The neutrino reaction on ^{71}Ga: new measurement of the neutrino response of ^{71}Ge from terrestrial neutrinos and of the ^{71}Ge EC Q-value

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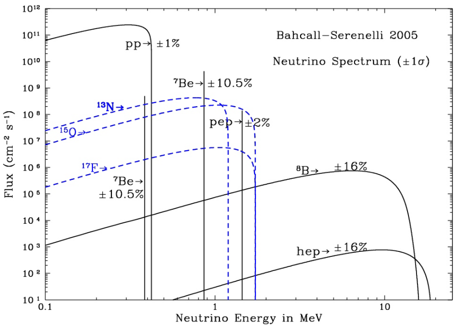
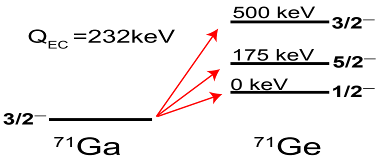
Reviewing the issue



Neutrino flux measured via the $^{71}\text{Ga}\left(\nu_e, e^-\right)^{71}\text{Ge}$-reaction

- expected rate after the SSM: ≈ 132 SNU
- detected rate (GALLEX/GNO): $67.6 \pm 4.0\,(\text{stat.})$ SNU
- detected rate (SAGE): $65.4^{+3.1}_{-3.0}$ SNU

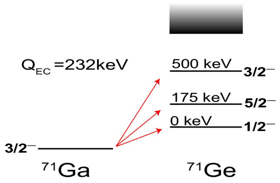
Calibration with ^{51}Cr (^{37}Ar) terrestrial ν-sources (EC-decay)



E_ν [keV]	transition	BR
747.3	K-EC $\rightarrow$ ^{51}V g.s.	81.6 %
752.1	L-EC $\rightarrow$ ^{51}V g.s.	8.5 %
427.1	K-EC $\rightarrow$ ^{51}V* (320)	8.95 %
432.0	L-EC $\rightarrow$ ^{51}V* (320)	0.9 %

exp.	source	ratio
GALLEX	^{51}Cr-1	0.95 ± 0.11
GALLEX	^{51}Cr-2	0.81 ± 0.11
SAGE	^{51}Cr	0.95 ± 0.12
SAGE	^{37}Ar	0.79 ± 0.10
Average	^{51}Cr, ^{37}Ar	0.87 ± 0.05

- **Origin of this discrepancy?!**
- lower detector efficiencies?
- neutrino cross section?
- unknown properties of neutrinos?



- ratio: # of measured ^{71}Ge atoms normalized to # of calculated atoms
- average value $\approx 2.5\sigma$ away from unity

Bahcall: Contribution from excited states: 5.1 %

$$\sigma\left({}^{51}\mathrm{Cr}-\nu\right) = \sigma_0\left({}^{51}\mathrm{Cr}-\nu\right)\left[1 + \underbrace{\underbrace{0.669\,\frac{B_1(GT)}{B_0(GT)}}_{0.028} + \underbrace{0.221\,\frac{B_2(GT)}{B_0(GT)}}_{0.146}}_{5.1\%}\right]$$

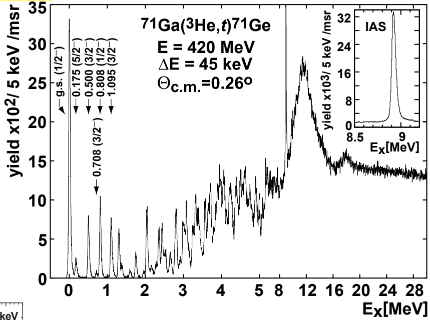
Extracting the B(GT)-strength via the $^{71}\mathrm{Ga}(^3\mathrm{He},t)^{71}$Ge-reaction @ RCNP

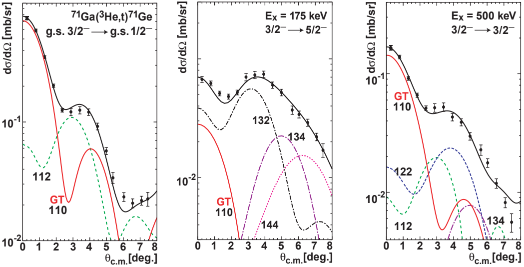
$$\frac{d\sigma(q_{tr}=0)}{d\Omega_{\mathrm{GT}}} = \left(\frac{\mu}{\pi\hbar^2}\right)^2 \frac{k_f}{k_i} N_{D_{\sigma\tau}} \left|J_{\sigma\tau}\right|^2 B\,(\mathbf{GT})$$

$N_{D_{\sigma\tau}}$: distortion factor

$|J_{\sigma\tau}|$: volume integral

E_x [keV]	J^π	GT	$\boldsymbol{B}$(GT)
g.s.	$1/2^-$	92%	0.0852(40)
175	$5/2^-$	40%	0.0034(26)
500	$3/2^-$	87%	0.0176(14)





Results

Contribution from the excited states: 7.2 ± 2.0 %

- 175 keV: 2.7 ± 2.0 %
- 500 keV: 4.5 ± 0.35 %

as opposed to 5.1 % taken by Bahcall

- discrepancy confirmed/slightly increased
- Contributions from the excited states do **NOT resolve** the discrepancy
  $\Rightarrow$ What else could contribute?

- **What about the Q_{EC} value of ^{71}Ge?**

$$\sigma_0\left(^{51}\mathrm{Cr}\right) = F(atom) \cdot \frac{1}{ft}$$
$$ft \propto Q^2_{\mathrm{EC}} \cdot t_{1/2}$$

How was the Q_{EC}-value measured before??

All measurements in context of 17 keV ν!

EC is accompanied by (IB)-photon ($1/10^4$)

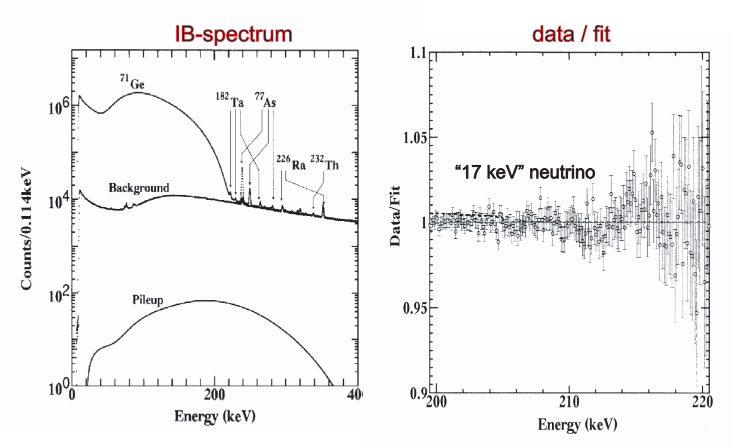
1. End-point spectrum is sensitive to neutrino mass
2. Q-value is determined by end-point energy
   $\Rightarrow$ **Q_{EC} only side effect!**

PROBLEMS:

1. Extremely strong sources needed ($\approx 10^{10}$ - 10^{11} Bq; (n,γ) activation)
2. Use of external source $\Rightarrow$ atomic excitations on the end-point energy!
3. Pile-up issues
4. background issues after activation??
5. detector efficiencies need to be known precisely!

^{71}Ge Q_{EC}-value by Lee et al. (1995)

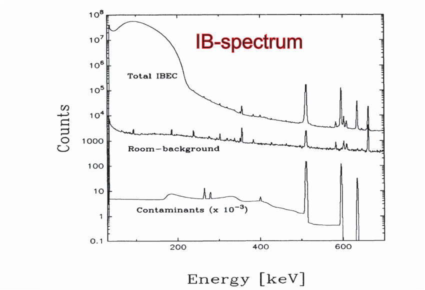
None of the internal bremsstrahlungs (IB)-EC expmts. were aimed at a precise determination of the Q_{EC}-value!!

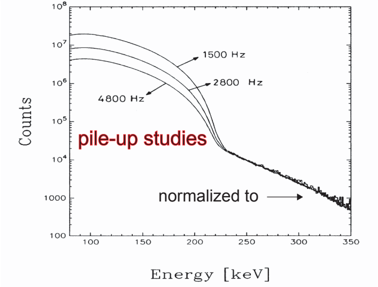


Q_{EC}-value: 232.65 ± 0.15 keV

^{71}Ge Q_{EC}-value by DiGrigorio et al. (1993)

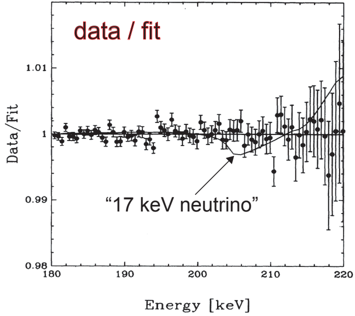
effect of atomic excitations on the end-point energy??





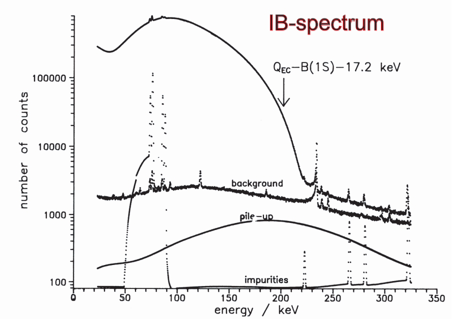
Q_{EC}-value:

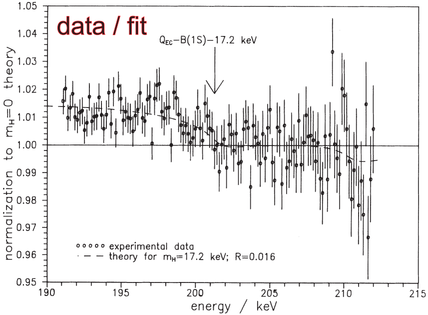
232.1 ± 0.1 keV



^{71}Ge Q_{EC}-value by Zlimen et al. (1991)

Also search for 17 keV ν with report of 17 keV ν
$\Rightarrow$ unreasonable error/calculation unclear





Q_{EC}-value: 229.0 ± 0.5 keV

^{71}Ge Q_{EC}-value measurement at TRIUMF's TITAN experiment - **New approach:** mass measurement via cyclotron frequencies

- Trap experiment
- radioactive beam of ^{71}Ge
- mass measurement of ^{71}Ge and ^{71}Ga via cyclotron frequencies

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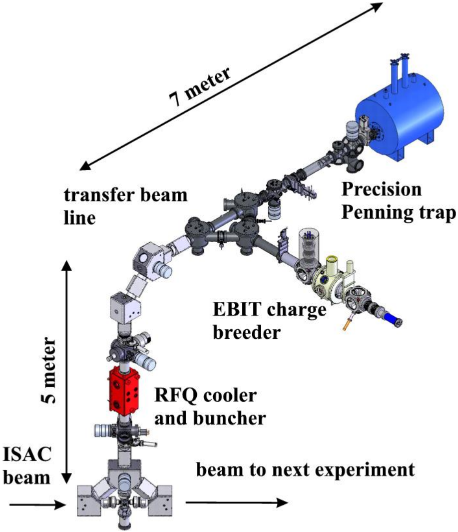
TITAN - TRIUMF's Ion Trap for Atomic and Nuclear science



1. Radioactive beam provided by ISAC
2. Transfer to EBIT (Charge breeding - creating highly charged ions)
3. Transfer to Penning trap (frequency determination via TOF measurement)

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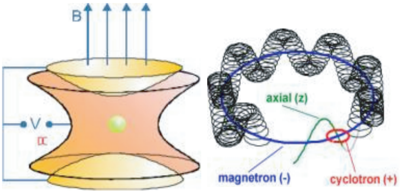
Principle of mass measurement with Penning Trap

1. Single ion injection
2. Confinement by B-field + electrostatic quadrupole field
3. Lorentz force ⇒ oscillation with cyclotron frequency
4. Trap opening & transfer of energy to E_{kin} ⇒ TOF-measurement



- ions oscillate with cyclotron frequency:

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

- Precision:

$$\frac{\delta m}{m} \approx \frac{m}{q \cdot B \cdot T_{RF} \sqrt{N}}$$

(T_{RF}: Excitation time)

⇒ Precision increases with charge state and number of measurements

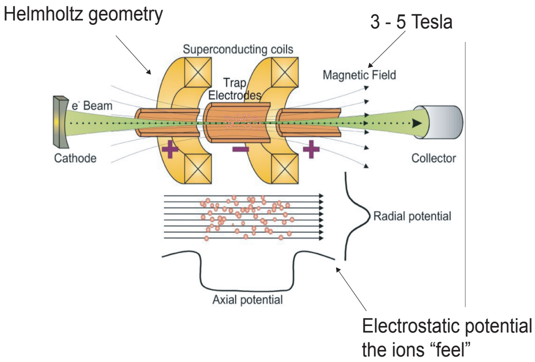
CAVEAT: HCI ⇒ increase of systematic effects:

1. HCI's interact with residual gas; i.e. increased damping
2. ion-ion interaction (when more than 1 ion in trap)

EBIT - Electron-Beam Ion Trap

produces and traps highly charges ions (HCI's) using a high-current electron beam

- e^--gun, trap center, e^--collector
- injected ions are accelerated towards trap center & compressed by B-field
- radial confinement by e^- beam space charge
- Ionisation by intense e^- beam (500mA)
- Ions are captured deeper in trap potential with every loss of e^-



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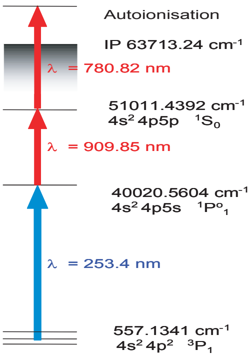
Novel approach: Production of ^{71}Ga and radioactive ^{71}Ge

- Ta-target + 50 μA, 500 MeV proton beam
  $\Rightarrow$ produce ^{71}Ga/^{71}Ge
  production rate $\approx 10^7$ - 10^8 p/s
- beam 1: **surface ionized** ^{71}Ga ($\approx 10^7$ p/s)
- beam 2: **surface ionized** ^{71}Ga + **laser ionized** ^{71}Ge ($\approx 10^6$ p/s)
- Beam transport to EBIT
- Charge breeding to **neon-like** charge states
  $\Rightarrow$ beam 1: Ga^{21+}
  $\Rightarrow$ beam 2: two species: Ga^{21+} and Ge^{22+}
- high purity and high isobaric mass separation due to HCI's
- assurance of single ion injection (minimize ion-ion interaction) into MPET

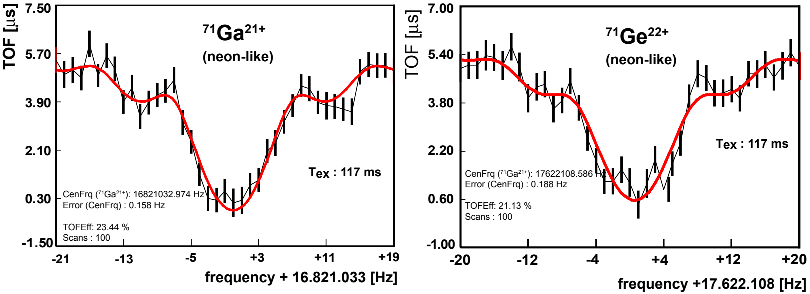
3-step photoionization
(developed @ TRIUMF)



Typical TOF-resonances for ^{71}Ga and ^{71}Ge

Excitation frequency versus the TOF

Minimum of the resonance corresponds to the **cyclotron frequency**



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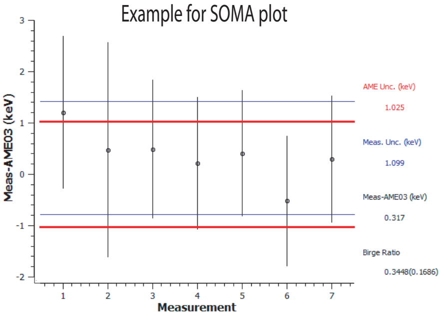
Calculation of atomic mass excess ⇒ Q_{EC}-value

$$m_1 = \frac{q_1}{q_2} \cdot \frac{\nu_2}{\nu_1} \cdot m_2$$



- stable nucleus (^{71}Ga) as reference (m_2)
- ⇒ mass measurement of ^{71}Ge (m_1)
- accounting for ionisation energies of each species
- additional calculations with other references (also highly charged)

⇒ Q_{EC}-value:

233.0 ± 0.6 keV

(Preliminary!)

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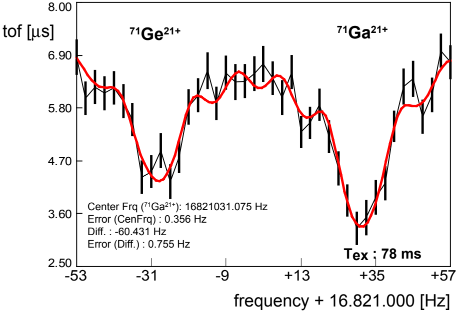
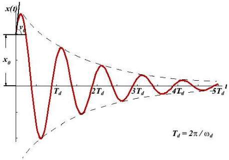
Double resonance

Independent measurement of Q_{EC}-value with two species trapped at the same time



$\Rightarrow$ **Q_{EC}-value: 234.8 ± 0.95 keV**
(Preliminary!)

- additional effect: ion-ion interaction of 2 species
- resonance-resonance interaction
- increased damping
- Effect on Q-value?
- $\Rightarrow$ Further investigation



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Systematic studies requiring further investigation

1. effect of excitation time (up to 156 ms) on charge exchange and frequency
2. effect of resonance damping (caused by charge exchange with residual gas)
3. ion-ion interaction
4. effect of Lorentz steering
5. calibration: study of well known (few eV) reference masses
   (i.e. $^{16}O^{5+}$, $^{84}Kr^{25+,26+}$, N^{4+})
6. relativistic q/m shift due to magnetic field

⇒ **attempt to reduce systematic error and study of systematics**

Consequences of Q_{EC}-value measurement

$ft \propto Q_{\mathrm{EC}}^2 \cdot t_{1/2}$

F.i.: If Q_{EC} is $\approx$ 1 keV higher $\Rightarrow$ ft-value $\approx$ 1% higher
$\Rightarrow$ phase space factor for B_2(GT)$\approx$ 14 % lower $\Rightarrow$ $\sigma_0\left({}^{51}\mathrm{Cr} - \nu\right)$ slightly reduced $\Rightarrow$ Only slightly reduced discrepancy

Conclusion

nuclear physics aspect of the neutrino cross section has been investigated with high precision

1. contribution from excited states: 7.2 % $\pm$ 2.0 % (5.1 % by Bahcall) $\Rightarrow$ slightly amplifies the discrepancy
2. Q_{EC} will be close to the value employed by Bahcall & reduces @ most contrib. from exct. states from 7.2 % to 6.5 %
3. new calculations of phase space factors required

the observed discrepancy is **NOT** due to any unknowns in Nuclear Physics!!

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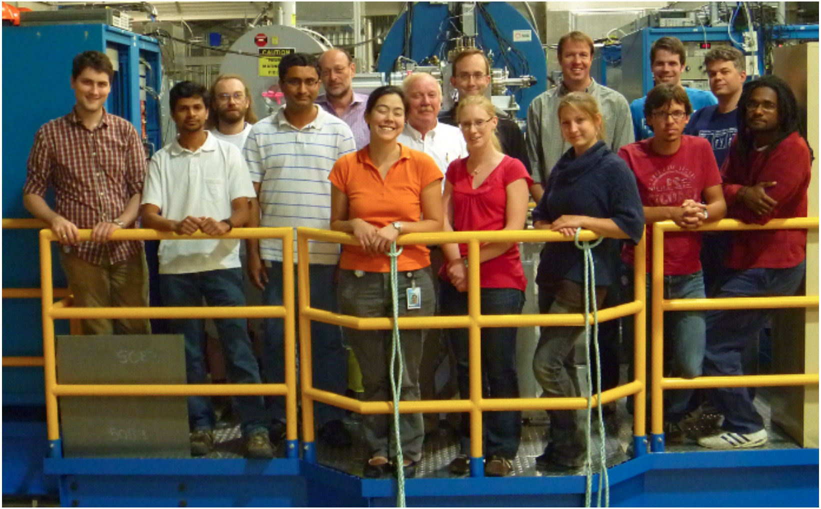

Thank you for your attention!

attachments - ^{71}Ge half life by Hampel

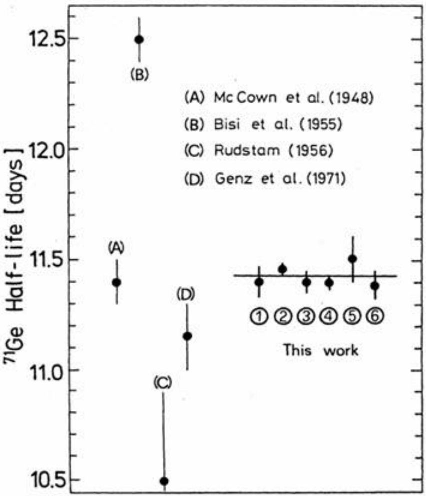

FIG. 1. ^{71}Ge half-life: Comparison of the new data with literature values. Numbers in circles refer to the run number in Table II.