Exploring a Calibration Discrepancy at SAGE & GALLEX: the direct Q-value measurement of $^{51}Cr(e^-,\nu_e)^{51}V$ at TITAN

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Overview

- Neutrino physics at SAGE and GALLEX
- The calibration discrepancy
- Penning trap mass spectrometry
- TITAN's $^{51}Cr(e^-,\nu_e)^{51}V$ Q-value measurement
- Preliminary results for $^{51}Cr(e^-,\nu_e)^{51}V$ and $^{71}Ga(\nu_e,e^-)^{71}Ge$
- Conclusions

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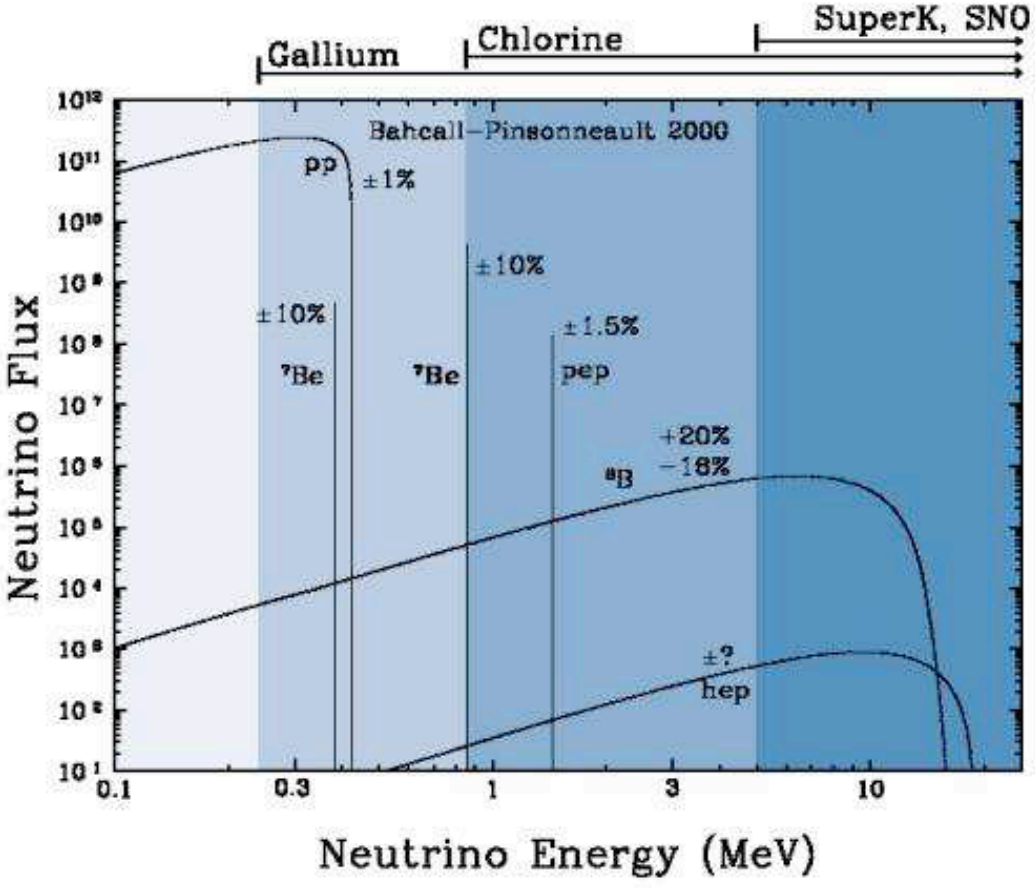
Solar Neutrino Experiments



- Nuclear reactions in the sun result in a solar neutrino flux
- Early chlorine detectors detected only 1/3 of the predicted flux
- Gallium detectors are sensitive to the more abundant pp neutrinos
- SAGE and GALLEX took data for 15+ years counting the number of Ge atoms produced via $^{71}Ga(\nu_e, e^-)^{71}Ge$
- Provided evidence for solar neutrino oscillations

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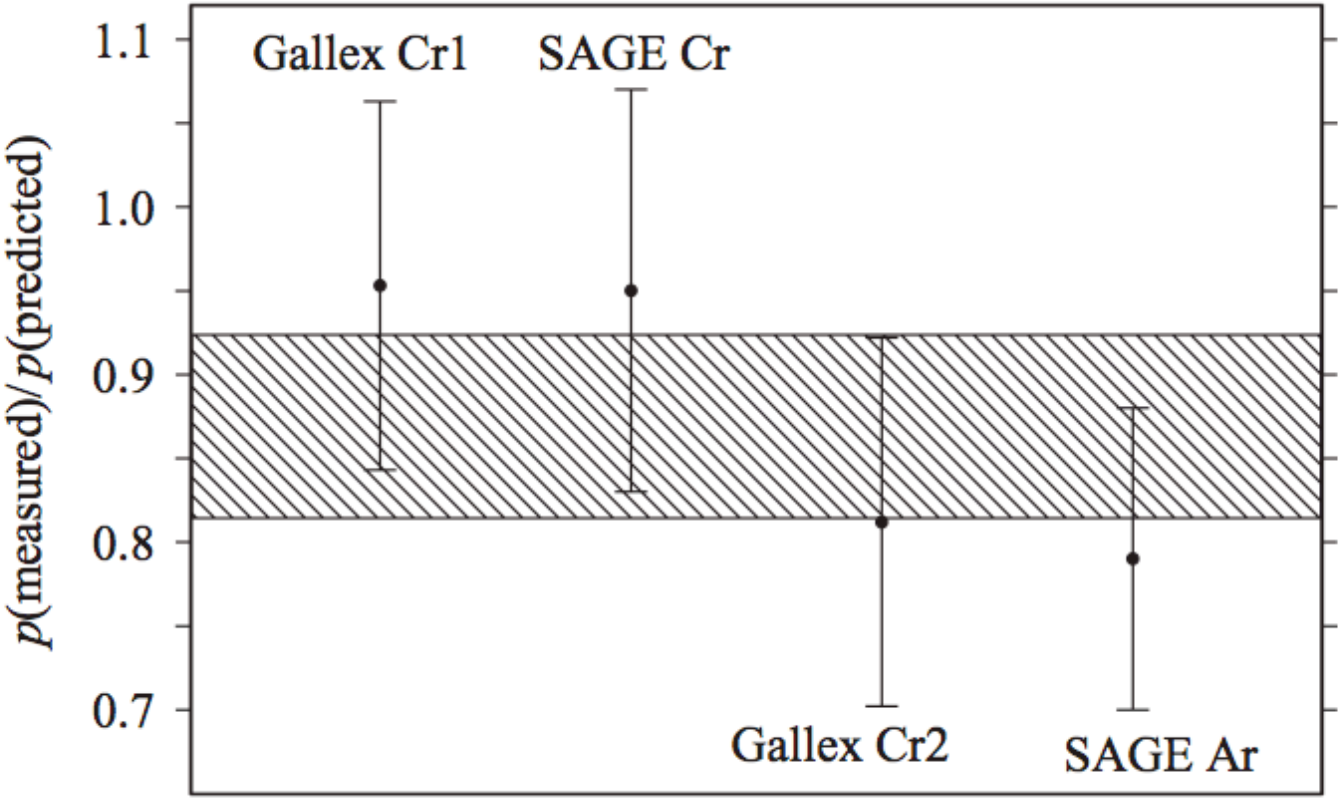
The Calibration Discrepancy

- Source experiments were performed to verify experimental procedures
- Employed a known neutrino flux from $^{51}Cr(e^-, \nu_e)^{51}V$ and $^{37}Ar(e^-, \nu_e)^{37}Cl$
- The ratio between the measured and expected production rates is 0.87±0.05: ~3σ deviation from unity



Results of all neutrino source experiments with gallium [PRC 80 015807 (2009)]

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A Bit of Nuclear Physics…

$$R = \sigma F N \varepsilon$$

R - rate of germanium detected
σ - cross-section for the reaction
F - neutrino flux
N - number of gallium atoms
ε - detector efficiency

- Possible explanations for the unexpected result include:
  - Efficiency factors: these have been well determined with many ancillary experiments
  - Number of gallium atoms: cannot account for the 3σ deviation
  - Statistical fluctuation: probability of observing the obtained result in agreement with unity is 5.3%
  - Physics of unknown origin: sterile neutrinos, quantum decoherence in neutrino oscillations…
  - Imprecise knowledge of production rates: cross-sections
- The cross section depends on the mass difference (Q-value) of the parent and daughter in both ^{51}Cr- and ^{71} Ge-decay→ TITAN

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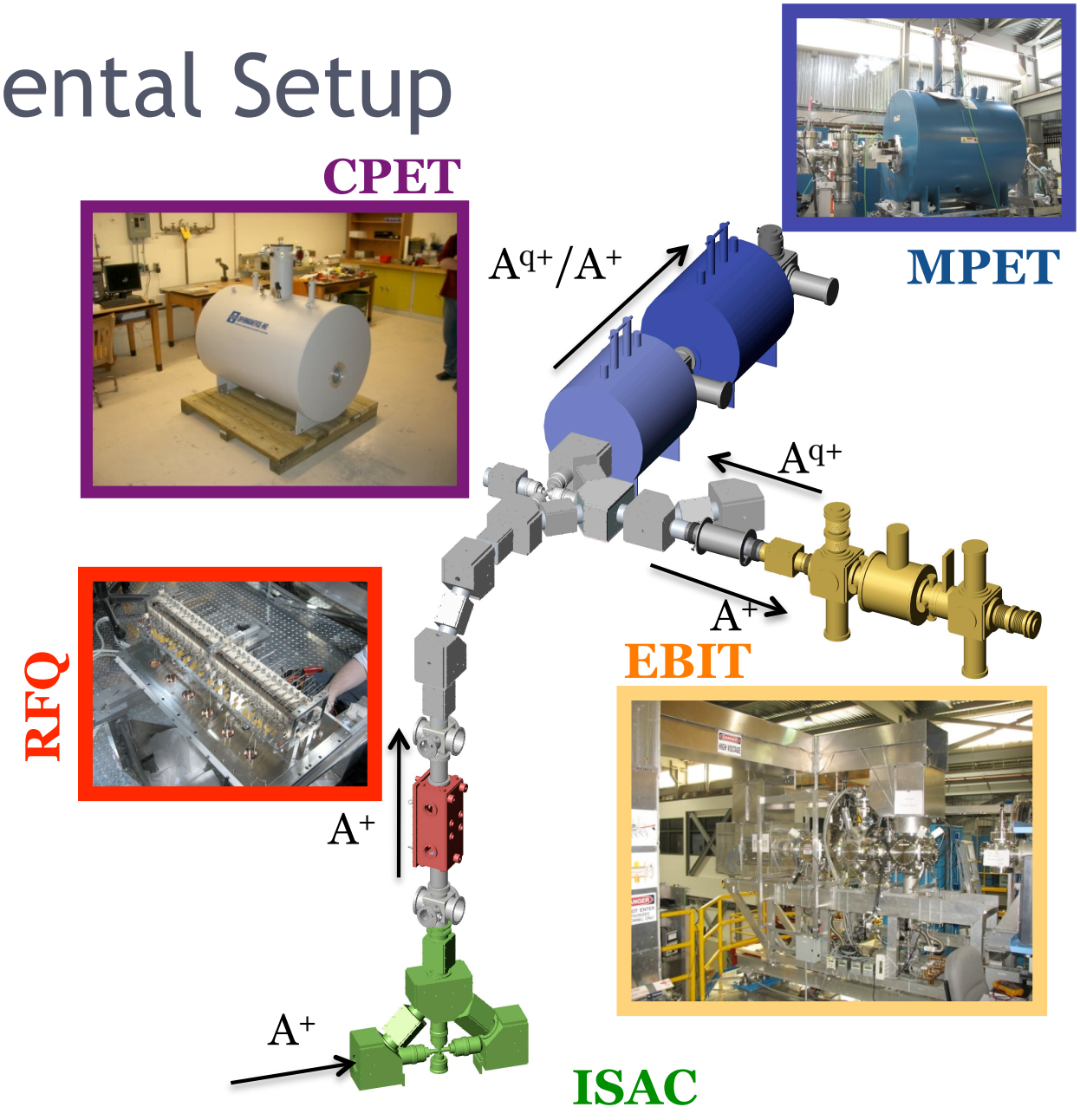
TITAN Experimental Setup

- ISAC : delivers isotope beam
- RFQ: accumulates, cools, and bunches
- EBIT: increases the q/m ratio by charge breeding
- CPET: cools the highly charged ion beam
- MPET: uses time-of-flight ion-cylcotron-resonance (TOF-ICR) technique for mass determination



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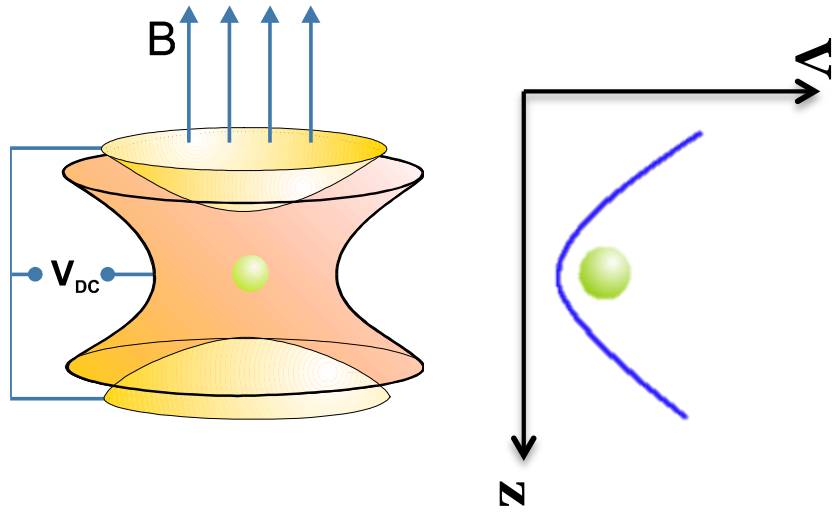
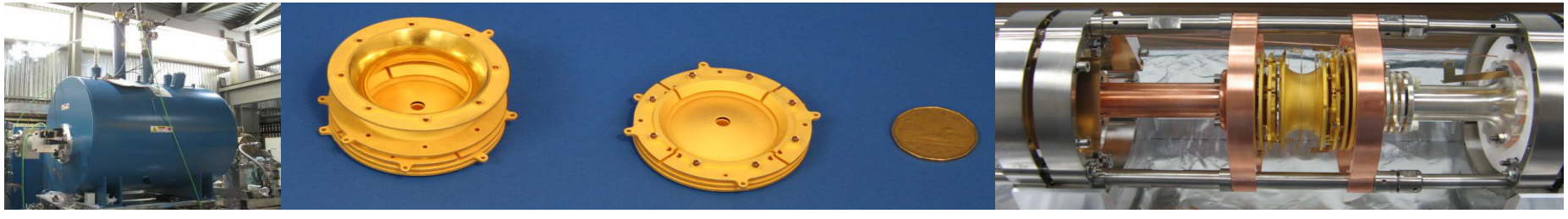
Penning Trap Mass Spectrometry

- Static electric quadrupole (axial) and strong magnetic field (radial) for confinement
- Ions undergo radial and axial harmonic motion
- The cyclotron frequency of an ion in a magnetic field is related to its charge to mass ratio:

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

- Most accurate and precise method for determining the mass of nucildes





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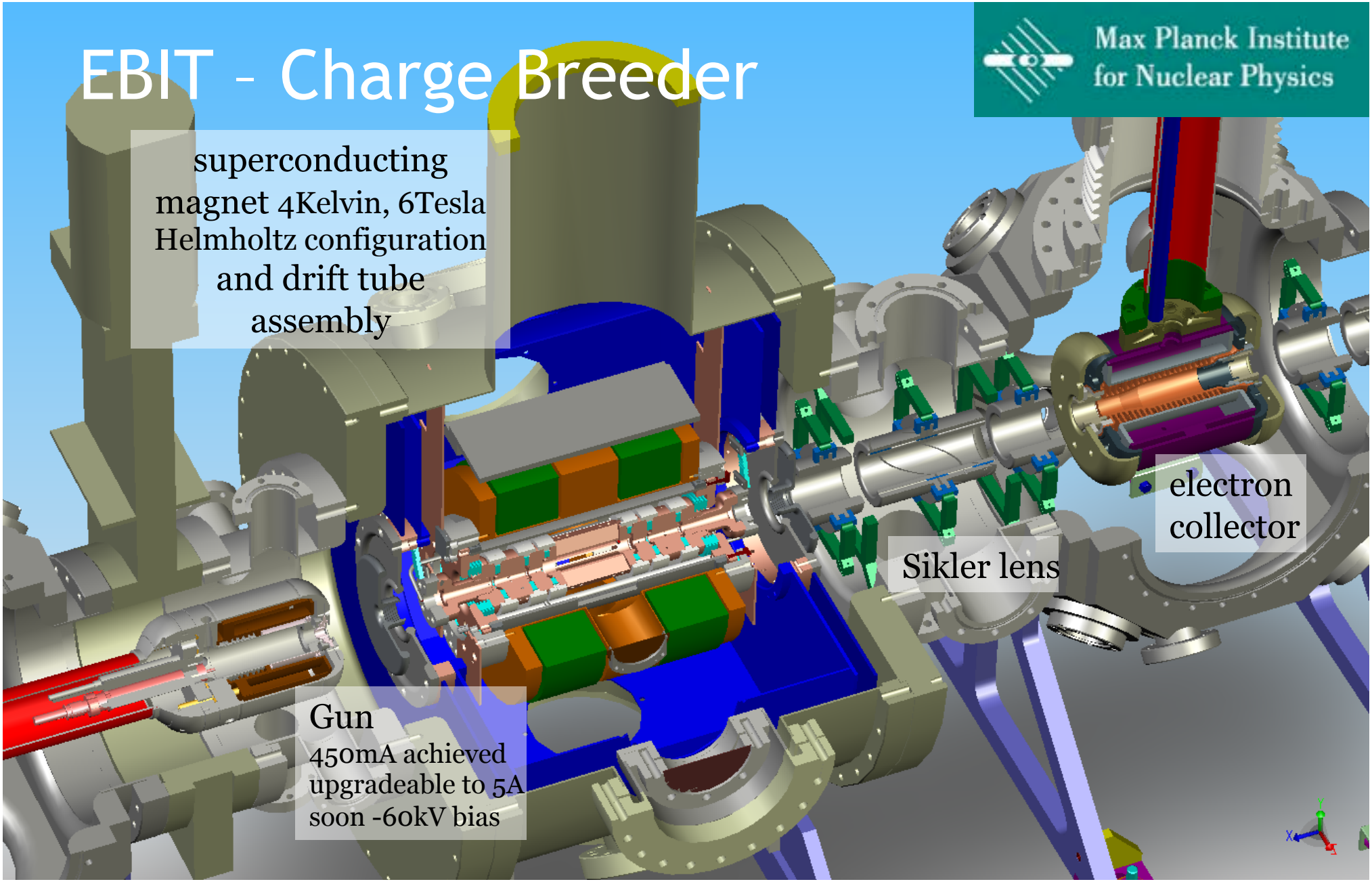
EBIT - Charge Breeder



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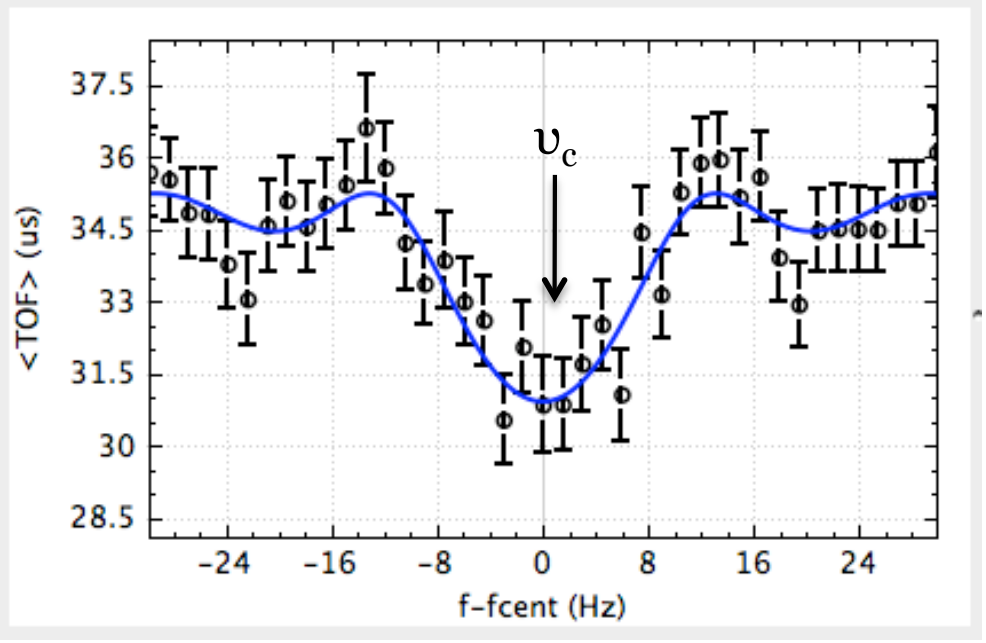
Q-value Measurement

- To remove the uncertainty from the magnetic field, the ratio of cyclotron frequencies is used
- $$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$
- $$R = \frac{\nu_1}{\nu_2} = \frac{q_1 m_2}{q_2 m_1}$$
- $$Q = (R-1)(M_1 - qm_e + BE_q)$$

$^{51}Cr^{5+}$ TOF-ICR Resonance



- A direct Q-value measurement is done by measuring the frequency of both chromium and vanadium

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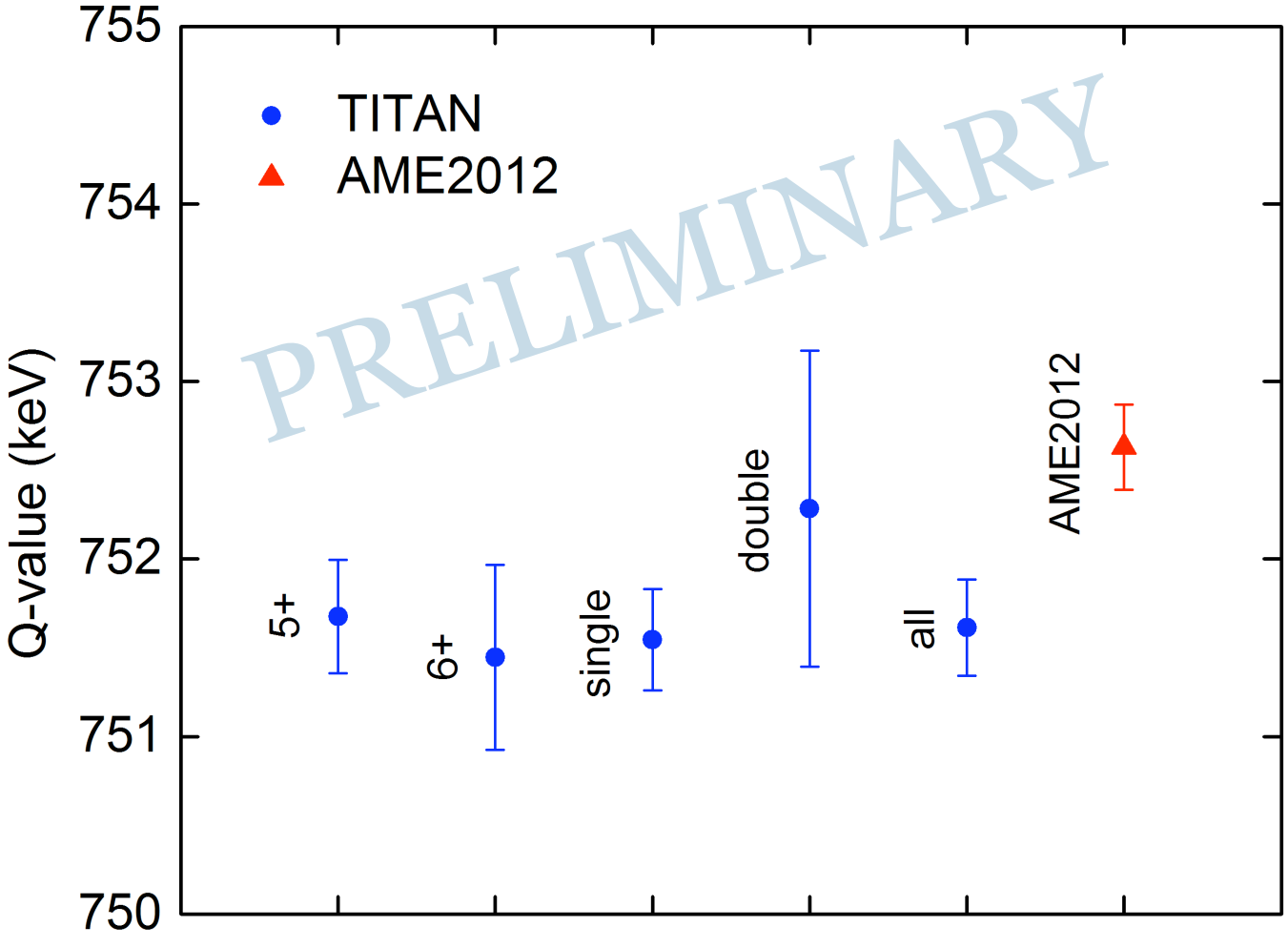
$^{51}Cr(e^-,\nu_e)^{51}V$ Preliminary Results



- A series of systematic tests measuring the Q-value
- Different charge states and different excitation schemes are all in agreement

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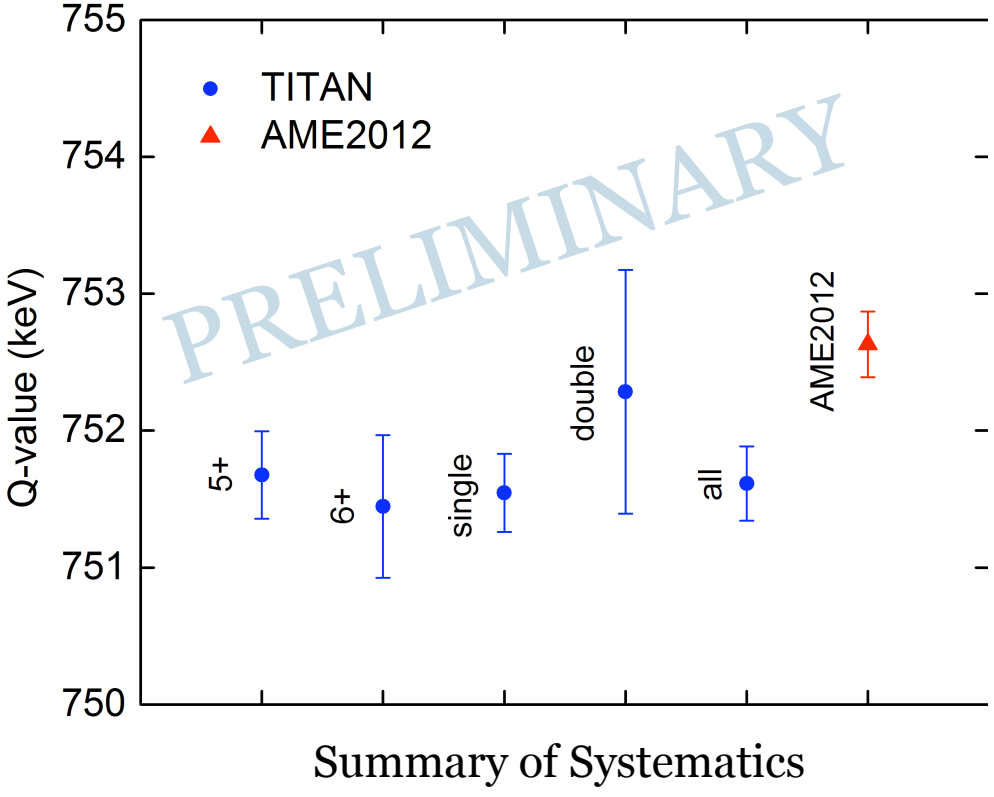
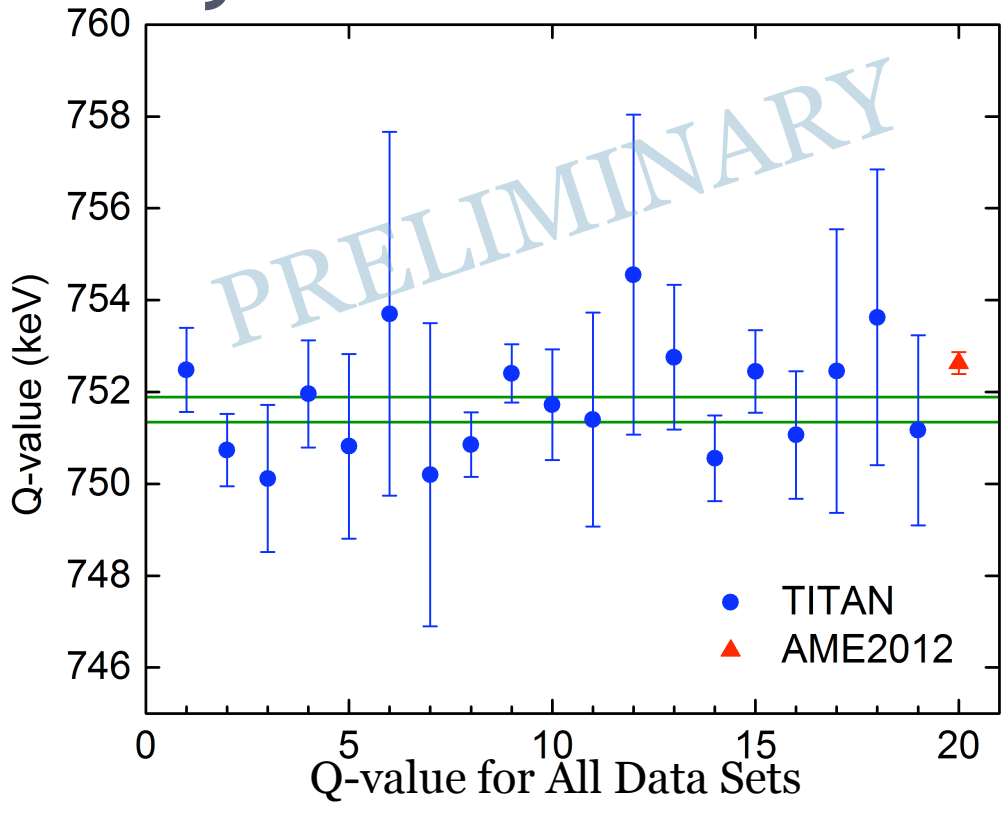
$^{51}Cr(e^-,\nu_e)^{51}V$ Preliminary Results





- Using the AME 2012 value of ^{51}V as the reference ion the preliminary result is 751.61(54) keV

Source	Q-value (keV)
AME 2003	752.58(24)
AME 2012	752.63(24)
TITAN	751.61(54)

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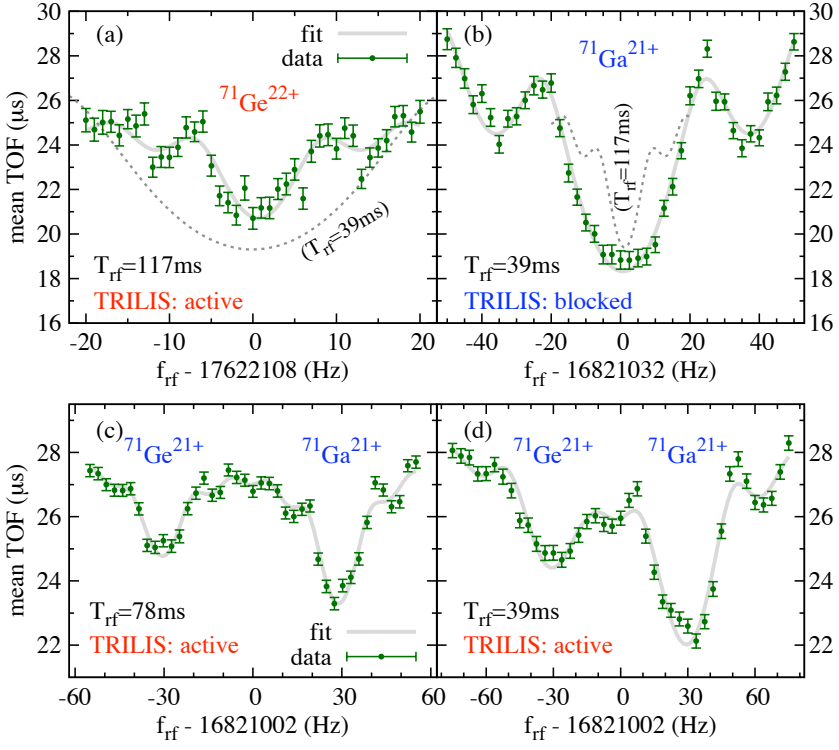
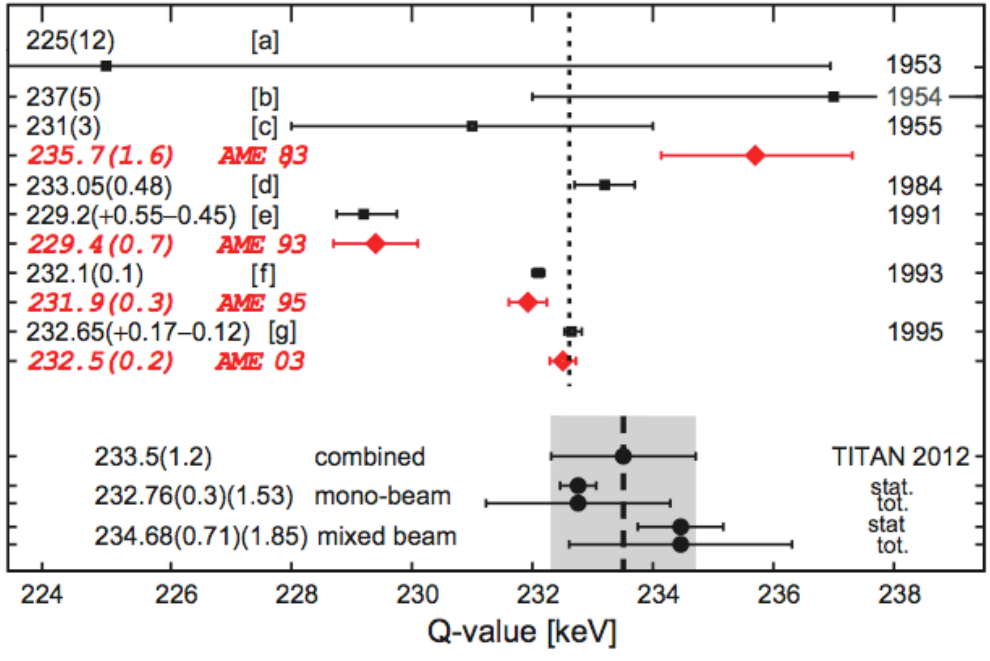
$^{71}Ga(\nu_e,e^-)^{71}Ge$ Q-value Measurement



$^{71}Ga(\nu_e,e^-)^{71}Ge$	Q-value (keV)
AME2012	**232.6(1.2)**
TITAN Total	**233.5(1.5)**

- The neutrino capture cross section in gallium depends on the Q-value for the reaction



D Frekers et al., submitted to PLB (2013)

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Conclusions

- The calibration discrepancy at solar neutrino experiments SAGE and GALLEX is yet unresolved
- Penning trap mass spectrometry is the most precise and accurate tool for direct mass measurements and it had not been used for Q-values relevant to SAGE and GALLEX until TITAN
- $^{51}Cr(\upsilon_e,e^-)^{51}V$ –result shows a statistically significant shift from the previous literature value, but the 0.1% change cannot account for the calibration discrepancy
- $^{71}Ga(e^-,\upsilon_e)^{71}G$ –result agrees with the previous literature value within the 1.5 keV uncertainty
- The results confirm that imprecise knowledge of the Q-values cannot account for the calibration discrepancy

Thanks to the TITAN Collaboration

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TU Munich
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One University. One World. Yours.

Questions…? Thank you!