



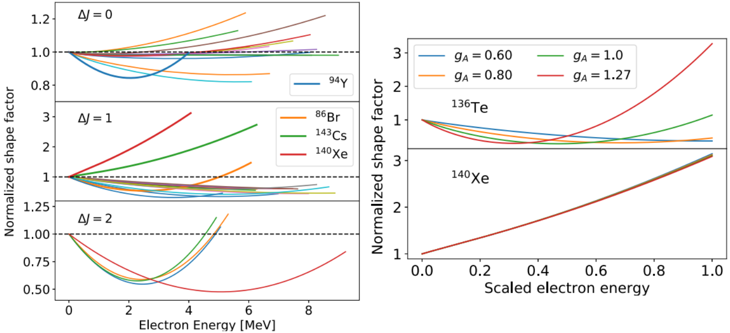
J. K. and J. Suhonen, Int. J. Mod. Phys. A **33**, 1843008 (2018).

We calculated 36 of the most important first forbidden transitions in the shell model framework. With the traditional ϵ_{MEC} and g_A adjustments we can reproduce experimental half-lives:

Nucleus	g_A with glbepn interaction		
	ϵ_{mec}=1.4	1.7	2.0
^{92}Rb	0.74(1)	0.62(1)	0.53(1)
^{93}Y	1.25(15)	1.03(17)	0.85(30)
^{95}Sr	0.88(4)	0.70(4)	0.58(3)
^{96}Y	0.96(1)	0.80(1)	0.69(1)
^{97}Y	0.85(15)	0.70(13)	0.59(12)
Average	0.94 ± 0.08	0.77 ± 0.07	0.65 ± 0.06

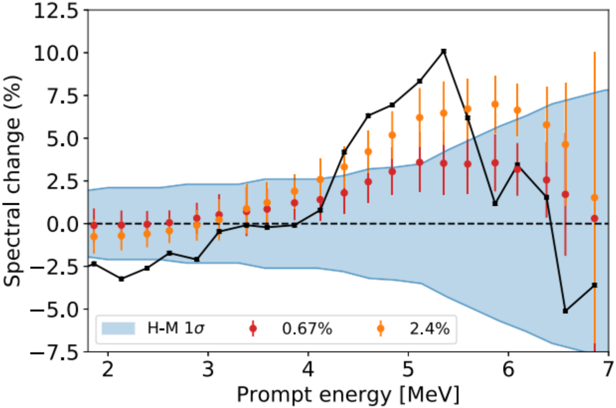
Nucleus	$g_A(\gamma_5)$ with jj56cdb int.			g_A with jj56pnb int.		
	ϵ_{mec}=1.4	1.7	2.0	1.4	1.7	2.0
^{133}Sn	0.94(2)	0.80(2)	0.69(2)	0.94(2)	0.80(2)	0.69(2)
^{134}Sb	1.18(6)	0.99(5)	0.85(5)	0.85(4)	0.71(4)	0.62(3)
^{135}Te	0.86(2)	0.74(3)	0.65(2)	0.96(3)	0.84(3)	0.74(3)
^{137}Xe	0.74(2)	0.65(2)	0.58(2)	0.81(3)	0.71(2)	0.64(3)
^{139}Ba	0.68(1)	0.60(1)	0.54(1)	0.72(1)	0.64(1)	0.58(1)
^{139}Cs	1.15(3)	1.00(2)	0.88(2)	0.91(2)	0.79(2)	0.69(2)
Average	0.93 ± 0.08	0.87 ± 0.06	0.70 ± 0.06	0.87 ± 0.04	0.75 ± 0.03	0.66 ± 0.03

The shape factors of 36 most important forbidden decays:



L. Hayen, J. K., N. Severijns, J. Suhonen, Phys Rev. C **100**, 054323 (2019). These decays account for about 40% cumulative spectrum between 4–7 MeV.

The inclusion of the forbidden spectra mitigates the spectral shoulder and increases the uncertainties related to the antineutrino flux.



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

The inclusion of the forbidden spectra mitigates the spectral shoulder and increases the uncertainties related to the antineutrino flux. The new calculations increase the total theoretical antineutrino spectrum by 0.8(13) %.

⇒ When combined with normalization uncertainties the statistical significance is unaltered.

⇒ The forbidden transitions must be taken into account without using the allowed or unique approximations. The uncertainties related to the forbidden decays are a leading cause for total flux uncertainty.

⇒ Precise measurement of these spectra (and the branching ratios) is needed to verify/explain the reactor antineutrino anomaly.

The inclusion of the forbidden spectra mitigates the spectral shoulder and increases the uncertainties related to the antineutrino flux. The new calculations increase the total theoretical antineutrino spectrum by 0.8(13) %.

⇒ When combined with normalization uncertainties the statistical significance is unaltered.

⇒ The forbidden transitions must be taken into account without using the allowed or unique approximations. The uncertainties related to the forbidden decays are a leading cause for total flux uncertainty.

⇒ Precise measurement of these spectra (and the branching ratios) is needed to verify/explain the reactor antineutrino anomaly.

The inclusion of the forbidden spectra mitigates the spectral shoulder and increases the uncertainties related to the antineutrino flux. The new calculations increase the total theoretical antineutrino spectrum by 0.8(13) %.

$\Rightarrow$ When combined with normalization uncertainties the statistical significance is unaltered.

$\Rightarrow$ The forbidden transitions must be taken into account without using the allowed or unique approximations. The uncertainties related to the forbidden decays are a leading cause for total flux uncertainty.

$\Rightarrow$ Precise measurement of these spectra (and the branching ratios) is needed to verify/explain the reactor antineutrino anomaly.

The inclusion of the forbidden spectra mitigates the spectral shoulder and increases the uncertainties related to the antineutrino flux. The new calculations increase the total theoretical antineutrino spectrum by 0.8(13) %.

$\Rightarrow$ When combined with normalization uncertainties the statistical significance is unaltered.

$\Rightarrow$ The forbidden transitions must be taken into account without using the allowed or unique approximations. The uncertainties related to the forbidden decays are a leading cause for total flux uncertainty.

$\Rightarrow$ Precise measurement of these spectra (and the branching ratios) is needed to verify/explain the reactor antineutrino anomaly.


Gallium anomaly

The gallium anomaly refers to the missing electron-neutrino flux from ^{37}Ar and ^{51}Cr electron-capture decays as measured by the GALLEX and SAGE solar-neutrino detectors

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 1 (small)

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.

The gallium anomaly refers to the missing electron-neutrino flux from ^{37}Ar and ^{51}Cr electron-capture decays as measured by the GALLEX and SAGE solar-neutrino detectors

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 1 (small)

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.

The gallium anomaly refers to the missing electron-neutrino flux from ^{37}Ar and ^{51}Cr electron-capture decays as measured by the GALLEX and SAGE solar-neutrino detectors

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 1 (small)

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.

The gallium anomaly refers to the missing electron-neutrino flux from ^{37}Ar and ^{51}Cr electron-capture decays as measured by the GALLEX and SAGE solar-neutrino detectors

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 1 (small)

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.

Problem 2 (big)

The statistical analysis includes large simplifications, such as assuming normal distributions where one should not.

Solution

It is possible to build a hierarchical model and compare the experimental and theoretical results using a Bayesian approach. This allows us to take into account all the uncertainties in a practically implementable way.

Problem 2 (big)

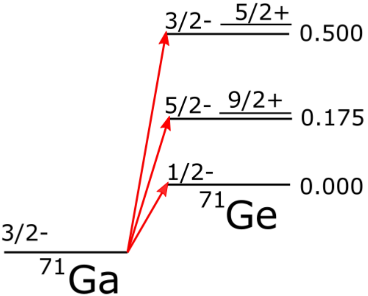
The statistical analysis includes large simplifications, such as assuming normal distributions where one should not.

Solution

It is possible to build a hierarchical model and compare the experimental and theoretical results using a Bayesian approach. This allows us to take into account all the uncertainties in a practically implementable way.

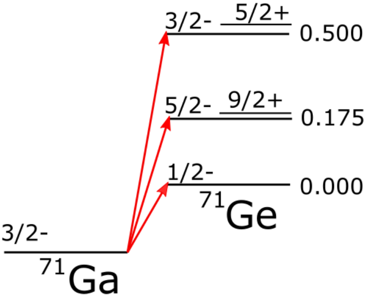
Evaluating the cross section:

- 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 $\mathrm{BGT}_{5/2-}/\mathrm{BGT}_{\mathrm{g.s.}}$)



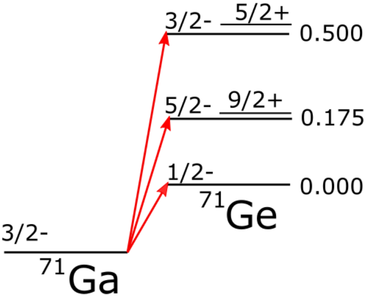
Evaluating the cross section:

- 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 $BGT_{5/2-}/BGT_{g.s.}$)



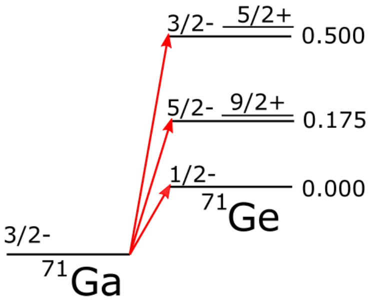
Evaluating the cross section:

- 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 $\mathrm{BGT}_{5/2-}/\mathrm{BGT}_{\mathrm{g.s.}}$)



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 $\mathrm{BGT}_{5/2-}/\mathrm{BGT}_{\mathrm{g.s.}}$)



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

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

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

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

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

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

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

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

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

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

Problem

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

Cross section can be expressed as

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

Study	Method	$\frac{\mathrm{BGT}_{5/2^-}}{\mathrm{BGT}_{gs}}$	$\frac{\mathrm{BGT}_{3/2^-}}{\mathrm{BGT}_{gs}}$
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
Kostensalo et al.	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.

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.

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.

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
$1/2^-$ 0.388 MeV
$3/2^-$ 1.496 MeV

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
$1/2^-$ 0.388 MeV
$3/2^-$ 1.496 MeV

This interaction's one-body transition densities (OBTDs) give the BGT values

$BGT_{1/2-}$ 0.390
$BGT_{5/2-}$ 0.001
$BGT_{3/2-}$ 0.271

Requires $g_A \approx 0.6$ to reproduce the experimental half life of ^{71}Ge.

Possible problem

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?

This interaction's one-body transition densities (OBTDs) give the BGT values

$BGT_{1/2-}$ 0.390
$BGT_{5/2-}$ 0.001
$BGT_{3/2-}$ 0.271

Requires $g_A \approx 0.6$ to reproduce the experimental half life of ^{71}Ge.

Possible problem

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?

This interaction's one-body transition densities (OBTDs) give the BGT values

$BGT_{1/2-}$ 0.390
$BGT_{5/2-}$ 0.001
$BGT_{3/2-}$ 0.271

Requires $g_A \approx 0.6$ to reproduce the experimental half life of ^{71}Ge.

Possible problem

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?

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

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

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

The interference can be constructive or destructive.

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.

The interference can be constructive or destructive.

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.

The interference can be constructive or destructive.

Anomalies & Sterile Neutrinos

Joel Kostensalo

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

State	$\langle f \| O_{\mathrm{GT}} \| i \rangle$	$\langle f \| O_{L=2} \| i \rangle$	$\mathrm{BGT}^{\mathrm{SM}}_{\beta}$	$\mathrm{BGT}^{\mathrm{SM}}_{(\mathrm{p,n})}$
$1/2^-_{\mathrm{g.s.}}$	-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
- There is a constructive interference for the $3/2^-$ state
- The ratio $\mathrm{BGT}_{3/2^-}/\mathrm{BGT}_{gs}$ is over estimated in CER

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
- 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

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

State	$\langle f \| O_{GT} \| i \rangle$	$\langle f \| O_{L=2} \| i \rangle$	BGT_{β}^{SM}	$BGT_{(p,n)}^{SM}$
$1/2^-_{g.s.}$	-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
- There is a constructive interference for the $3/2^-$ state
- The ratio $BGT_{3/2^-}/BGT_{gs}$ is over estimated in CER

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

State	$\langle f \Vert O_{GT} \Vert i \rangle$	$\langle f \Vert O_{L=2} \Vert i \rangle$	BGT^{SM}_{β}	$BGT^{SM}_{(p,n)}$
$1/2^-_{g.s.}$	-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
- There is a constructive interference for the $3/2^-$ state
- The ratio $BGT_{3/2^-}/BGT_{gs}$ is over estimated in CER

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

State	$\langle f \lVert O_{\mathrm{GT}} \rVert i \rangle$	$\langle f \lVert O_{L=2} \rVert i \rangle$	$\mathrm{BGT}_{\beta}^{\mathrm{SM}}$	$\mathrm{BGT}_{(\mathrm{p,n})}^{\mathrm{SM}}$
$1/2^-_{\mathrm{g.s.}}$	-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
- 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 $BGT_{3/2^-}/BGT_{gs}$ 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.

Solution 2

The shell model wave functions are underestimate the contribution of the excited states.

$L = 2$ matrix element

Suggests that the ratio $BGT_{3/2^-}/BGT_{gs}$ 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.

Solution 2

The shell model wave functions are underestimate the contribution of the excited states.

$L = 2$ matrix element

Suggests that the ratio $BGT_{3/2^-}/BGT_{gs}$ 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.

Solution 2

The shell model wave functions are underestimate the contribution of the excited states.

$L = 2$ matrix element

Suggests that the ratio $BGT_{3/2^-}/BGT_{gs}$ 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.

Solution 2

The shell model wave functions are underestimate the contribution of the excited states.

Maximum likelihood analysis is problematic for neutrino experiments, since the uncertainty estimates are off when

1. The number of events is small
2. The likelihood function is skewed

Instead of this one can formulate the estimation of the experiment to theory ratio R using a Bayesian approach.

Maximum likelihood analysis is problematic for neutrino experiments, since the uncertainty estimates are off when

1. The number of events is small
2. The likelihood function is skewed

Instead of this one can formulate the estimation of the experiment to theory ratio R using a Bayesian approach.

The basic idea of the model is to view a neutrino detection experiment as a repeated *Bernoulli trial*. One trial consists of a single ^{71}Ga atom in a 1 cm^2 area, and a single neutrino hitting a uniformly distributed random spot. If an interaction happens, this constitutes a "success".

We can use the fact Beta distribution is a conjugate prior and select a highly uninformative prior, such as Beta$(1/2, 1)$ for the cross section.

Since the cross section is $<< 1$, it is easy to see that the relative uncertainty of the cross section $\sqrt{\mathrm{Var}(\sigma)}/\mathbb{E}[\sigma] \propto 1/\sqrt{\mathrm{events}}$. It is also easy to see that the total number of events is a sufficient statistic for the cross section $\Rightarrow$ this contains all the information relevant for the determination of σ.

The basic idea of the model is to view a neutrino detection experiment as a repeated *Bernoulli trial*. One trial consists of a single ^{71}Ga atom in a 1 cm^2 area, and a single neutrino hitting a uniformly distributed random spot. If an interaction happens, this constitutes a "success".

We can use the fact Beta distribution is a conjugate prior and select a highly uninformative prior, such as Beta$(1/2, 1)$ for the cross section.

Since the cross section is $<< 1$, it is easy to see that the relative uncertainty of the cross section $\sqrt{\text{Var}(\sigma)}/\mathbb{E}[\sigma] \propto 1/\sqrt{\text{events}}$. It is also easy to see that the total number of events is a sufficient statistic for the cross section $\Rightarrow$ this contains all the information relevant for the determination of σ.

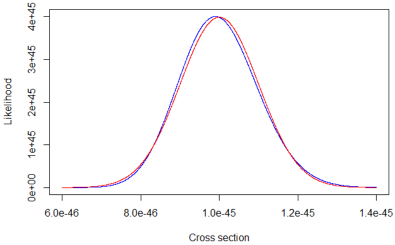
The basic idea of the model is to view a neutrino detection experiment as a repeated *Bernoulli trial*. One trial consists of a single ^{71}Ga atom in a 1 cm^2 area, and a single neutrino hitting a uniformly distributed random spot. If an interaction happens, this constitutes a "success".

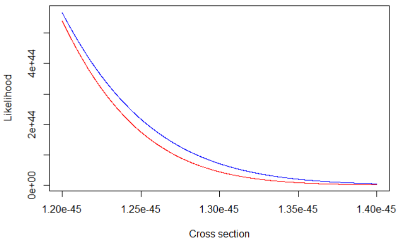
We can use the fact Beta distribution is a conjugate prior and select a highly uninformative prior, such as Beta$(1/2, 1)$ for the cross section.

Since the cross section is $<< 1$, it is easy to see that the relative uncertainty of the cross section $\sqrt{\mathrm{Var}(\sigma)}/\mathbb{E}[\sigma] \propto 1/\sqrt{\mathrm{events}}$. It is also easy to see that the total number of events is a sufficient statistic for the cross section $\Rightarrow$ this contains all the information relevant for the determination of σ.

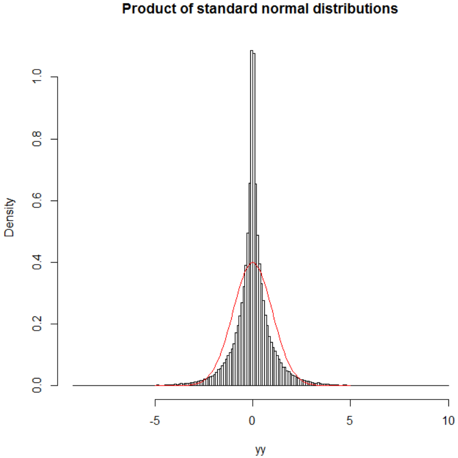
Example:

Assume 10^{47} trials with 100 events (with no uncertainties related to the neutrino flux, the detector or the number of events) and a prior Beta$(10^{-6}, 1)$. Posterior (blue) and a normal distribution with the same expected value and variance (red):





	Trials (10^{44})	Events
G1	$703.9^{+12.21}_{-17.76}$(stat.) $^{+3.520}_{-3.942}$(syst.)	389.76 ± 38.28
G2	$775.6^{+37.04}_{-17.76}$(stat.) $^{+3.878}_{-4.343}$(syst.)	365.93 ± 41.82
S1	$6.766 \times (72.6 \pm 0.2) \times (1.9114 \pm 0.022)^{+5.7\%}_{-5.6\%}$(syst.)	518.21 ± 62.93
S2	$6.603 \times (72.6 \pm 0.2) \times (1.513 \pm 0.007)^{+5.4\%}_{-5.2\%}$(syst.)	$401.58^{+36.51}_{-32.86}$



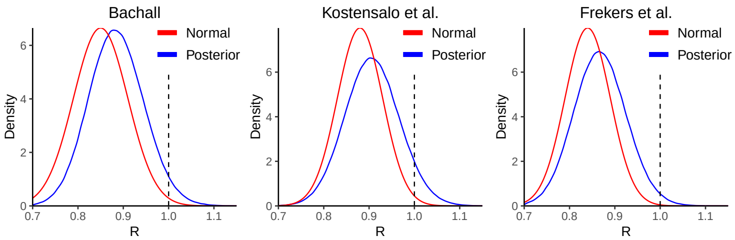
In the original fits of SAGE and GALLEX solar neutrino backgrounds 0.27/day and 0.67 ± 0.11/day were included in the maximum likelihood fits of each individual run. An improvement to this would be to just calculate the total number of source+solar events and subtract the number of solar events as a Poisson distributed variable.

The calculations were done with R using JAGS (Just Another Gibbs Sampler).

In the original fits of SAGE and GALLEX solar neutrino backgrounds 0.27/day and 0.67 ± 0.11/day were included in the maximum likelihood fits of each individual run. An improvement to this would be to just calculate the total number of source+solar events and subtract the number of solar events as a Poisson distributed variable.

The calculations were done with R using JAGS (Just Another Gibbs Sampler).

Theory	Posterior ETI	Significance	Normal
Bachall	0.936	1.85σ	2.6σ
Bachall corr.	0.894	1.62σ	
Kostensalo et al.	0.873	1.52σ	2.3σ
Frekers et al.	0.974	2.22σ	3.0σ
Frekers et al. corr.	0.942	1.90σ	
Comb. theory	0.915	1.72σ	



The statistical significance of the reactor anomaly is claimed to be about 2–3σ. Non-randomly missing data for the branching ratios makes a reliable estimate extremely hard to do.

The statistical significance of the gallium anomaly is taking all theoretical estimates into account approximately 1.72σ.

For new physics we usually require a discrepancy of 5σ. This can be reformulated by assuming *prior odds*

$$\frac{p(\mathrm{NP}=1)}{p(\mathrm{NP}=0)} = \frac{1-\Phi(4.4)}{\Phi(4.4)}$$

with a single 5σ observation the posterior odds ratio would be 19, i.e. we would be 95% sure that there are new physics.

Assuming one could come up with a consistent model for sterile neutrinos (or something else) which could explain both these anomalies, the odds ratio for new physics is

OR(NP) = 0.005 (RAA 2 sigma)   OR(NP) = 0.090 (3 sigma)

For previous gallium anomaly estimates the odds ratios would have been (RAA 2σ)

0.021 (Kostensalo et al.),   0.05 (Bahcall),   0.17 (Frekers et al.)

or (RAA 3σ)

0.39 (Kostensalo et al.),   0.86 (Bahcall),   2.96 (Frekers et al.)

Assuming one could come up with a consistent model for sterile neutrinos (or something else) which could explain both these anomalies, the odds ratio for new physics is

OR(NP) = 0.005 (RAA 2 sigma)   OR(NP) = 0.090 (3 sigma)

For previous gallium anomaly estimates the odds ratios would have been (RAA 2σ)

0.021 (Kostensalo et al.),   0.05 (Bahcall),   0.17 (Frekers et al.)

or (RAA 3σ)

0.39 (Kostensalo et al.),   0.86 (Bahcall),   2.96 (Frekers et al.)

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- New calculations for the reactor neutrino anomaly:
  1) Demonstrate the importance of the first forbidden transitions in the RAA.
  2) Mitigate the spectral shoulder.
- New calculations for the gallium anomaly:
  1) Explain a large part of the discrepancies between experimental and theoretical neutrino-nucleus scattering cross-sections.
  2) Explain partially the difference between the charge-exchange BGTs and the shell model GALLEX/SAGE results.
  3) Provide a new framework for analyzing results from neutrino experiments in a way which allows us to take into account uncertainties to a much higher degree of accuracy.
- Conclusion: forbidden spectral shapes, tensor contributions in CERs, and the asymmetric uncertainties must be taken into account in order to make strong claims regarding the reactor and gallium anomalies.

- What are the next steps for the theoretical part of the reactor antineutrino anomaly?
  1) Include nuclear structure corrections for the allowed decays
  2) We plan on trying to reproduce TAGS spectra to test the theoretical accuracy
  3) Include even more transitions to cover more of the total flux

- What about the Gallium anomaly?
  1) A final step one can take is to get all the original data and construct a hierarchical model which takes all the available information into account. The uncertainty estimates for the number of events still relies on the numbers obtained by GALLEX/SAGE using the traditional approximations.

- What are the next steps for the theoretical part of the reactor antineutrino anomaly?
  1) Include nuclear structure corrections for the allowed decays
  2) We plan on trying to reproduce TAGS spectra to test the theoretical accuracy
  3) Include even more transitions to cover more of the total flux

- What about the Gallium anomaly?
  1) A final step one can take is to get all the original data and construct a hierarchical model which takes all the available information into account. The uncertainty estimates for the number of events still relies on the numbers obtained by GALLEX/SAGE using the traditional approximations.

- What are the next steps for the theoretical part of the reactor antineutrino anomaly?
  1) Include nuclear structure corrections for the allowed decays
  2) We plan on trying to reproduce TAGS spectra to test the theoretical accuracy
  3) Include even more transitions to cover more of the total flux
- What about the Gallium anomaly?
  1) A final step one can take is to get all the original data and construct a hierarchical model which takes all the available information into account. The uncertainty estimates for the number of events still relies on the numbers obtained by GALLEX/SAGE using the traditional approximations.

- What are the next steps for the theoretical part of the reactor antineutrino anomaly?
  1) Include nuclear structure corrections for the allowed decays
  2) We plan on trying to reproduce TAGS spectra to test the theoretical accuracy
  3) Include even more transitions to cover more of the total flux

- What about the Gallium anomaly?
  1) A final step one can take is to get all the original data and construct a hierarchical model which takes all the available information into account. The uncertainty estimates for the number of events still relies on the numbers obtained by GALLEX/SAGE using the traditional approximations.

- What are the next steps for the theoretical part of the reactor antineutrino anomaly?
  1) Include nuclear structure corrections for the allowed decays
  2) We plan on trying to reproduce TAGS spectra to test the theoretical accuracy
  3) Include even more transitions to cover more of the total flux

- What about the Gallium anomaly?
  1) A final step one can take is to get all the original data and construct a hierarchical model which takes all the available information into account. The uncertainty estimates for the number of events still relies on the numbers obtained by GALLEX/SAGE using the traditional approximations.

- What are the next steps for the theoretical part of the reactor antineutrino anomaly?
  1) Include nuclear structure corrections for the allowed decays
  2) We plan on trying to reproduce TAGS spectra to test the theoretical accuracy
  3) Include even more transitions to cover more of the total flux

- What about the Gallium anomaly?
  1) A final step one can take is to get all the original data and construct a hierarchical model which takes all the available information into account. The uncertainty estimates for the number of events still relies on the numbers obtained by GALLEX/SAGE using the traditional approximations.

- L. Hayen, J. K., N. Severijns, J. Suhonen, Phys Rev. C **99**, 031301(R) (2019).
- Carlo Giunti and Marco Laveder Phys. Rev. C **83**, 065504 (2011).
- John N. Bahcall Phys. Rev. C **56**, 3391 (1997).
- W. Haxton, PLB 431 (1998).
- Frekers et al. PLB 706 134–138 (2011).

University of Jyväskylä

- Jouni Suhonen
- Santtu Tikka

KU Leuven

- Leendert Hayen
- Nathal Severijns

INFN

- Carlo Giunti

TU Dresden

- Kai Zuber

Funding

Jenny and Antti Wihuri Foundation

Thank you!