Status and Prospect of Sterile Neutrino Search with Neutrino Sources

Steve Elliott, LANL

Baksan Experiment on Sterile Transitions (BEST)

Spokesperson – Vladimir Gavrin

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Outline

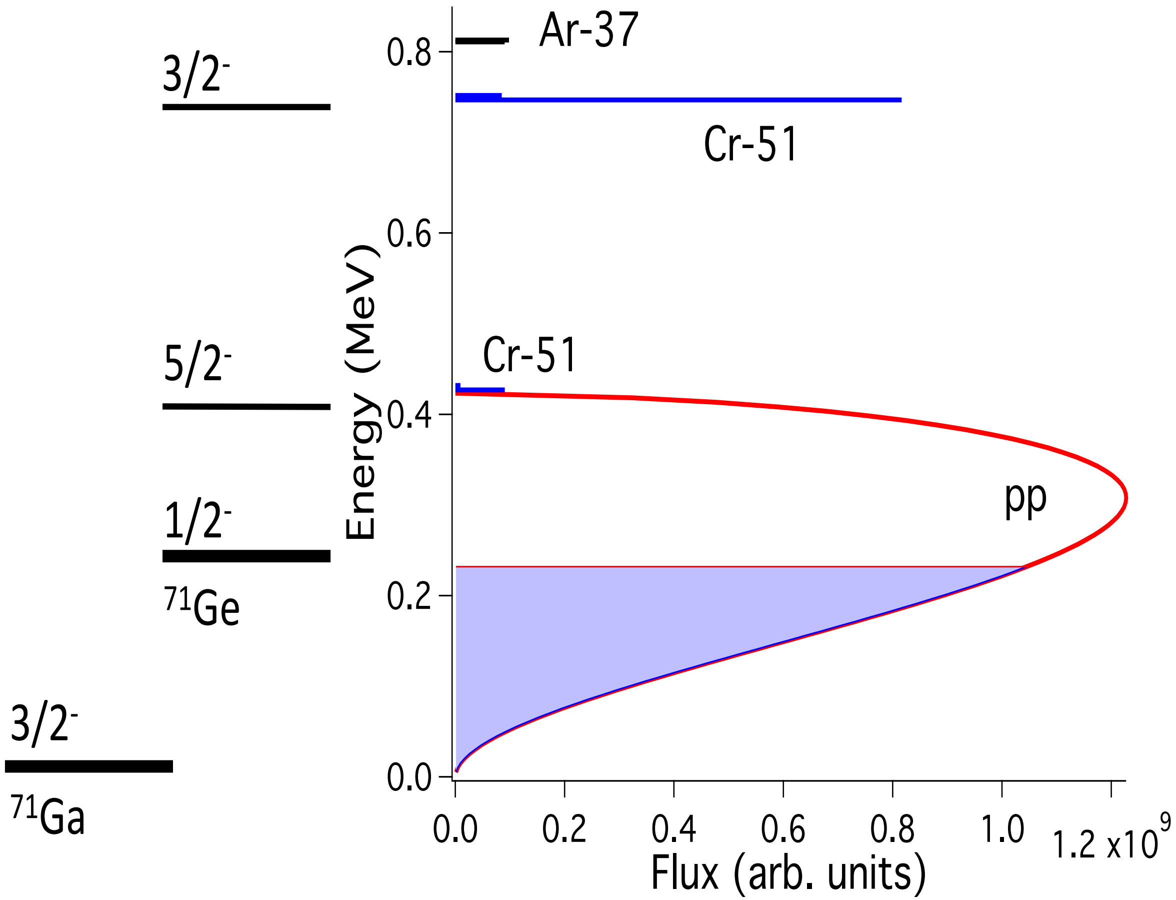
The Gallium Anomaly: The measurements of the charged-current capture rate of neutrinos on ^{71}Ga from strong radioactive sources have yielded results below those expected, based on the known strength of the principal transition supplemented by theory.

- SAGE History and the Gallium Anomaly
- BEST Description and Results
- Systematic Concerns
- Possible Future Measurements

Key References
BEST Coll. PRL 128 (2021) 232501
BEST Coll. PRC 105 (2021) 015031
Cross section PRC 108 (2023) 035502
PPNP review in press (online)

Key Time Frames in the History of SAGE

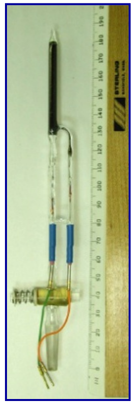
- Mid 1980's, two collaborations formed to measure the low-energy neutrinos from proton-proton fusion within the Sun using Ga as a target. A well-predicted flux from the known solar luminosity.
  - The Soviet-American Gallium Experiment (SAGE).
  - The Gallium Experiment (GALLEX).
- Early 1990s, the Soviet Union separated into various states and the collaboration became the Russian-American Gallium Experiment. The new acronym seemed unfortunate and we stuck with SAGE.

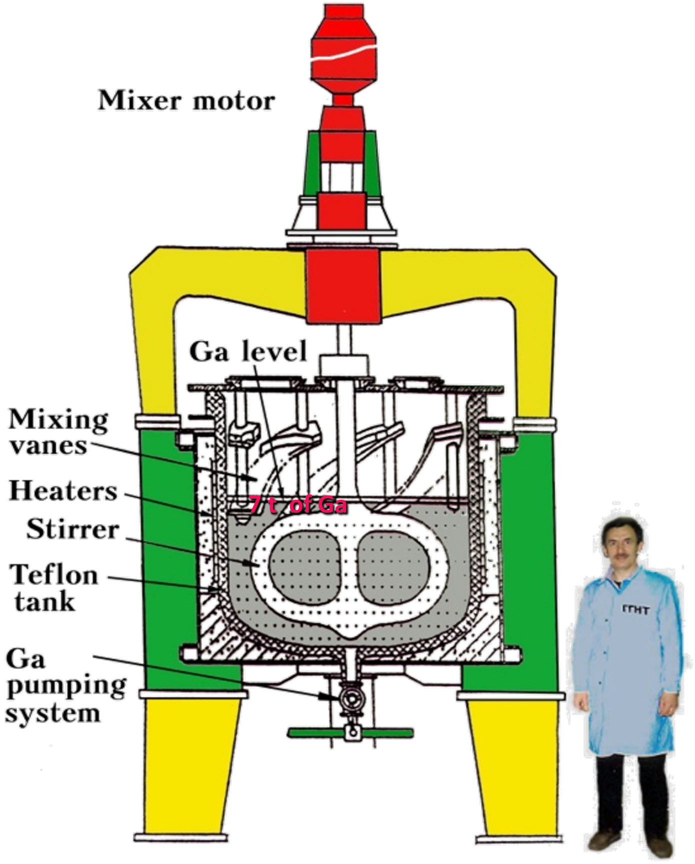


Only sensitive to ν_e.

The Gallium Solar Neutrino Experiments (Kuzmin Eksp. Teor. Fiz. 49 (1965) 1532)

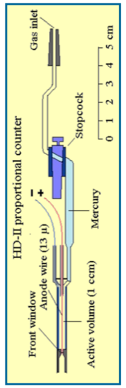
SAGE 50 t of Ga

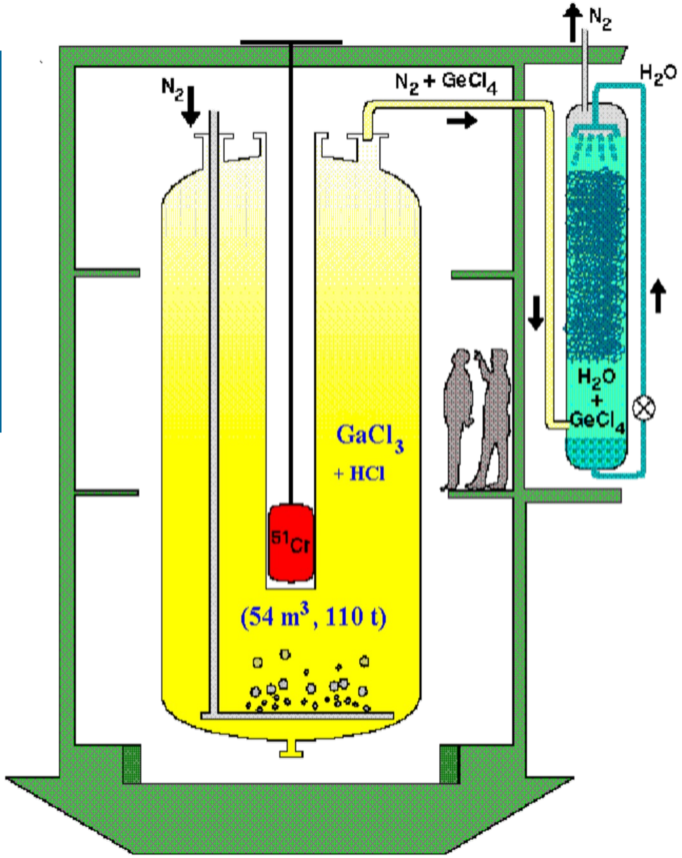




Both experiments were based on radio-chemical extraction technology of a few ^{71}Ge atoms from tons of a Ga target and on technology of counting of ^{71}Ge decays in small proportional counters (~0.5 cm^3).

GALLEX/GNO 30.3 t of Ga





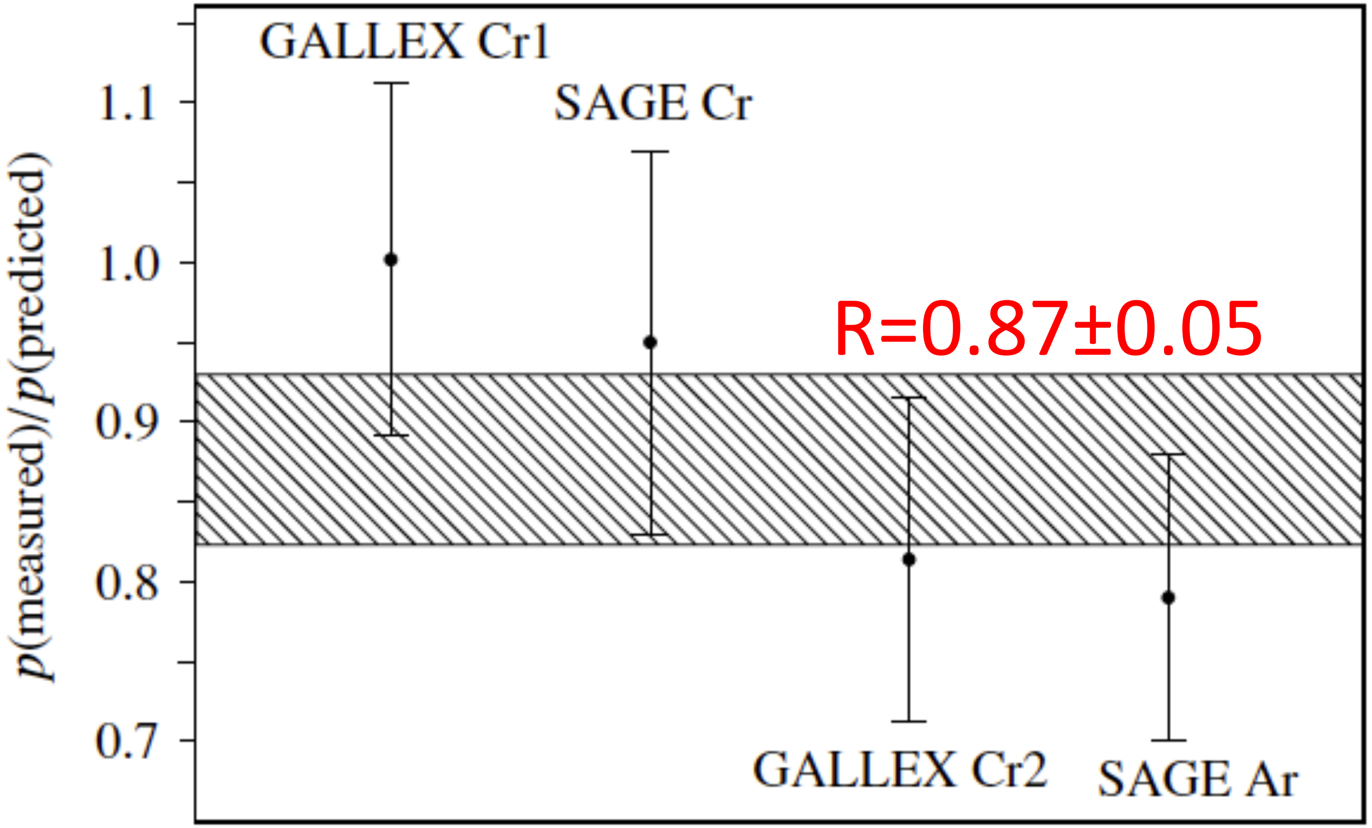
Laboratory Photo showing extraction reactors

Global intensity of muon
$(3.03 \pm 0.19) \times 10^{-9}$ /(cm^2s)
Fast neutron flux (>3MeV)
$(6.28 \pm 2.20) \times 10^{-8}$ /(cm^2s)

Source Tests of the Ga Results

The importance of the solar ν deficit led to systematic studies, including irradiation with a known ν source.

- The measured rates of ^{71}Ga(ν_e,e)^{71}Ge were lower than that predicted from the known cross section and ν_e flux.
- The statistical precision was not compelling but it drew attention.
- The ν_e sources were the electron-capture isotopes, ^{51}Cr or ^{37}Ar.



PRC 73 (2006) 045805, PRC 80 (2009) 015807

New Experiment: Which Hypothesis to Falsify?

- Standard model extensions to explain the sterile neutrino evidence are ubiquitous.
  - 6x6 neutrino matrix with all its mixing angles, masses and phases; CPT violation; non-standard neutrino interactions; neutrino decay; Lorentz violation; extra dimensions; energy dependent mixing parameters; dark photons; neutrinos coupled to fuzzy dark matter or dark energy; bulk neutrinos.
  - Surely more ideas will come.
- Difficult to design an experiment to verify or falsify such an hypothesis.
  - There is always a caveat to any null experiment.
- Better to design an experiment to test the hypothesis that the Ga anomaly is real.
  - Although BEST was designed with some oscillation sensitivity,
  - it was, in particular, a high-sensitivity test to falsify the premise that the Ga anomaly is real.

Volcanoes National Park

Source Measurement Overview

- Neutrinos produced at center of Ga by ^{51}Cr decay:

$$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e$$

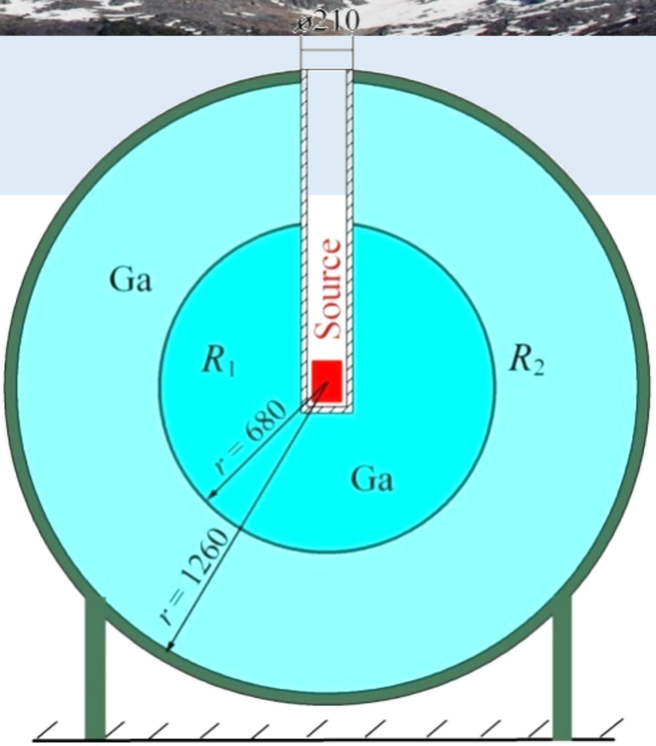
- This is a well-understood monochromatic spectrum of a compact source. The source intensity is well measured.
- These neutrinos are detected via a charged-current (CC) reaction on Ga surrounding the source:

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

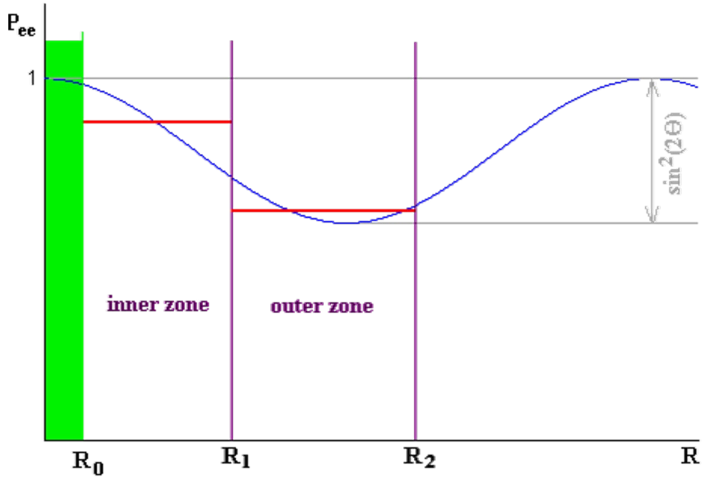
- ^{71}Ge is radioactive and can be counted when it decays.
- Almost zero ν background. Mainly from the Sun.

  The source, 3.4 MCi, greatly exceeds the solar rate.

- Well established experimental procedures for extraction and counting of the ^{71}Ge developed in SAGE solar measurements.



Schematic drawing of the BEST neutrino source experiment.



BEST Schedule

Construction began 2011

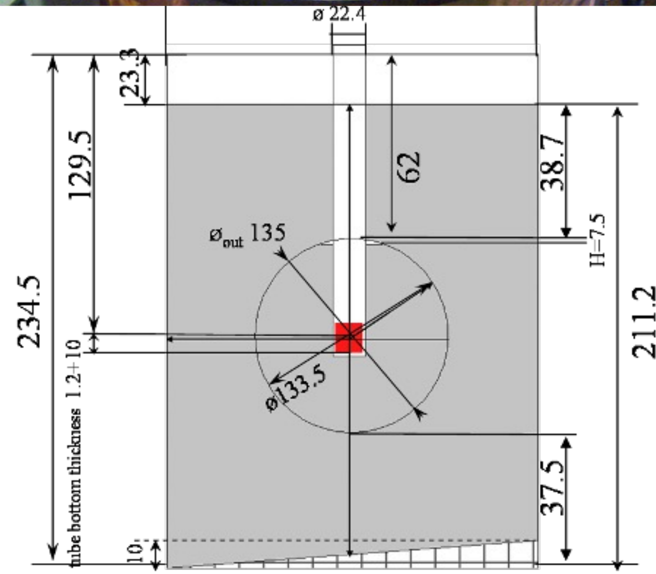
Source Arrived: July 5, 2019

Exposures: July 5 – Oct. 13, 2019

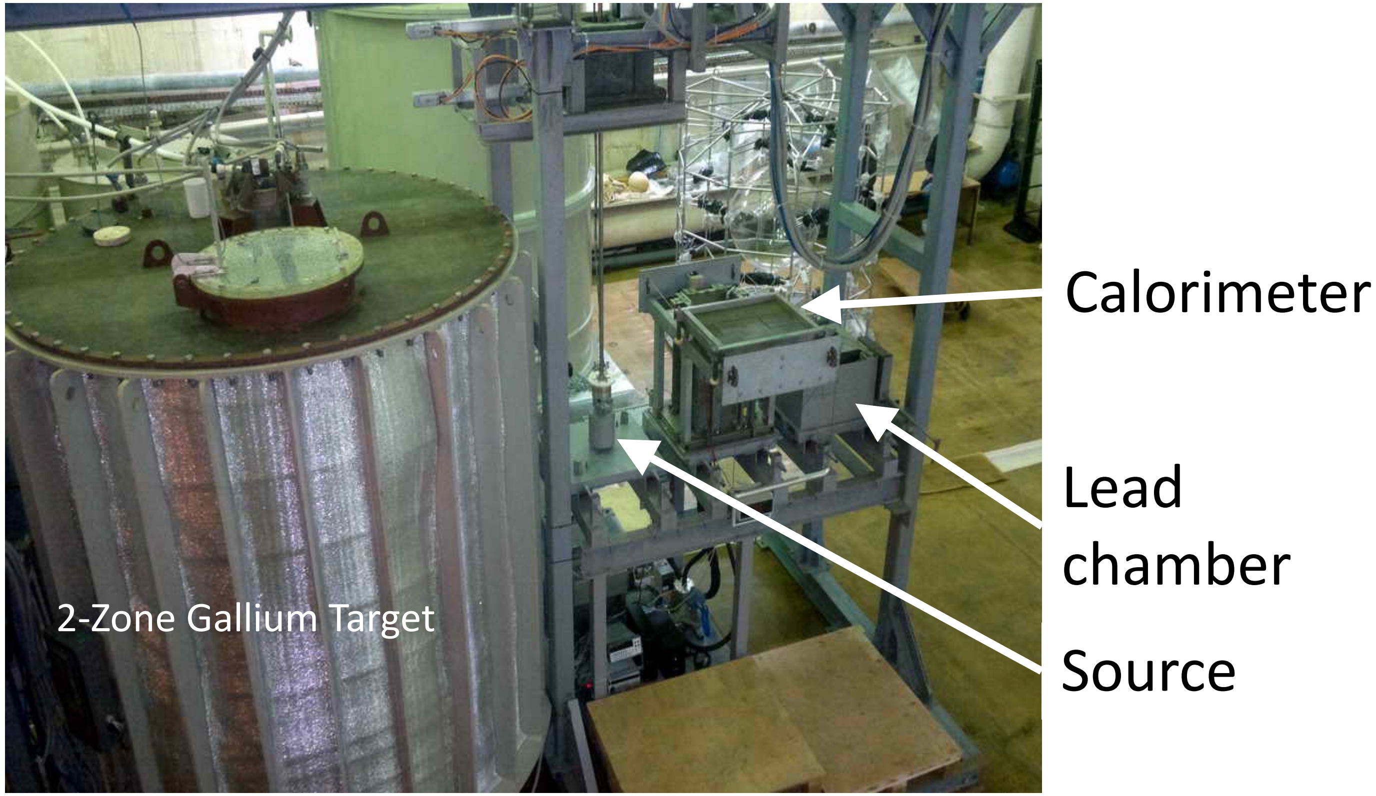
Counting: July 16, 2019 – Mar. 20, 2020

Counter Calibration: Mar. 2020 – Jan. 2021

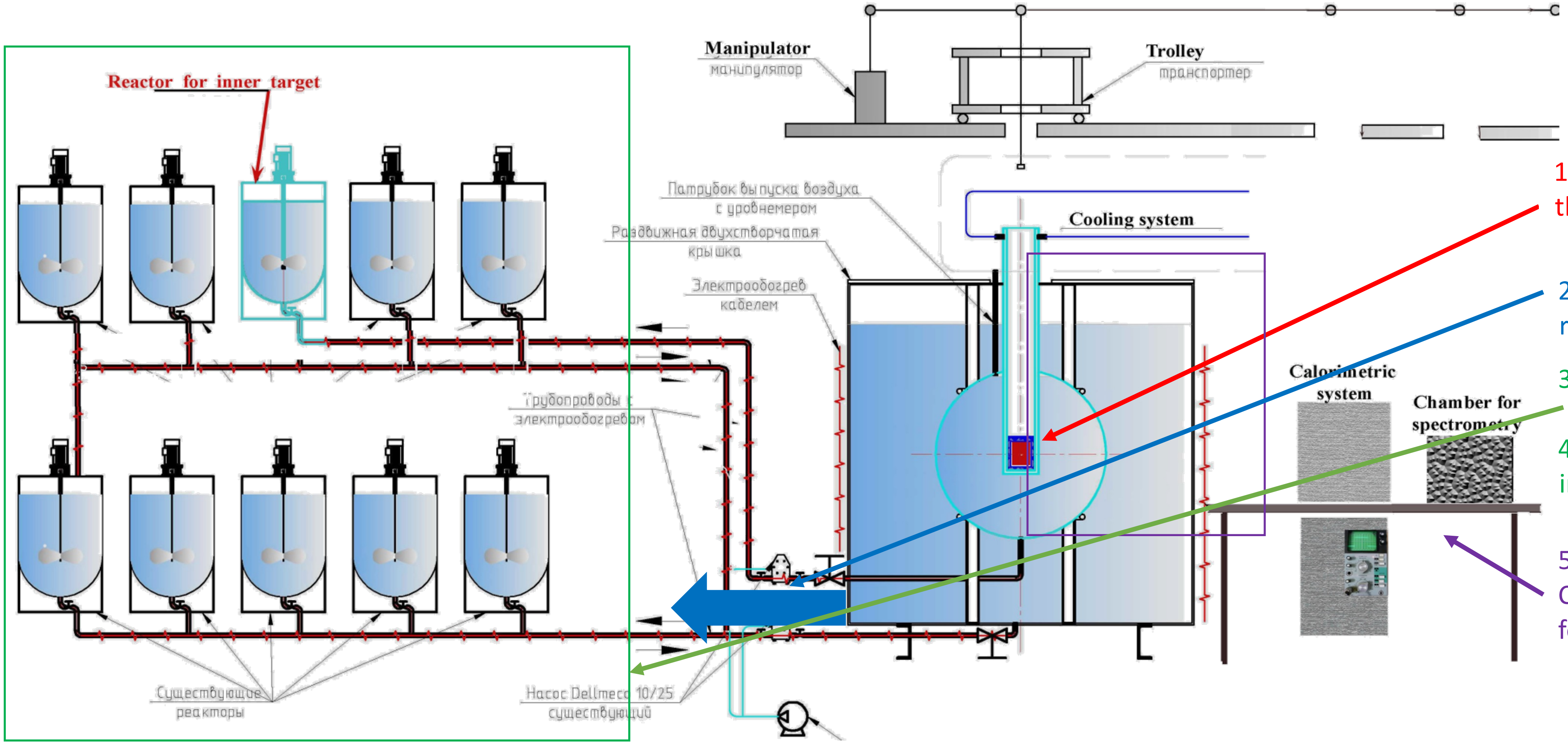
PRL draft posted: Sept. 2021



Construction started in 2011

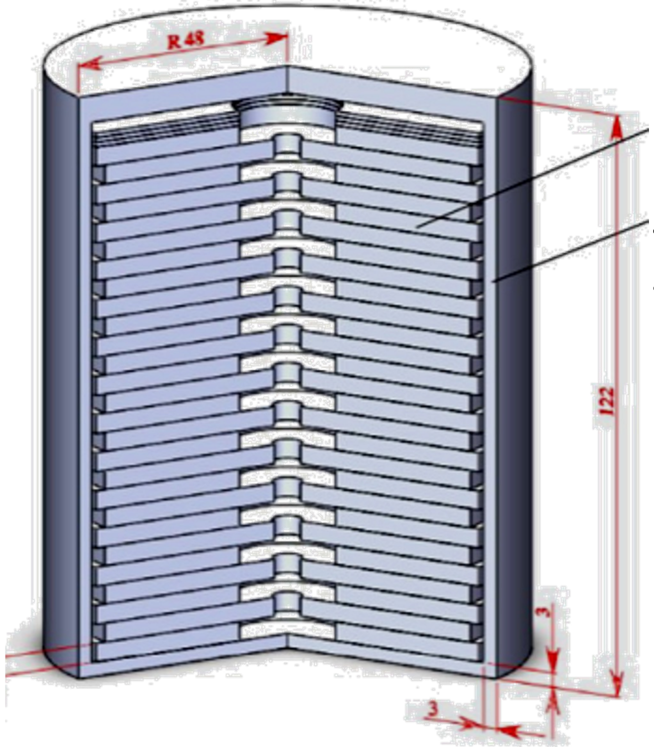


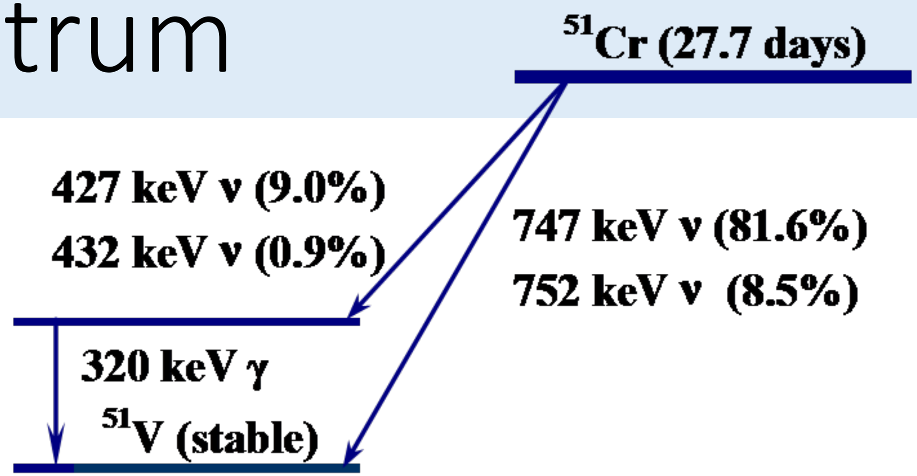
Installation and Operation



1. Expose gallium targets to the source
   $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
2. Pump Ga to the chemical reactors
3. ^{71}Ge chemical extraction
4. ^{71}Ge decay measurement in proportional counters
5. Semiconductor & Calorimetric measurement for source activity

Well-Understood Neutrino Spectrum





4 kg 97%-enriched ^{50}Cr,
h = 4 mm, ∅ 84 and 88 mm.

Irradiated for ~100 days with thermal neutrons (RIAR, Dmitrovgrad)
Thermal neutron flux density – $5{\times}10^{15}$ n/(cm^2 s)

^{51}Cr Source (JINST 16 (2021) P04012)

Neutrino Source

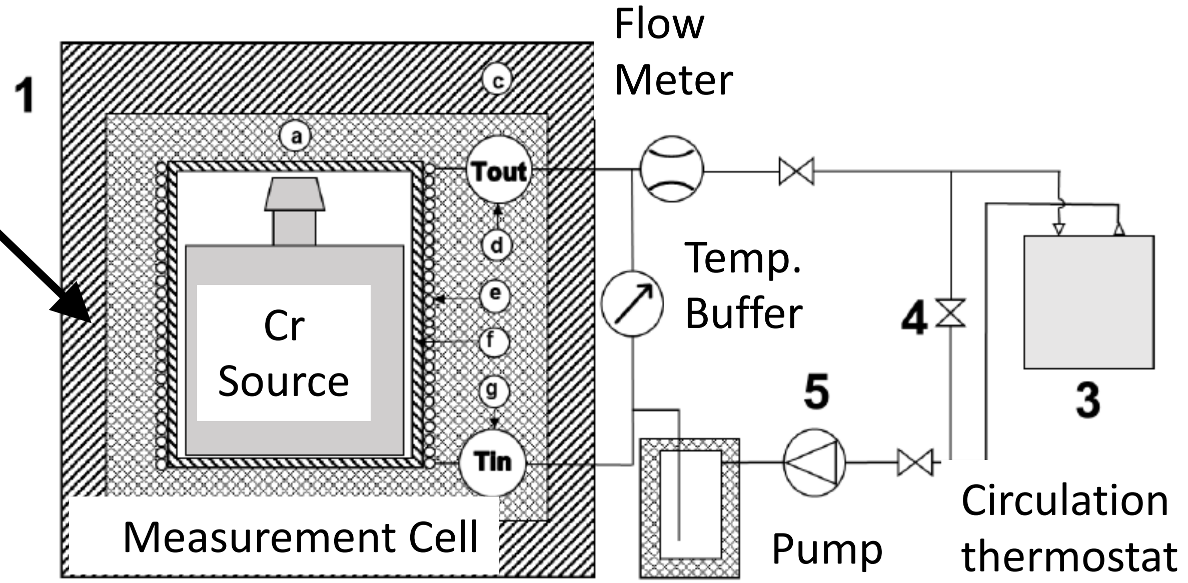
Transport Container

Measurement Cell
Of Calorimeter

Activity at 14:02 on July 5, 2019

A = 3.414 ± 0.008 MCi

Energy/decay = 36.750 ± 0.84 keV



BEST Extraction Procedure (PRC 60 (1999) 055801)

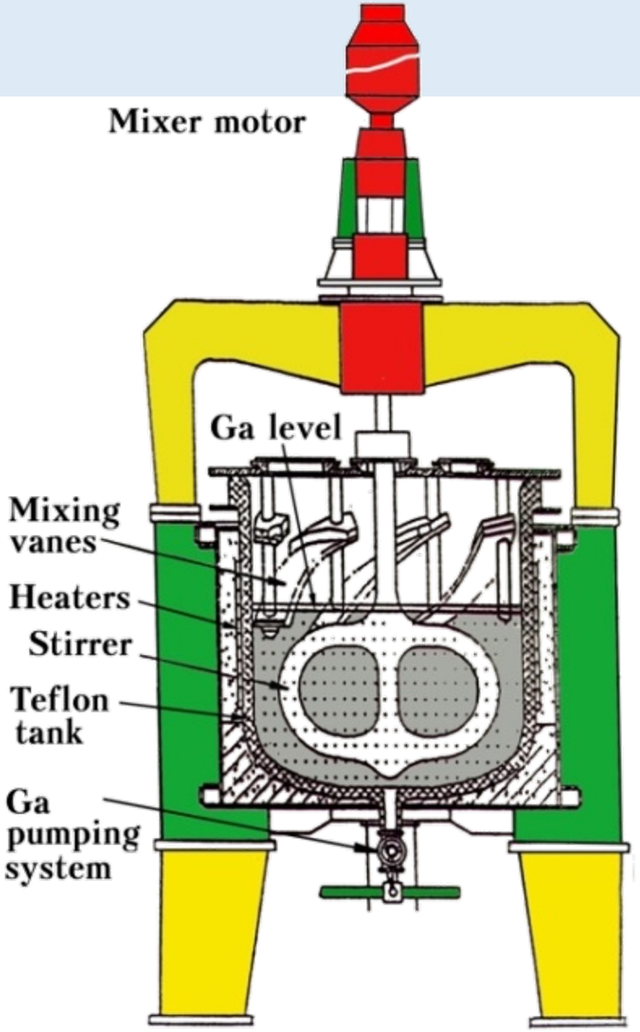
^{71}Ge extraction (30 hours in *total*) :

1) Add Ge carrier to Ga.
2) Pump Ga from each zone to chemical reactors:
   inner zone → 1 reactor, outer zone → 6 reactors.

2) The Ge is extracted through an oxidation reaction.

4) The gas GeH_4 is synthesized, mixed with Xe, and placed into a proportional counter.

5) ^{71}Ge decays are counted. *(60 – 150 days)*



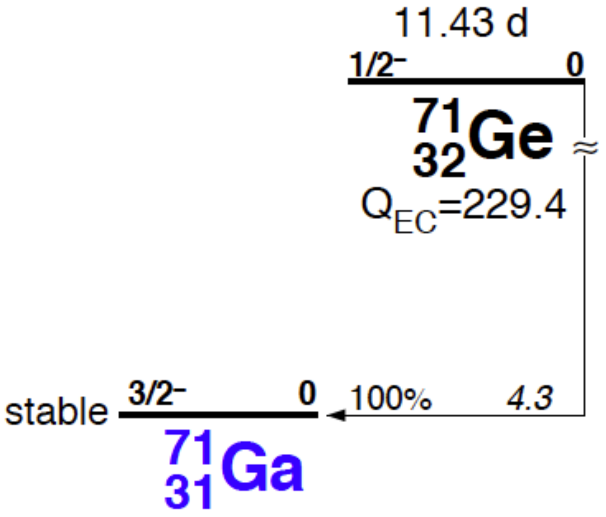
^{71}Ge Decay

Auger decays produce point-like ionization in gas. In contrast β's or Compton recoils might deposit a similar amount of energy, but over an extended path.

Leads to a pulse shape analysis technique to remove them. BEST fits the pulse waveform.

ADP (Cl expt.): Astrophys. J. 496 (1998) 505
Pulse fit: NIM A290 (1990) 158

- Half-life of 11.43 d, ground state transition
  - New measurement 11.468±0.008 d (this meeting)
- K Capture (88% of all decays)
  - 41.5% Auger e- 10.367 keV
  - 41.2% Auger e- 1.2 keV & x ray 9.2 keV
  - 5.3% Auger e- 0.12 keV & x ray 10.26 keV
- L and M capture give almost entirely Auger e-
  - L gives 1.2 keV Auger, M gives 0.12 keV Auger
- The proportional counter observes Auger e- with high efficiency
  - The X ray efficiency is much less
  - As a result, the number of K/L peak counts are about equal

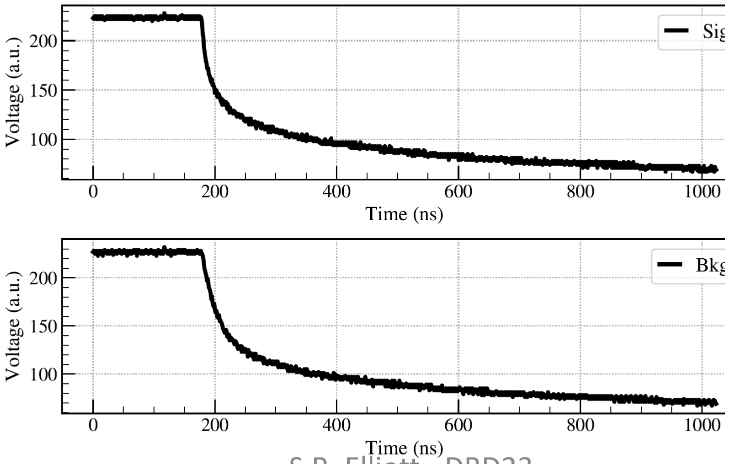


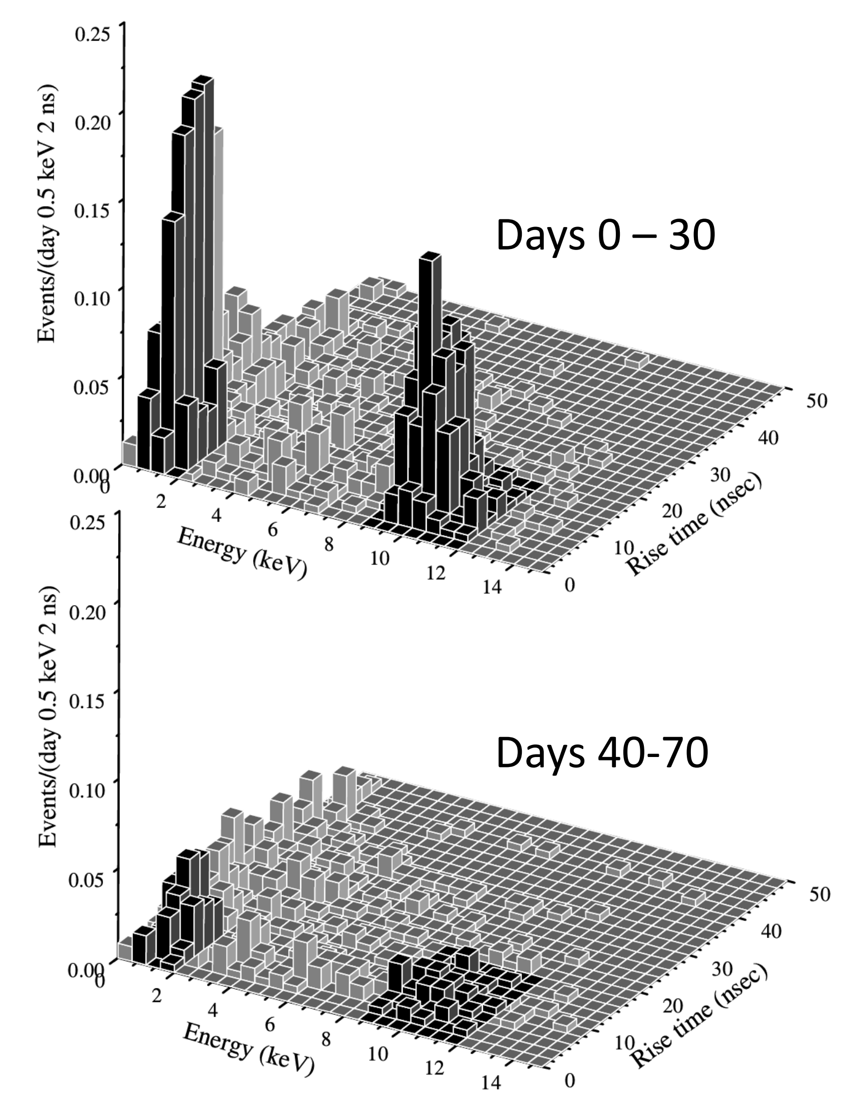
^{71}Ge Candidate Event Selection

- Energy calibration
- Time tagging
  - Periods of expected high background
    - Reject 2.6-hour periods after shield opening for Rn
  - Anti-coincidence with NaI system
  - Pulse shape analysis
    - Alpha-induced events
    - High-voltage breakdowns
    - Compton scattering
    - Beta-induced backgrounds

~1.5 evts /day (High-voltage breakdowns, Compton scattering)

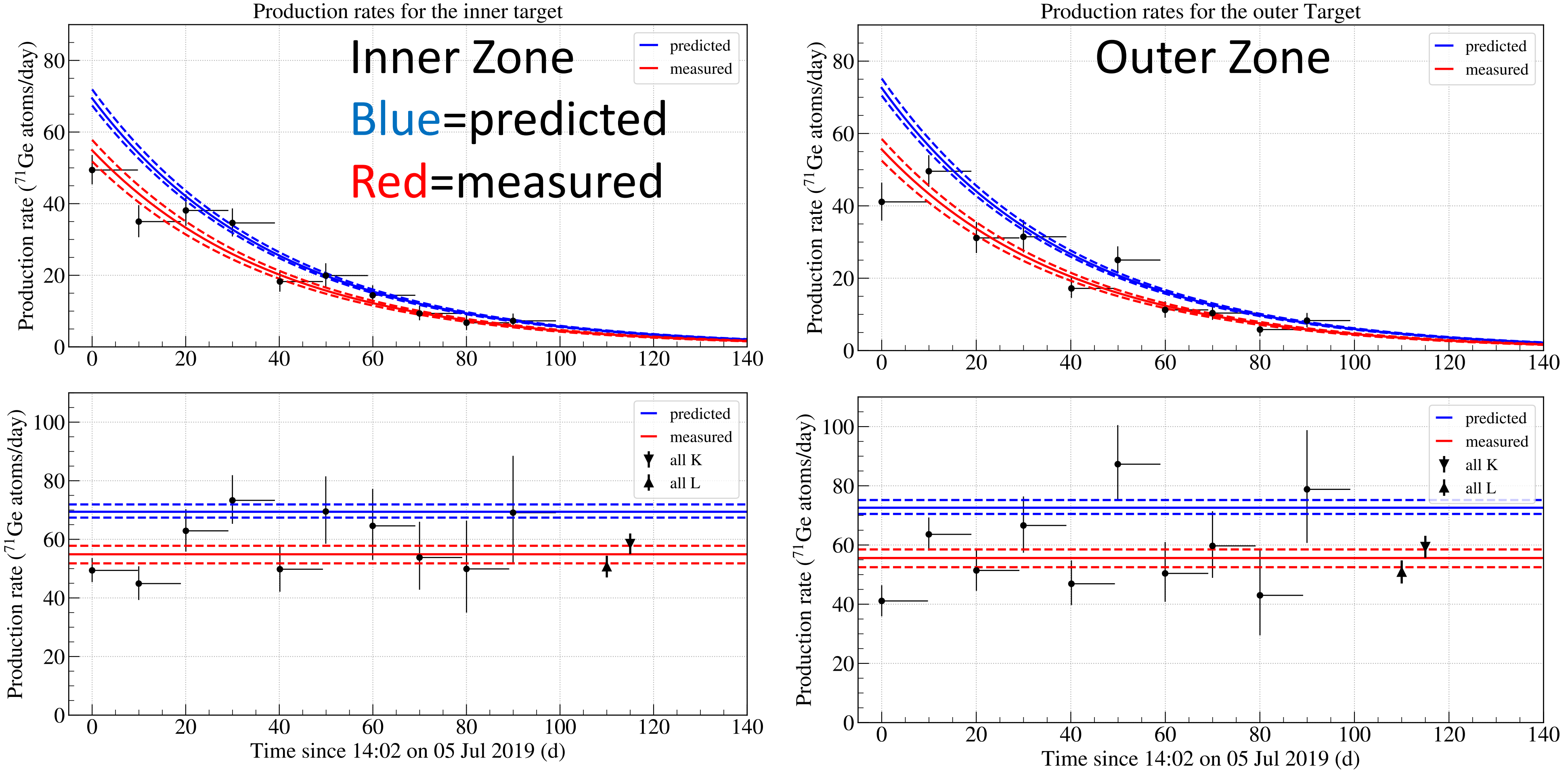
Risetime (RT) of the pulses





Counting Results: Ten 10-day exposures of each zone

Perform Exposures until Cr has decayed away.



Predicted vs. Measured Production Rates (BEST PRC, old σ)

K+L-peak

Extraction	Number of candidate events	Number fit to ^{71}Ge	^{51}Cr source production	Solar ν production	Carryover	^{71}Ge Production decay rate (atoms/day)
Inner-1	180	176.3	175.5	0.8	0.0	$49.4^{+4.0}_{-4.2}$
Inner-2	129	111.5	107.7	0.8	3.1	$44.9^{+5.6}_{-5.9}$
Inner-3	132	117.6	115.3	0.7	1.6	$62.9^{+7.1}_{-7.4}$
Inner-4	93	87.3	85.6	0.6	1.1	$73.3^{+8.0}_{-8.6}$
Inner-5	134	60.2	58.4	0.6	1.2	$49.8^{+7.7}_{-8.2}$
Inner-6	81	48.8	47.7	0.4	0.7	$69.5^{+11.0}_{-12.0}$
Inner-7	91	45.0	43.9	0.5	0.6	$64.6^{+11.6}_{-12.6}$
Inner-8	59	33.6	32.4	0.6	0.6	$53.8^{+11.0}_{-12.2}$
Inner-9	106	23.7	22.7	0.6	0.4	$49.9^{+14.9}_{-16.5}$
Inner-10	88	25.2	24.3	0.6	0.3	$69.1^{+17.3}_{-19.4}$
Comb. K+L	1093	724.0	708.2	6.1	9.7	$54.9^{+2.4}_{-2.5}$

K+L-peak

Extraction	Number of candidate events	Number fit to ^{71}Ge	^{51}Cr source production	Solar ν production	Carryover	^{71}Ge Production decay rate (atoms/day)
Outer-1	181	133.4	129.6	3.7	0.1	$41.1^{+5.2}_{-5.3}$
Outer-2	174	163.8	158.6	3.3	1.9	$63.6^{+5.5}_{-5.7}$
Outer-3	116	92.5	88.2	2.8	1.5	$51.4^{+6.9}_{-7.3}$
Outer-4	98	82.3	78.9	2.5	0.8	$66.6^{+9.2}_{-9.8}$
Outer-5	120	64.0	59.5	3.5	1.0	$46.9^{+7.2}_{-7.9}$
Outer-6	97	62.3	59.3	2.6	0.4	$87.3^{+12.3}_{-13.2}$
Outer-7	69	38.0	34.4	3.2	0.4	$50.4^{+9.6}_{-10.6}$
Outer-8	68	43.4	39.2	3.9	0.4	$59.7^{+10.8}_{-11.7}$
Outer-9	66	20.2	17.0	3.0	0.2	$43.0^{+13.5}_{-15.3}$
Outer-10	81	31.8	28.0	3.6	0.2	$78.8^{+18.1}_{-20.0}$
Comb. K+L	1069	738.8	699.8	32.2	6.8	$55.6^{+2.6}_{-2.7}$

	IN	OUT
Predicted	$69.41^{+2.5}_{-2.0}$	$72.59^{+2.6}_{-2.1}$
Measured	54.9 ± 2.9	55.6 ± 3.1
Ratio	0.79 ± 0.05	0.77 ± 0.05

4.2σ and 4.8σ less than the unity

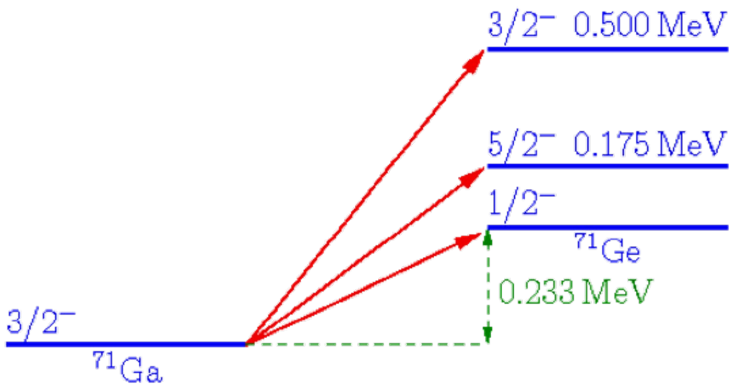
Note: $$\frac{0.77 \pm 0.05}{0.79 \pm 0.05} = 0.97 \pm 0.07$$

Similar deficits observed in both zones

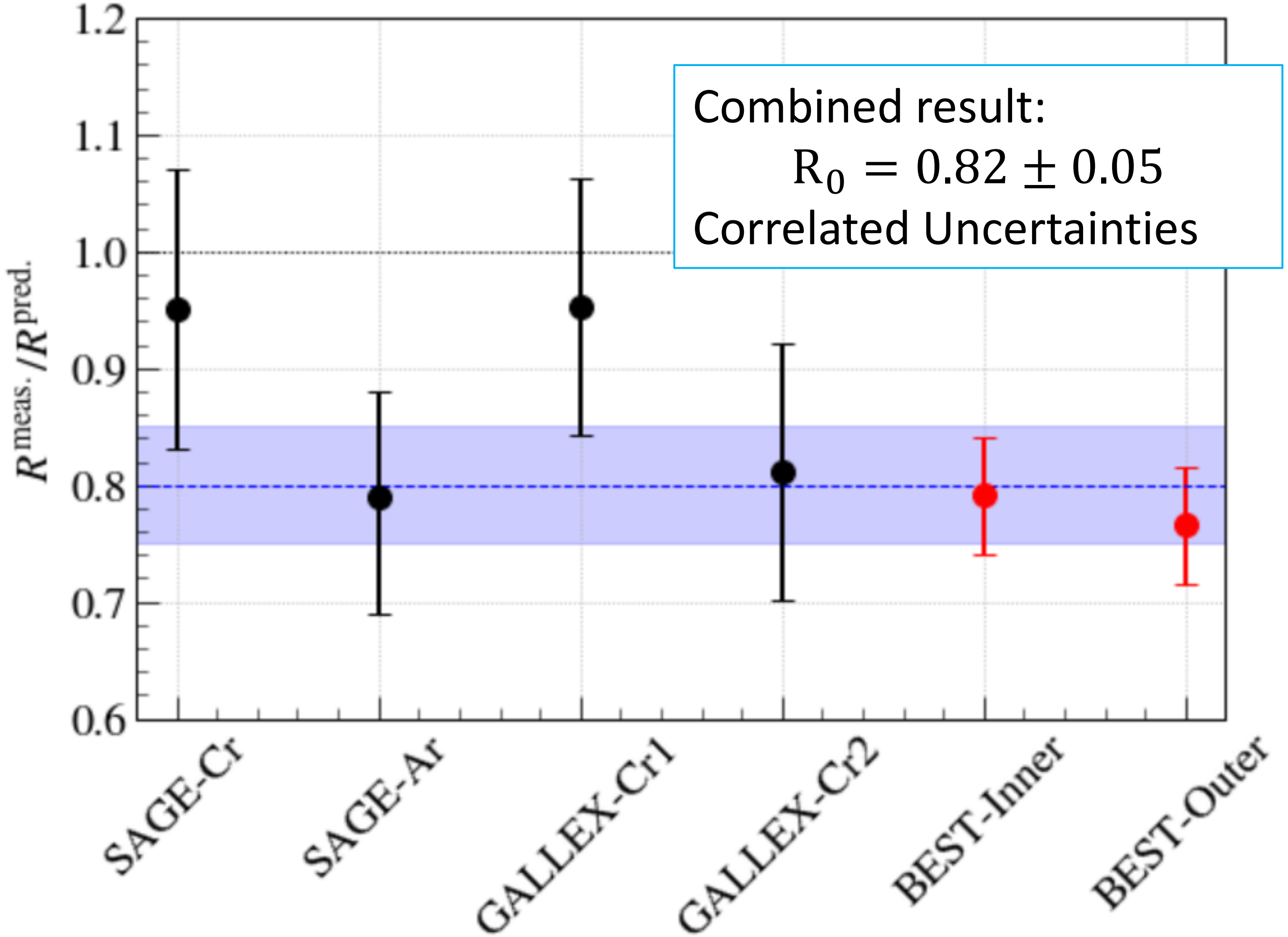
Haxton and Rule cross section analysis (PRC 108 (2023) 035502)

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

- Recent re-examination of the cross section and its uncertainties.
- Considered effects not previously evaluated, weak magnetism, non-universality in radiative corrections. These turned out to be small (~0.5% each).
- Developed shell-model technique to estimate the interference between Gamow-Teller and Tensor contributions to the charge exchange measurements. This is critical when the GT strength is small – like the case of ^{71}Ga.
  - Compared to experimental cases of (p,n) and beta decay amplitudes.
  - Found $(5.69^{+0.28}_{-0.06})$x10^{-46} cm^2 compared to Bahcall $(5.81^{+0.21}_{-0.16})$x10^{-46} cm^2.
  - Agrees to 1σ.



Combined Analysis after Update σ. Small Change.



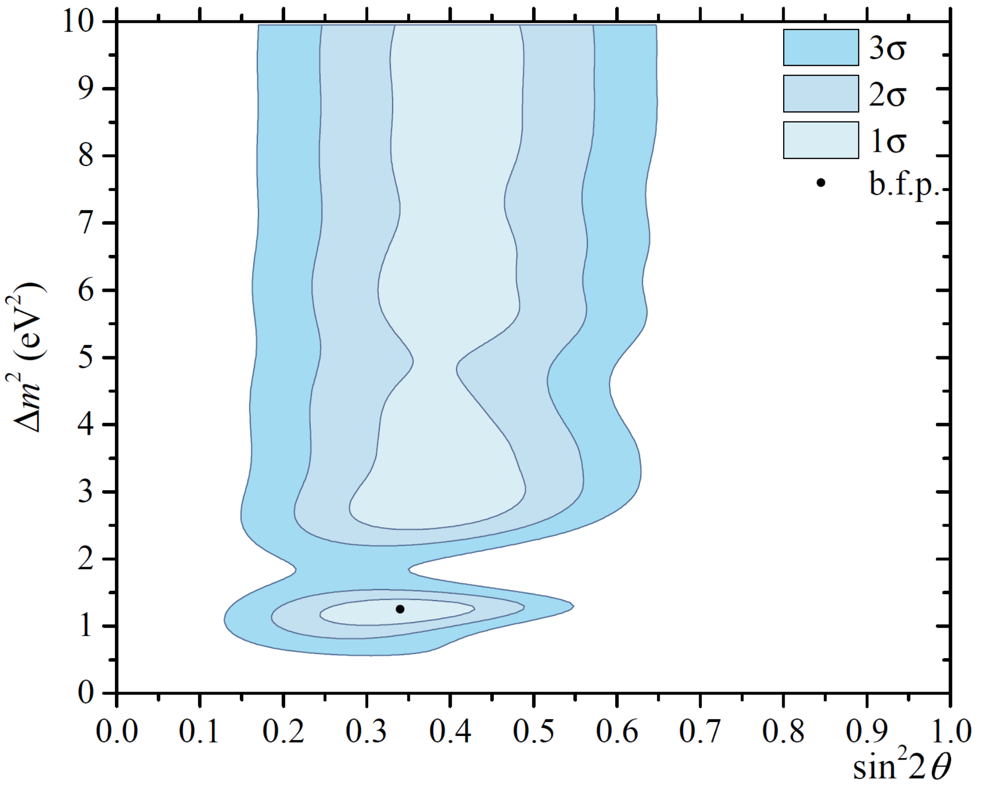
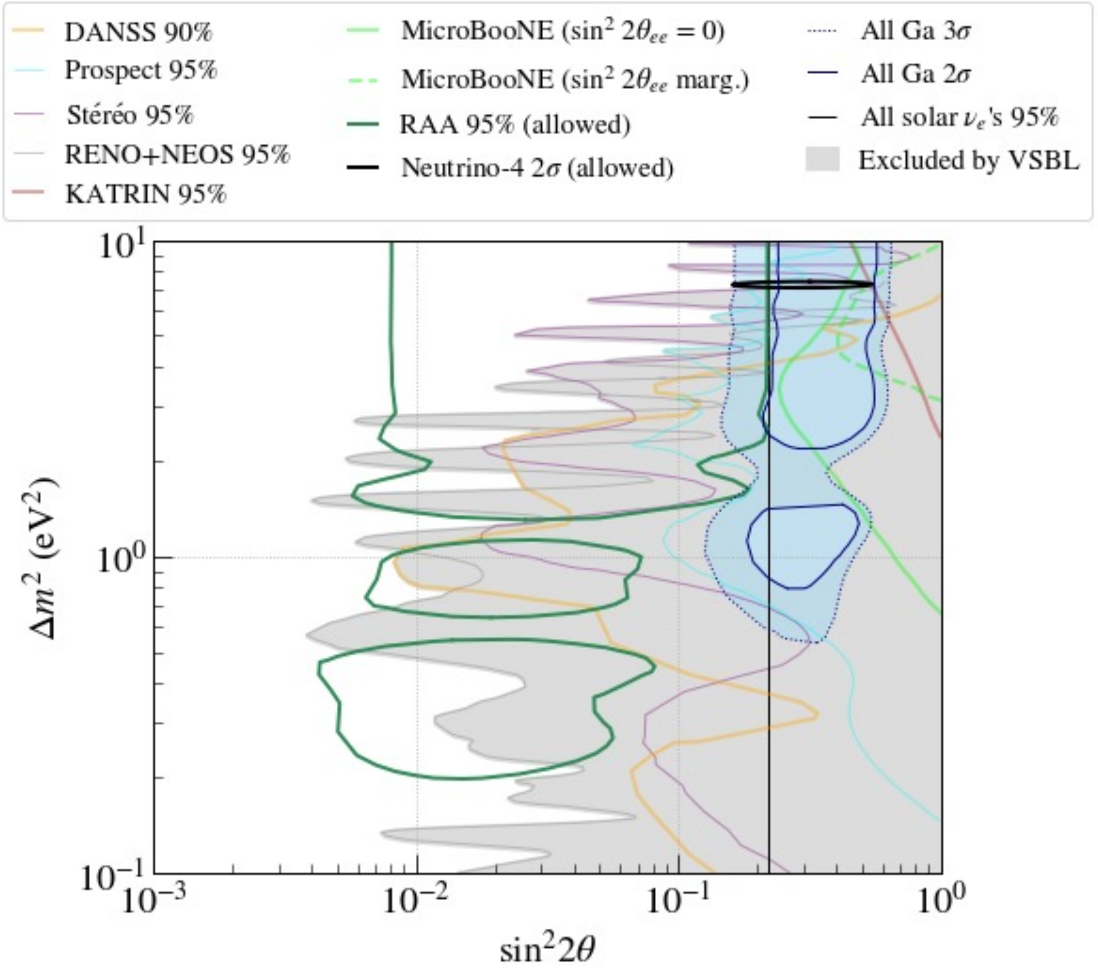


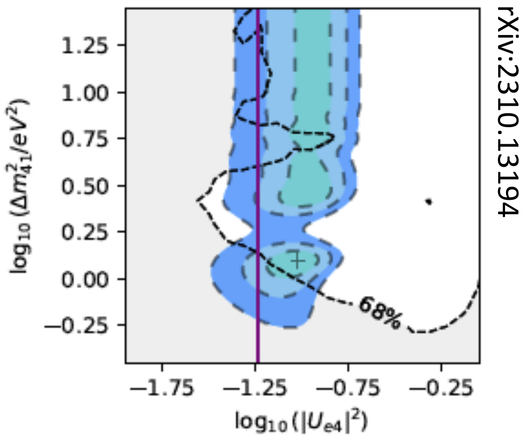
FIG. 8. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta$=0.33, Δm^2 = 1.25 eV^2 and is indicated by a point.

Comparison to Other Oscillation Results



Clear tension between the numerous results.

Coherent Scattering



BEST Best-fit point

$$\Delta m^2 = 1.25\,, \sin^2 2\theta = 0.34$$

DANSS: Int. J. Mod. Phys. A **35**, 2044015 (2020)
Prospect: PRD **103**,032001 (2021)
Stereo: PRD **102**, 052002 (2020)
RENO+NEOS: arXiv:2011.00896 (2020)
KATRIN: PRL **126**, 091803 (2021)
MicroBooNE: arXiv:2111.10359
RAA: PRD **83**, 073006 (2011)
Neutrino-4: JETP Lett. **112**, 199 (2020)
Model indep. solar: PLB **816**, 136214 (2021)
Coherent ν scattering: arXiv:2310.13194

Consistent with, but not Proof of, Oscillations

These results reaffirm the Ga anomaly, with higher statistical precision.

But no dependence on oscillation length was observed. So although the results are consistent with oscillations, there is no ‘smoking gun’ evidence that is not subject to caveats.

Because the rate in the two volumes is equally depressed, a number of potential explanations beyond oscillations have been considered. No clear alternative has been identified.

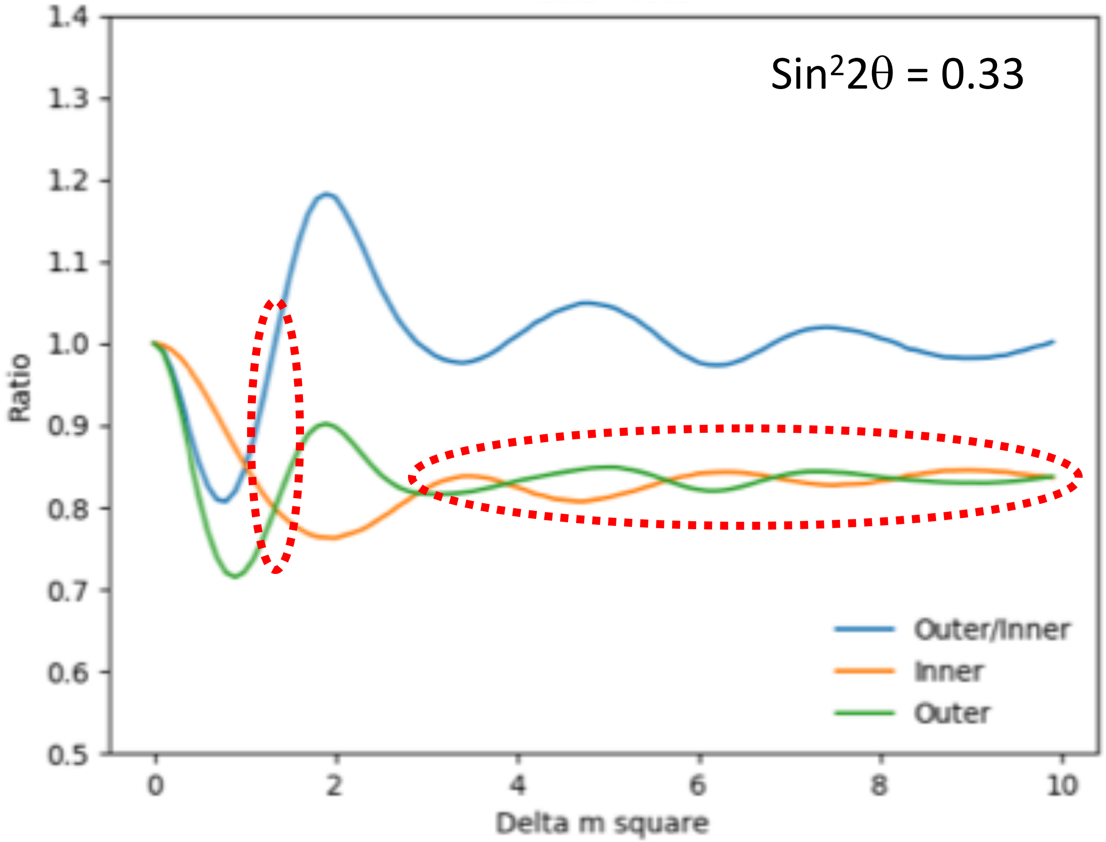
- Cross Section
- Source Strength
- Extraction Efficiencies
- Counting Efficiencies
- Average Path Length

Possible Future Experiment

If oscillations, the oscillation length is short (large Δm^2). BEST has poor Δm^2 resolution for values greater than ~2 eV^2.

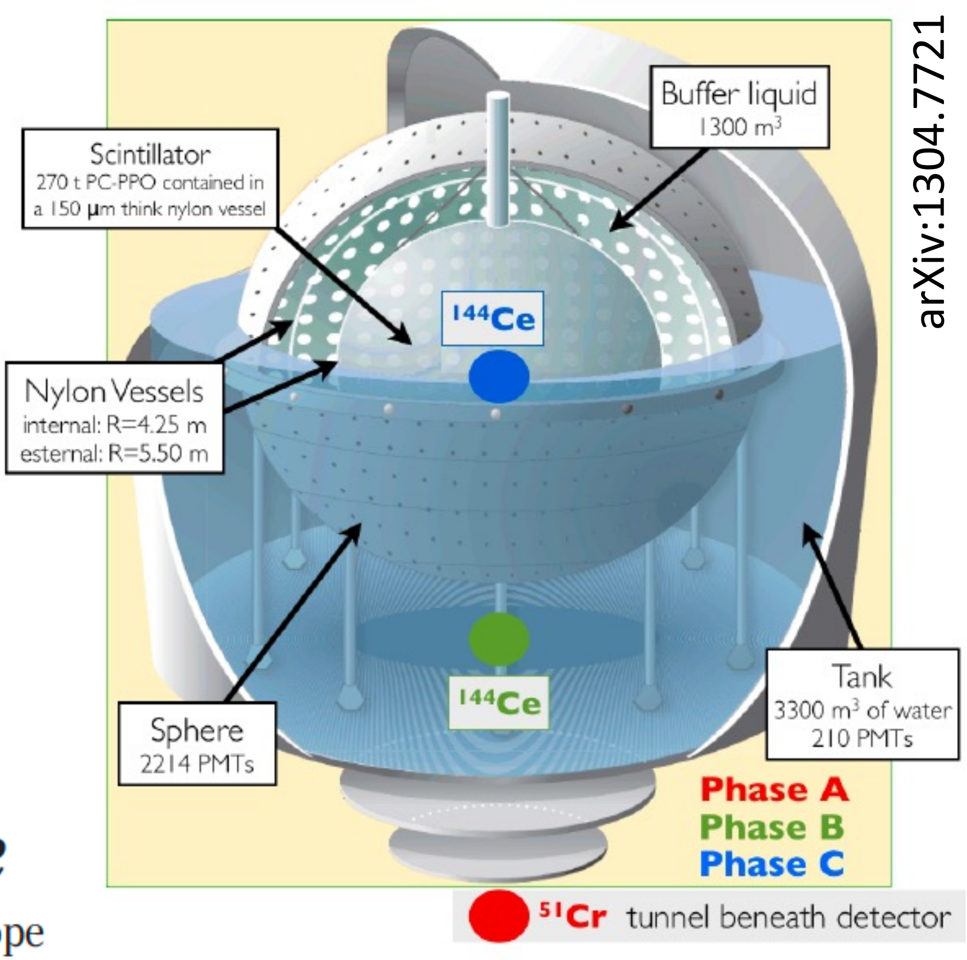
- Smaller inner volume probably not feasible.
  - Half the volume, need 8x the source strength.
- ^{65}Zn Source (PRD 97 (2018) 073001)
  - Higher energy source (1.35 MeV vs. 0.75 MeV).
  - Almost twice the cross section.
    - But adds excited states.
  - 6-7 kg of enriched ^{64}Zn to produce 0.5 MCi.
  - About 9x longer half life (244 d), many more events.

Regions where inner/outer both about 0.8 of expectation



The SOX Experiment

- SOX planned a ^{144}Ce source to expose BOREXINO.
  - $\tau_{1/2}$ - 285 d, Q_β = 3.00 MeV
- Description of anti-neutrino sources
  - PRD 91 (2015) 072005
- BOREXINO Proposal: Eur. Phys. J. C 76 (2016) 550
  - Also considered a ^{51}Cr source.
- Fabrication of source failed



arXiv:1304.7721

NUCLEAR SAFETY

Isotope cloud linked to failed neutrino source

Mishandling of spent fuel in Russia may have caused radioactivity to spread across Europe

Science 359 (2018) 729

Summary: see arXiv:2109.11482

- BEST measured the ^{71}Ge production in Ga from neutrinos emitted by ^{51}Cr at two distances.
- The ratio of the measured-to-predicted rates in both the inner and outer zones are depressed by about 20% from unity. The ratio-of-ratios is ~1.
- The Ga Anomaly is reaffirmed.
- No dependence on oscillation length was observed.