Gallium Anomaly: An Unsolvable Puzzle?

Luca Ferro

University of Cagliari & INFN Cagliari

MAYORANA School 2025
19-25 June

History of the Gallium Anomaly

- Since the 1990s, the SAGE and GALLEX experiments have been studying solar neutrinos through the neutrino capture reaction on a gallium target:

$$\nu_e + {}^{71}_{31}\mathrm{Ga} \rightarrow \mathrm{e}^- + {}^{71}_{32}\mathrm{Ge}$$

Two deficits in electron neutrinos were observed:

1. One related to the flux of solar neutrinos → resolved through the formalism of solar neutrino oscillations into other flavors.

2. The other related to neutrinos from the source used in the experiments' calibrations → still not understood today, it is known as the «Gallium anomaly».

2022: First results from **BEST**


PHYSICAL REVIEW LETTERS

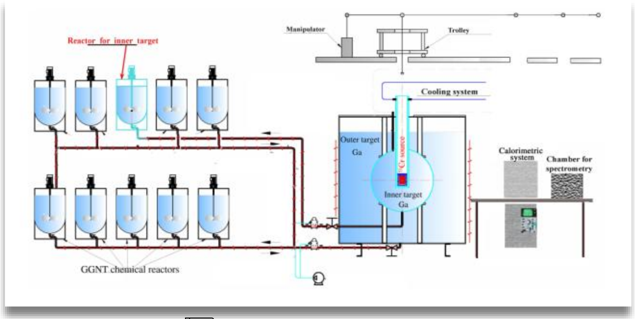
Highlights Recent Accepted Collections Authors Referees Search Press About Editorial Team

Results from the Baksan Experiment on Sterile Transitions (BEST)

V. V. Barinov *et al.*

Phys. Rev. Lett. 128, 232501 – Published 9 June 2022

$$R = \frac{N_{\mathrm{exp}}}{N_{\mathrm{cal}}} \simeq 0.8$$



Phys. Rev. Lett. 128 (23 giu. 2022)

- Chromium produces neutrinos via electron capture.

$${}^{51}_{24}\mathrm{Cr} + \mathrm{e}^- \rightarrow {}^{51}_{23}\mathrm{V} + \nu_e$$

- Confirms the anomaly and increases its significance to approximately 5σ.

Ground state cross section

The process under examination is an inverse beta decay (IBD), which in its simplest form is: $\nu_e + \mathrm{n} \rightarrow \mathrm{e}^- + \mathrm{p}$

- The cross section for the ground state (gs) is expressed as:

CKM Matrix el. Energy e Nuclear Matrix el. Radiative corrections

$$\sigma_{\mathrm{gs}} = \frac{G_F^2 \cos^2\theta_C}{\pi}\, p_e E_e\, \mathcal{F}_n(Z, E_e)\, g_A^2\, \tilde{B}_{\mathrm{GT}}^{(\nu,e)}(\mathrm{gs})\, \frac{[1 + g_{v,b}]_{(\nu,e)}}{[1 + g_{v,b}]_{\mathrm{EC}}} [1 + \epsilon_q]$$

Fermi constant Momentum e Fermi function Interference between G-T strength and weak magnetism

Ground state cross section

The process under examination is an inverse beta decay (IBD), which in its simplest form is:

$$\nu_e + \mathrm{n} \rightarrow \mathrm{e}^- + \mathrm{p}$$

- The cross section for the ground state (gs) is expressed as:

$$\sigma_{\mathrm{gs}} = \frac{G_F^2 \cos^2\theta_C}{\pi}\, p_e E_e\, \boxed{\mathcal{F}_n(Z,E_e)}\, g_A^2\, \boxed{\tilde{B}_{\mathrm{GT}}^{(\nu,e)}(\mathrm{gs})}\, \frac{[1+g_{v,b}]_{(\nu,e)}}{[1+g_{v,b}]_{\mathrm{EC}}}[1+\epsilon_q]$$

- In my work, I focused on the Fermi function and the nuclear matrix element.

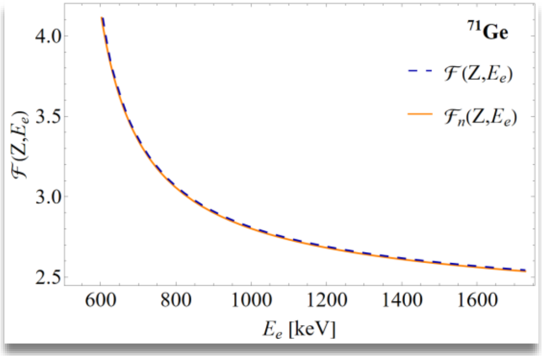
Fermi function

- $F_n(Z,E_e)$ is obtained by solving Dirac equation using DHFS method.

$$\mathcal{F}_n(Z,E_e) = \underbrace{F_0(Z,E_e)\; L_0(Z,E_e)\; U(Z,E_e)}\; S(Z,E_e)$$

$$F_n(Z,E_e) = \lim_{r\to 0} \frac{\boxed{f_1^2(r)} + \boxed{g_{-1}^2(r)}}{r^2}.$$

Asintotically free electronic wave functions



Nuclear matrix element

- The nuclear matrix element is obtained from the reverse process, which is an electron capture (EC):

$$\mathrm{e}^- + {}^{71}_{32}\mathrm{Ge} \rightarrow \nu_e + {}^{71}_{31}\mathrm{Ga}.$$

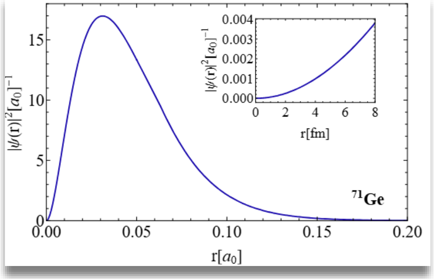
$$\omega = \frac{\ln 2}{t_{1/2}} = \frac{G_F^2 \cos^2\theta_C}{\pi}\; g_A^2\; \tilde{B}_{\mathrm{GT}}^{(\nu,e)}(\mathrm{gs})\; [1+\epsilon_q]_{\mathrm{EC}}\; f_{\mathrm{EC}}$$

^{71}Ge half-life ~ 11.46 d

Phase space factor of electron capture

$$f_{\mathrm{EC}} = |\psi_{1s}|^2\, E_{\nu,1s}^2\, [2(1+\epsilon_o^{1s})(1+\tfrac{\mathrm{L+M}}{\mathrm{K}})]$$

Bound state electron wave function



$$\boxed{\tilde{B}_{\mathrm{GT}}^{(\nu,e)}(\mathrm{gs}) \propto \frac{1}{(ft_{1/2})_{\mathrm{EC}}}}$$

f_{EC} $[(\hbar/m_e c)^3]$	$\tilde{B}_{\mathrm{GT}}^{(\nu,e)}(\mathrm{gs})$
0.0219(3)	0.0887(13)

Total cross section and interpretation with sterile neutrinos

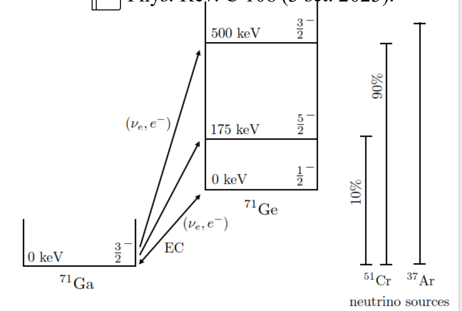
$$\sigma_{gs} = \frac{\ln 2}{\boxed{(ft_{1/2})_{EC}}} \frac{[1+\epsilon_q]}{[1+\epsilon_q]_{EC}} \frac{[1+g_{v,b}]_{(\nu,e)}}{[1+g_{v,b}]_{EC}} p_e E_e \boxed{\mathcal{F}_n(Z,E_e)}$$

- The ratios $\frac{B_{GT}(5/2^-)}{B_{GT}(gs)}$ and $\frac{B_{GT}(3/2^-)}{B_{GT}(gs)}$ are obtained experimentally by studying:

1. $p + {}^{71}_{31}Ga \rightarrow n + {}^{71}_{32}Ge$
2. ${}^{3}_{2}He + {}^{71}_{31}Ga \rightarrow {}^{3}_{1}H + {}^{71}_{32}Ge$

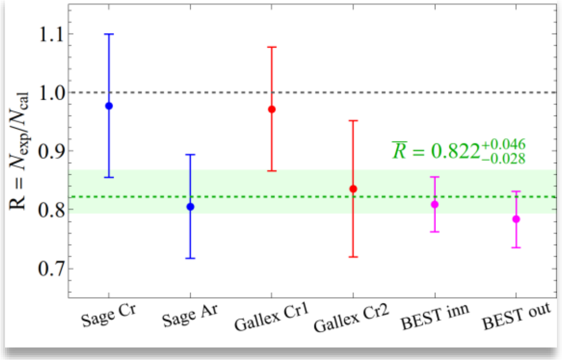
The increase in the cross section is of the order of 5% and 9%, respectively.

Phys. Rev. C 108 (3 set. 2023).



$$\sigma = \sigma_{gs}\left[1 + \xi(\tfrac{5}{2}^-)\frac{B_{GT}(\frac{5}{2}^-)}{B_{GT}(gs)} + \xi(\tfrac{3}{2}^-)\frac{B_{GT}(\frac{3}{2}^-)}{B_{GT}(gs)}\right]$$

Source	$\sigma_{gs}[\times 10^{-45}\ cm^2]$	$\sigma_{(p,n)}[\times 10^{-45}\ cm^2]$	$\sigma_{(^3He,^3H)}[\times 10^{-45}\ cm^2]$
^{51}Cr	5.55 ± 0.08	$5.86^{+0.28}_{-0.09}$	6.03 ± 0.18
^{37}Ar	6.65 ± 0.09	$7.06^{+0.35}_{-0.11}$	7.33 ± 0.22



Possible interpretations of the anomaly

Possibility of electron neutrino oscillations into sterile neutrinos on scales of a few meters.

This hypothesis has not been completely ruled out yet but is under strong tension due to the lack of experimental evidence.

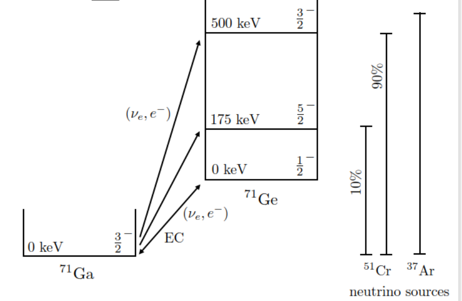
Total cross section and interpretation with sterile neutrinos

$$\sigma_{gs} = \frac{\ln 2}{\boxed{(ft_{1/2})_{EC}}} \frac{[1+\epsilon_q]}{[1+\epsilon_q]_{EC}} \frac{[1+g_{v,b}]_{(\nu,e)}}{[1+g_{v,b}]_{EC}} p_e E_e \boxed{\mathcal{F}_n(Z,E_e)}$$

- The ratios $\frac{B_{GT}(5/2^-)}{B_{GT}(gs)}$ and $\frac{B_{GT}(3/2^-)}{B_{GT}(gs)}$ are obtained experimentally by studying:

1. $p + {}^{71}_{31}Ga \rightarrow n + {}^{71}_{32}Ge$
2. ${}^{3}_{2}He + {}^{71}_{31}Ga \rightarrow {}^{3}_{1}H + {}^{71}_{32}Ge$

Phys. Rev. C 108 (3 set. 2023).



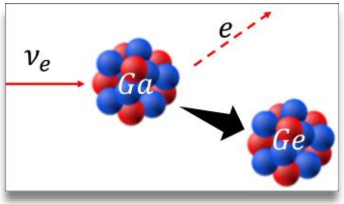
$$\sigma = \sigma_{gs}\left[1 + \xi(\tfrac{5}{2}^-)\frac{B_{GT}(\frac{5}{2}^-)}{B_{GT}(gs)} + \xi(\tfrac{3}{2}^-)\frac{B_{GT}(\frac{3}{2}^-)}{B_{GT}(gs)}\right]$$

The increase in the cross section is of the order of 5% and 9%, respectively.

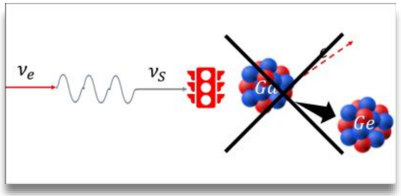
Source	$\sigma_{gs}[\times 10^{-45}\ cm^2]$	$\sigma_{(p,n)}[\times 10^{-45}\ cm^2]$	$\sigma_{(^3He,^3H)}[\times 10^{-45}\ cm^2]$
^{51}Cr	5.55 ± 0.08	$5.86^{+0.28}_{-0.09}$	6.03 ± 0.18
^{37}Ar	6.65 ± 0.09	$7.06^{+0.35}_{-0.11}$	7.33 ± 0.22

Interpretation with sterile neutrinos

Without oscillation



With oscillation

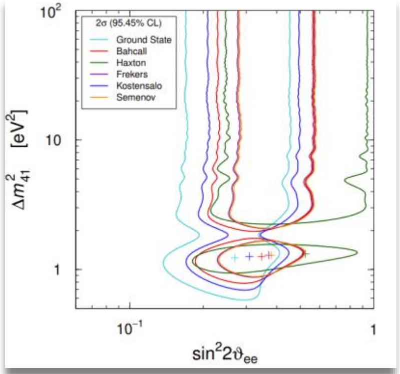


$$P_{ee} \simeq 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

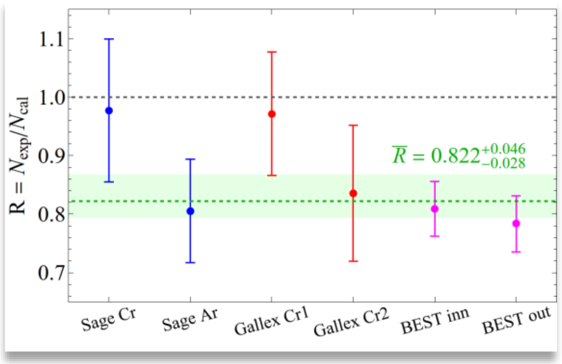
- The anomaly can be explained by short-baseline neutrino oscillations in the 3+1 scenario.

Suggested parameter space :

- $\Delta m^2_{41} \sim 1\ eV^2$.
- Large values of $\sin^2 2\theta_{ee}$.



J. High Energ. Phys. 2022, 164



Possible interpretations of the anomaly

Possibility of electron neutrino oscillations into sterile neutrinos on scales of a few meters.

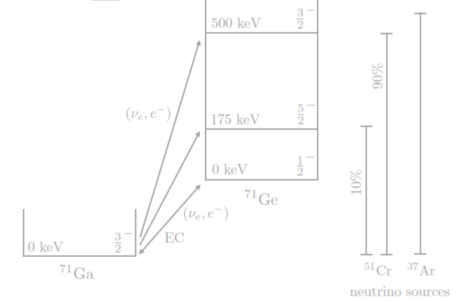
This hypothesis has not been completely ruled out yet but is under strong tension due to the lack of experimental evidence.

Total cross section and interpretation with sterile neutrinos

$$\sigma_{gs} = \frac{\ln 2}{\boxed{(ft_{1/2})_{EC}}} \frac{[1+\epsilon_q]}{[1+\epsilon_q]_{EC}} \frac{[1+g_{v,b}]_{(\nu,e)}}{[1+g_{v,b}]_{EC}} p_e E_e \boxed{\mathcal{F}_n(Z,E_e)}$$

- The ratios $\frac{B_{GT}(5/2^-)}{B_{GT}(gs)}$ and $\frac{B_{GT}(3/2^-)}{B_{GT}(gs)}$ are obtained ... by studying:

Phys. Rev. C 108 (3 set. 2023).

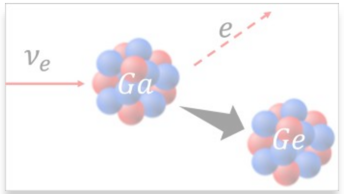


$$\sigma = \sigma_{gs}\left[1+\xi(\tfrac{5}{2}^-)\frac{B_{GT}(\frac{5}{2}^-)}{B_{GT}(gs)}+\xi(\tfrac{3}{2}^-)\frac{B_{GT}(\frac{3}{2}^-)}{B_{GT}(gs)}\right]$$

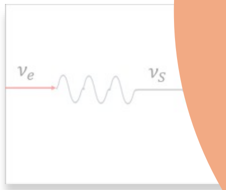
Thank you!!

Interpretation with sterile neutrinos

Without oscillation



With o



... of the order of 5%

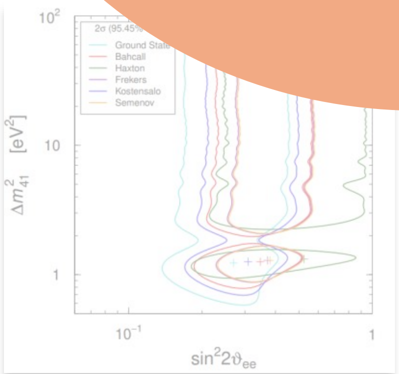
... $\times 10^{-45}$ cm^2]	$\sigma_{(p,n)}[\times 10^{-45}$ cm^2]	$\sigma_{(^3He,^3H)}[\times 10^{-45}$ cm^2]
...55 ± 0.08	$5.86^{+0.28}_{-0.09}$	6.03 ± 0.18
...6.65 ± 0.09	$7.06^{+0.35}_{-0.11}$	7.33 ± 0.22

$$P_{ee} \simeq 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

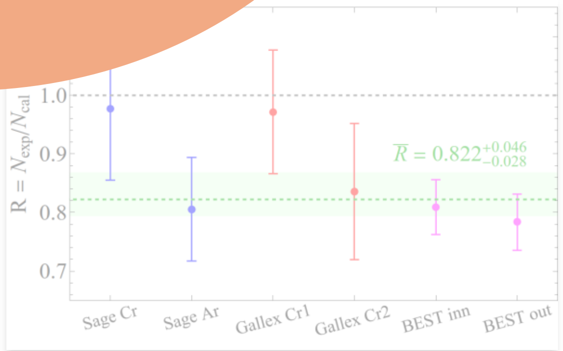
- The anomaly can be explained by short-baseline neutrino oscillations in the 3+1 scenario.

Suggested parameter space :

- $\Delta m^2_{41} \sim 1$ eV^2.
- Large values of $\sin^2 2\theta_{ee}$.



J. High Energ. Phys. 2022, 164



Possible interpretations of the anomaly

Possibility of electron neutrino oscillations into sterile neutrinos on scales of a few meters.

This hypothesis has not been completely ruled out yet but is under strong tension due to the lack of experimental evidence.