The neutrino reaction on ^{71}Ga:

a) new measurement of the neutrino response of ^{71}Ge from terrestrial ν's
b) ^{71}Ge EC Q-value

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DPG Tagung, Mainz
22. März 2012

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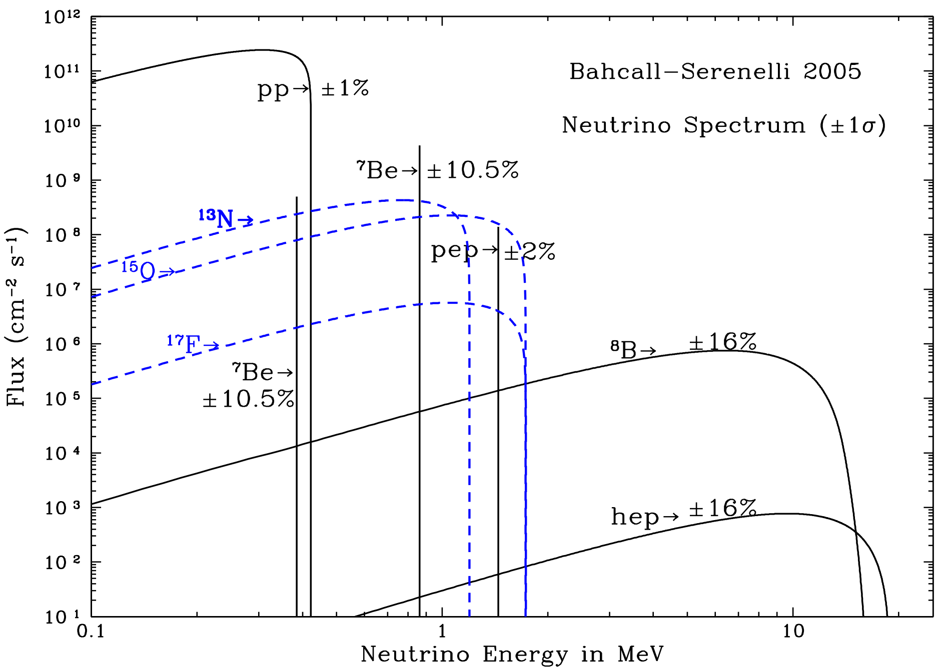
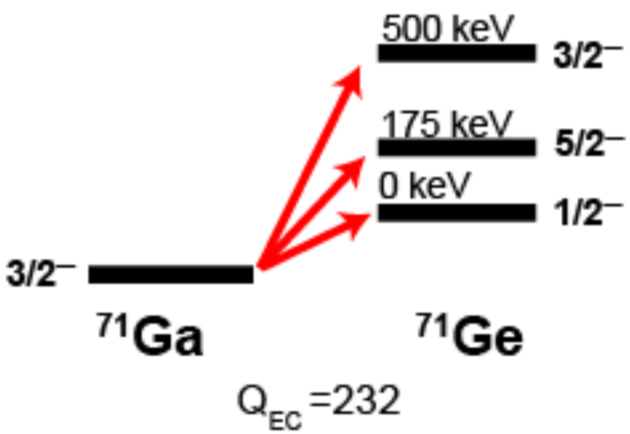
Reviewing the issue



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

- Expected rate after the SSM: **≈132 SNU**
- Detected rate (GALLEX/GNO): **67.6±4.0 (stat.) SNU**
- Detected rate (SAGE): **65.4+3.1 SNU**
- **Confirmed missing flux!**



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

^{51}Cr

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

Low reaction threshold! ➡ Sensitive to pp I ν's

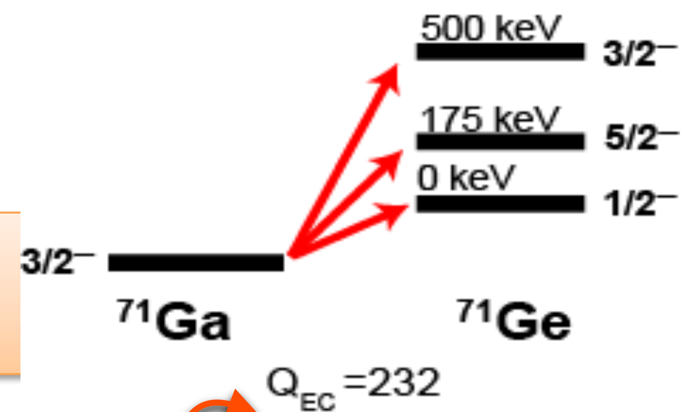
Exp.	source	ratio
GALLEX	^{51}Cr-1	0.95 ± 0.11
GALLEX	^{51}Cr-2	0.81 ± 0.11
SAGE	^{51}Cr	0.95 ± 0.12
SAGE	^{37}Ar	0.79 ± 0.10
Average	^{51}Cr, ^{37}Ar	0.87 ± 0.05

Origin of the discrepancy?

- Lower detector efficiencies?
- Neutrino cross section?
- Unknown properties of neutrinos?

- **Ratio:** # of measured ^{71}Ge atoms Normalized to # of calculated atoms
- Average value ≈**2.5** σ away from unity

J. Bahcall:
Contribution from excited states: 5.1 %



$$\sigma\left({}^{51}\mathrm{Cr}\right) = \sigma_0({}^{51}\mathrm{Cr}) \left[1 + 0.67\frac{B_1(GT)}{B_0(GT)} + 0.22\frac{B_2(GT)}{B_0(GT)}\right]$$

5.1%

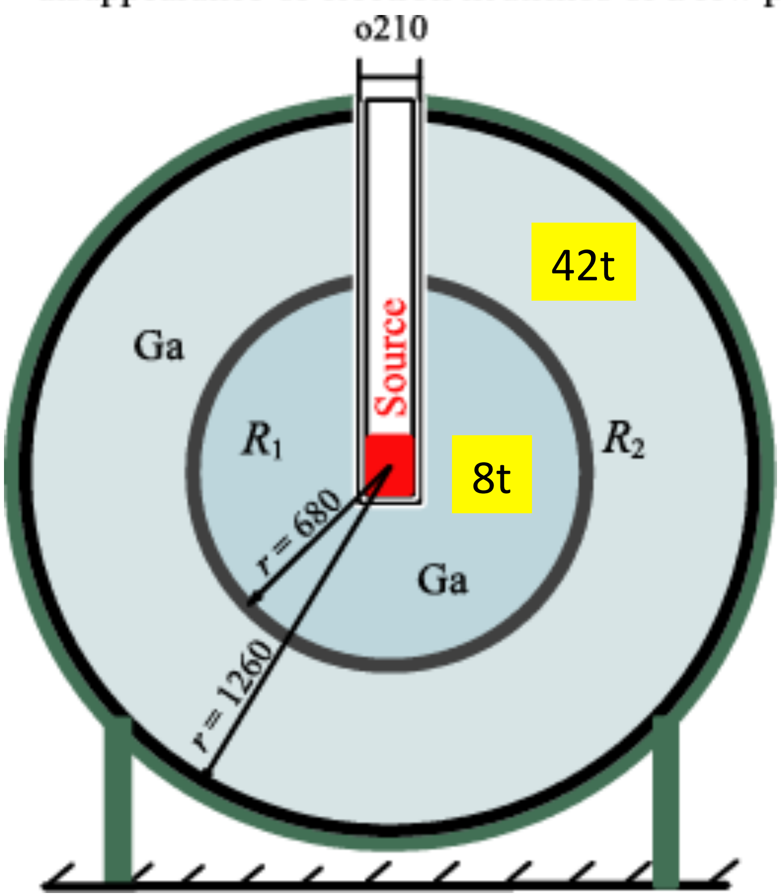
B(GT) values taken from
^{71}Ga(p,n)^{71}Ge exp. (Krofcheck, Sugarbaker, Rapaport) → **Poor energy resolution!** (≈200 keV)

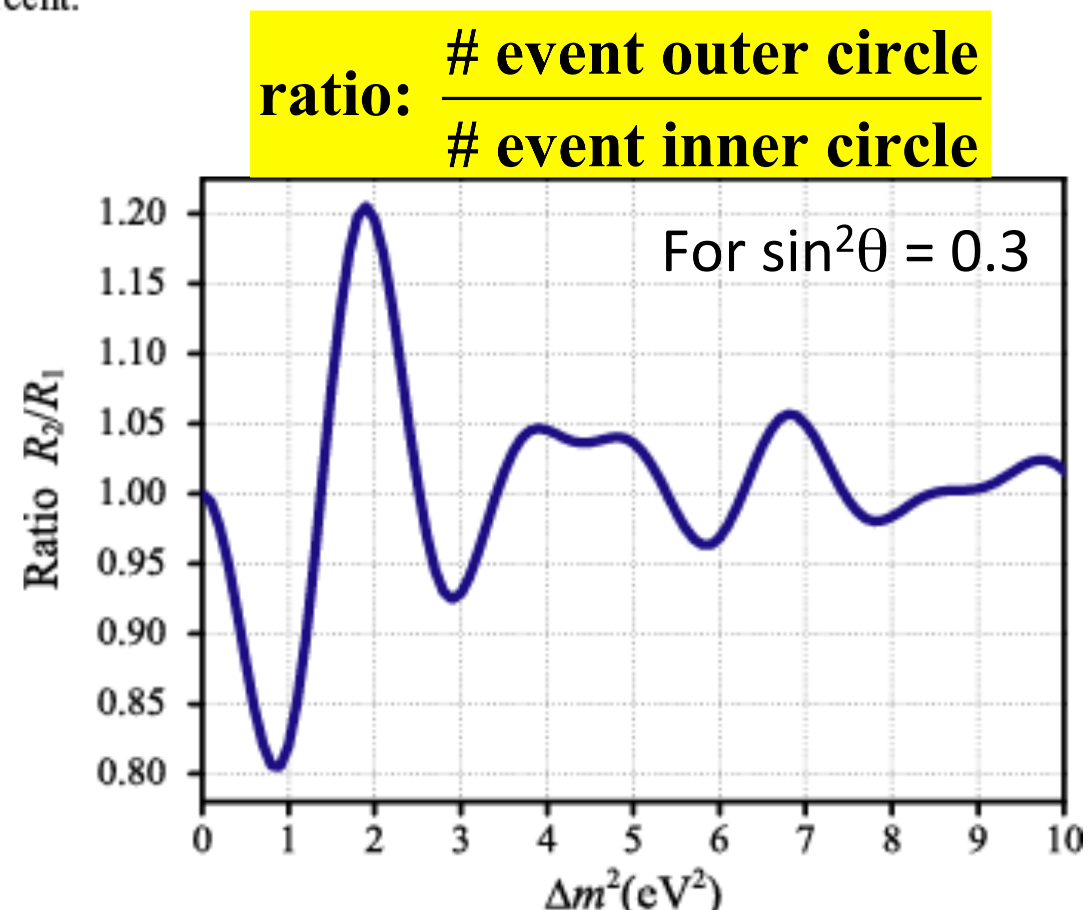
Gallium experiments with artificial neutrino sources as a tool for investigation of transition to sterile states

V. N. Gavrin,* V. V. Gorbachev,* E. P. Veretenkin,* and B. T. Cleveland†

20 July 2010

We propose to place a very intense source of ^{51}Cr at the center of a 50–tonne target of gallium metal that is divided into two concentric spherical zones and to measure the neutrino capture rate in each zone. This experiment can set limits on transitions from active to sterile neutrinos with $\Delta m^2 \approx 1$ eV^2 with a sensitivity to disappearance of electron neutrinos of a few percent.



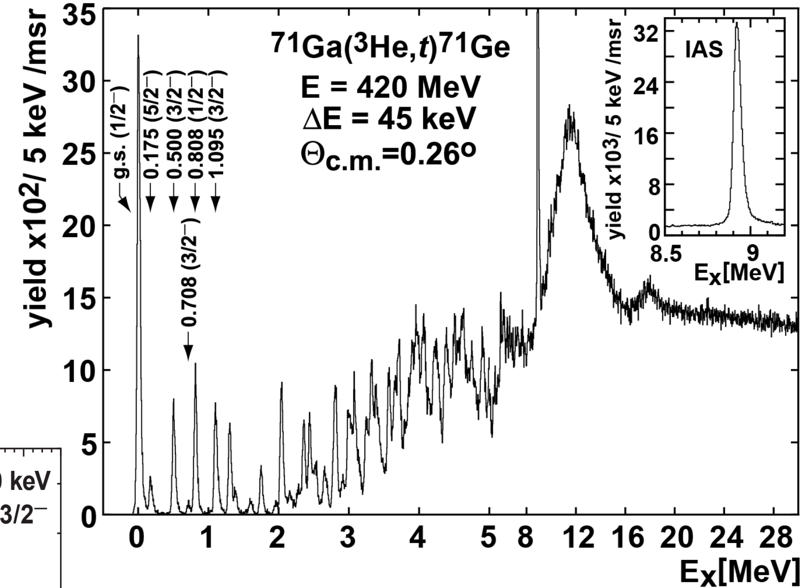


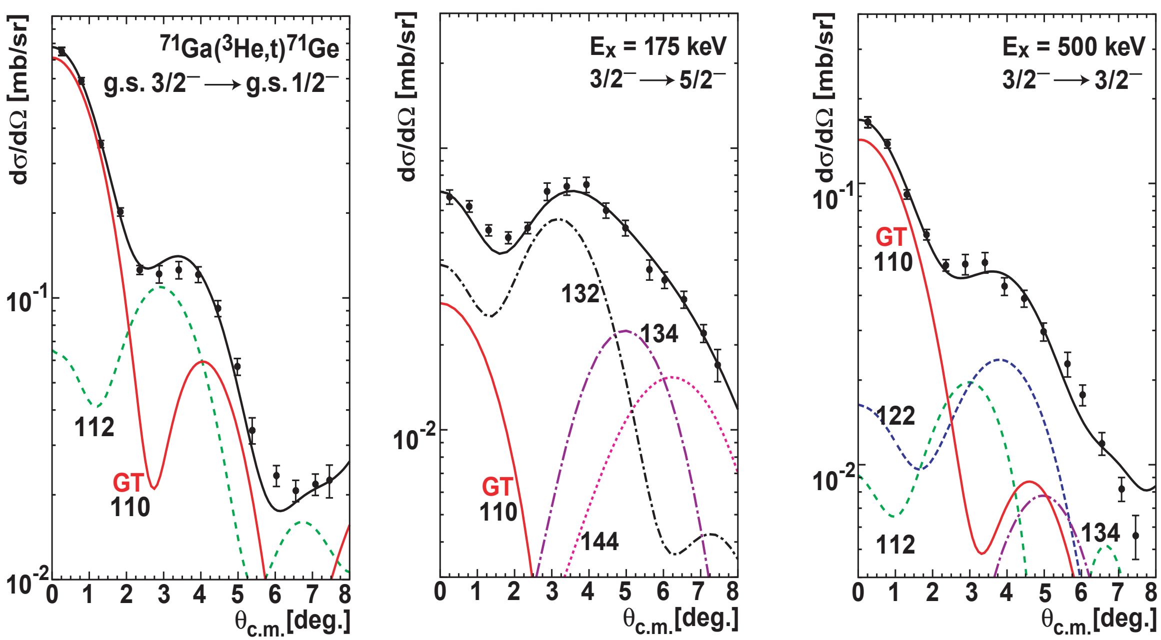
Extracting the B(GT)-strength via the $^{71}Ga(^{3}He,t)^{71}Ge$-reaction @ RCNP

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

CER sensitive to B(GT) strength

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





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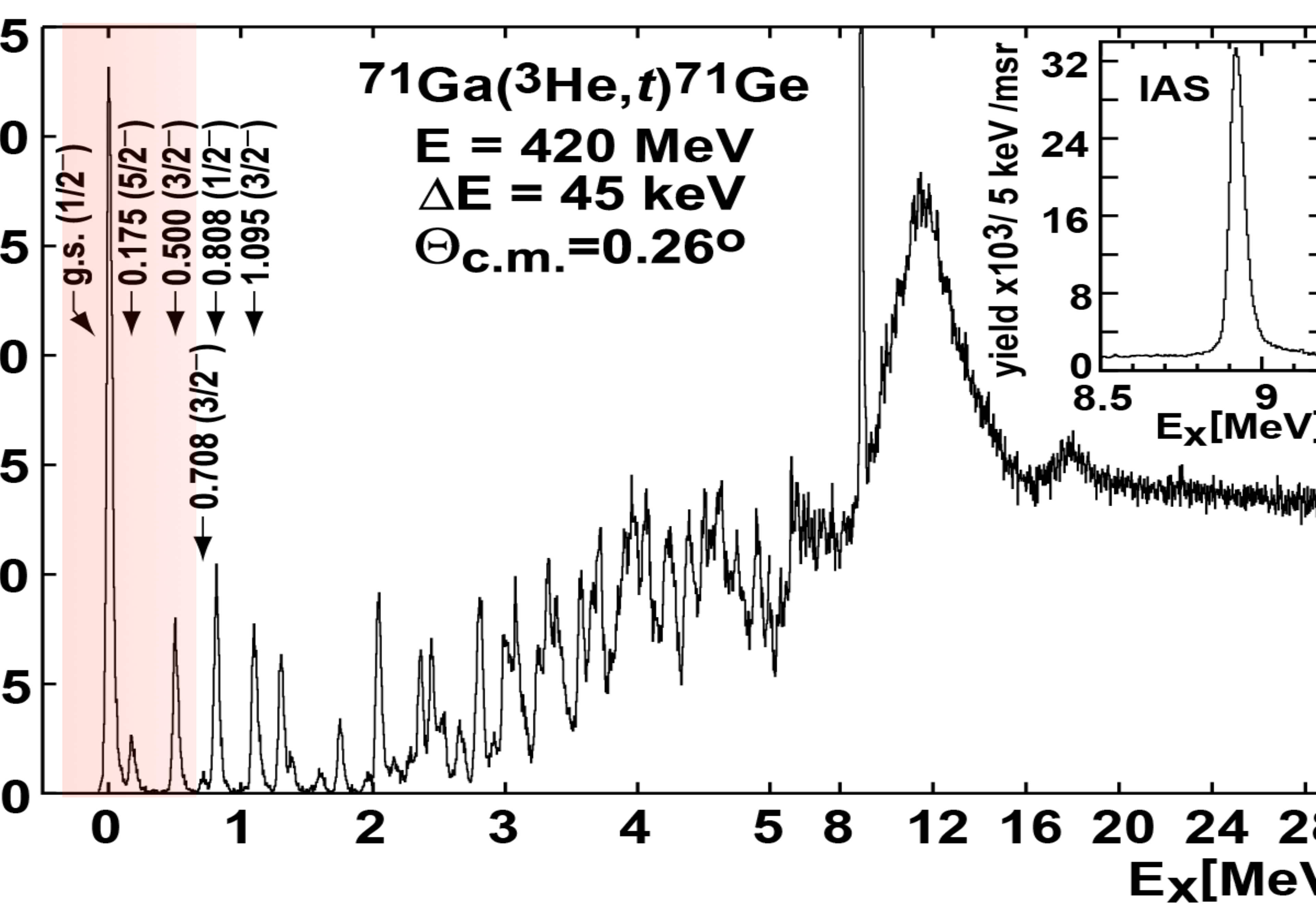


71Ga(3He,t)71Ge
E = 420 MeV
ΔE = 45 keV
Θc.m.=0.26o
g.s. (1/2−)
0.175 (5/2−)
0.500 (3/2−)
0.808 (1/2−)
1.095 (3/2−)
0.708 (3/2−)
IAS
yield x10³/ 5 keV /msr
32
24
16
8
0
8.5
9
Ex[MeV]
0
1
2
3
4
5
8
12
16
20
24
Ex[MeV]

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 J. Bahcall

- Discrepancy confirmed/slightly increased
- Contributions from the excited states do **NOT resolve** the discrepancy

What else could contribute?

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

$$\sigma_0\left({}^{51}\mathrm{Cr}\right) = F(atom) \cdot \frac{1}{ft}$$

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

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

All measurements in context of 17 keV ν!

EC is accompanied by Internal bremsstrahlungs-photon (1/10^4)

1. End-point spectrum is sensitive to neutrino mass
2. Q-value is determined by end-point energy

→ **Q_{EC}-value only side effect!!**

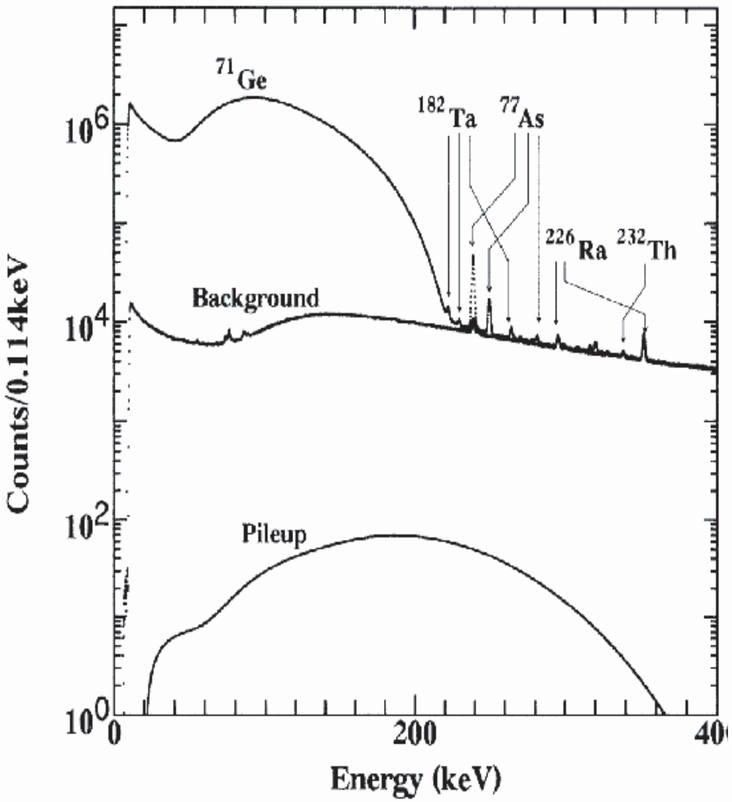
PROBLEMS!

1. Lack of precicse knowledge about the end-point spectrum near Q_{EC}-($E(K_\alpha)$) ≈ 8-10 keV
2. Extremely strong sources needed (≈10^{10} – 10^{11} Bq) (thru (n,γ) activation)
3. Use of external source → atomic excitations on the end-point energy!
4. Pile-up issues
5. Background issues after activation?
6. Detector efficiencies need to be know precisely!

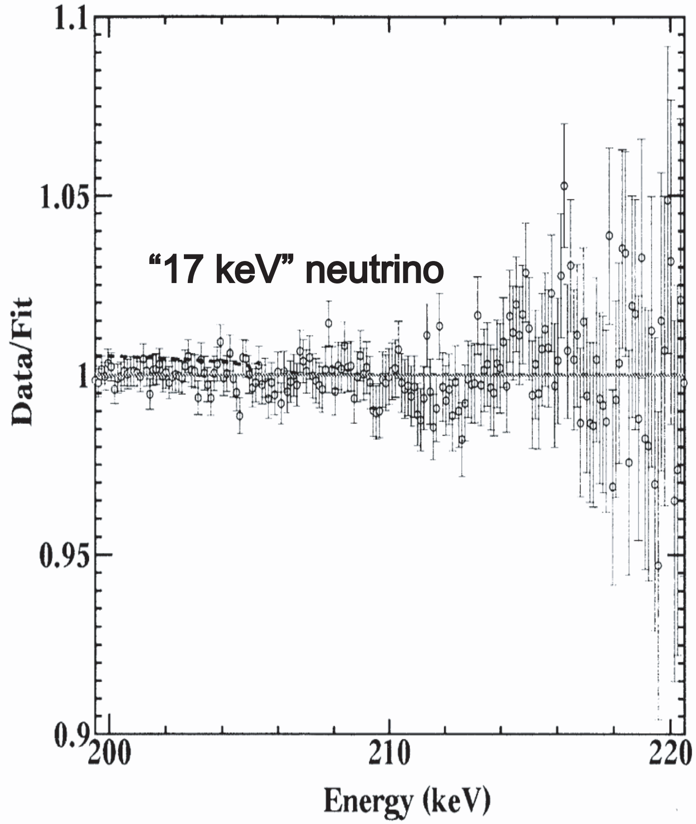
^{71}Ge Q_{EC}-value by Lee at al. (1995)

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

IB-spectrum



data / fit



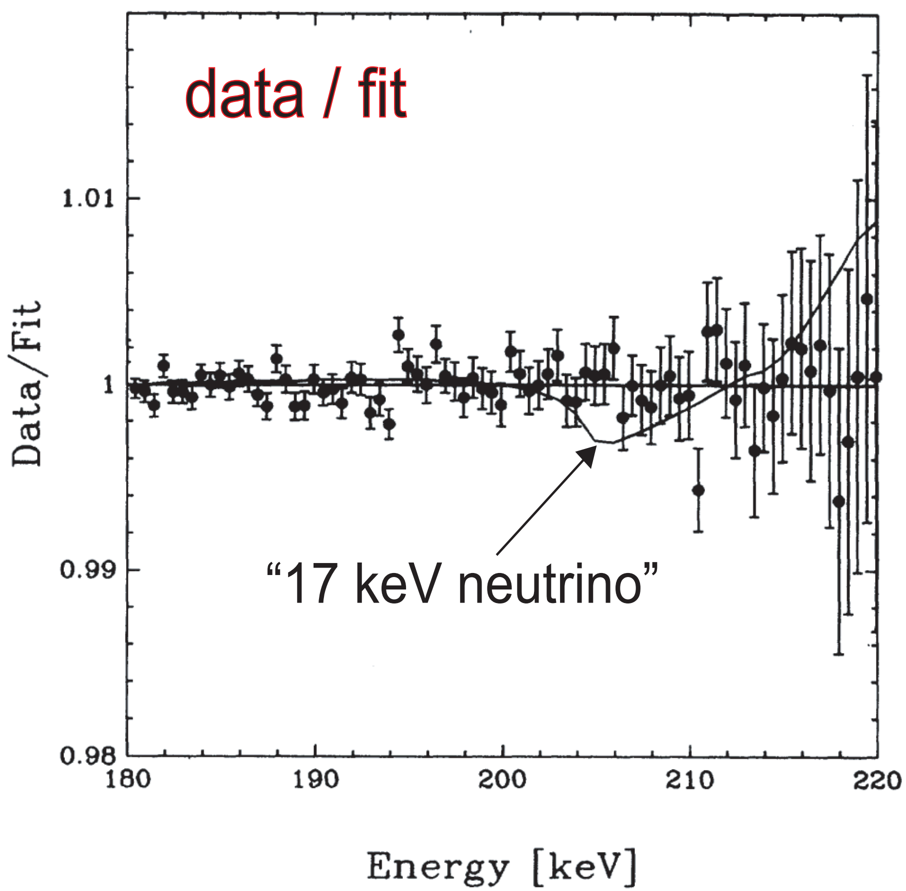
70 mg Ge target irradiated with n's

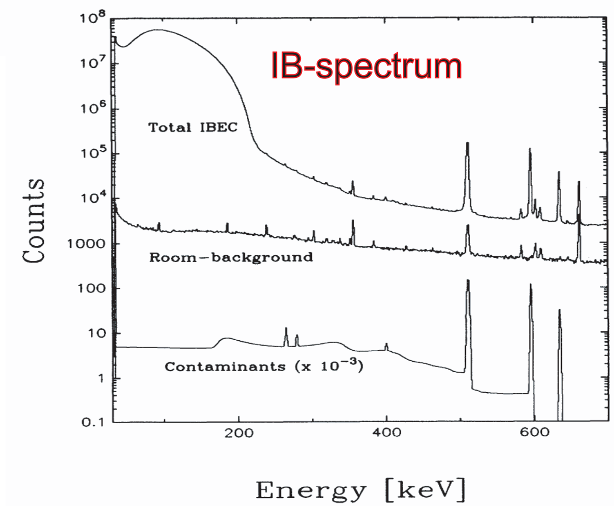
^{71}Ge activity: 6.5 GBq

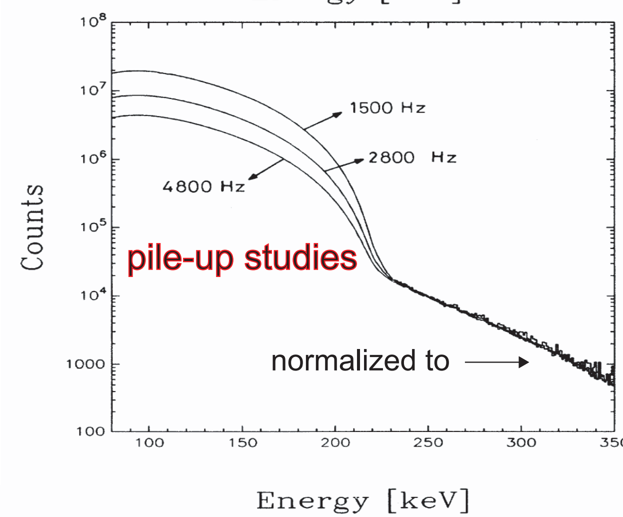
external source → effect of atomic X-ray de-excitation on the final spectrum??

Q_{EC}-value: 232.65 ± 0.15 keV

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



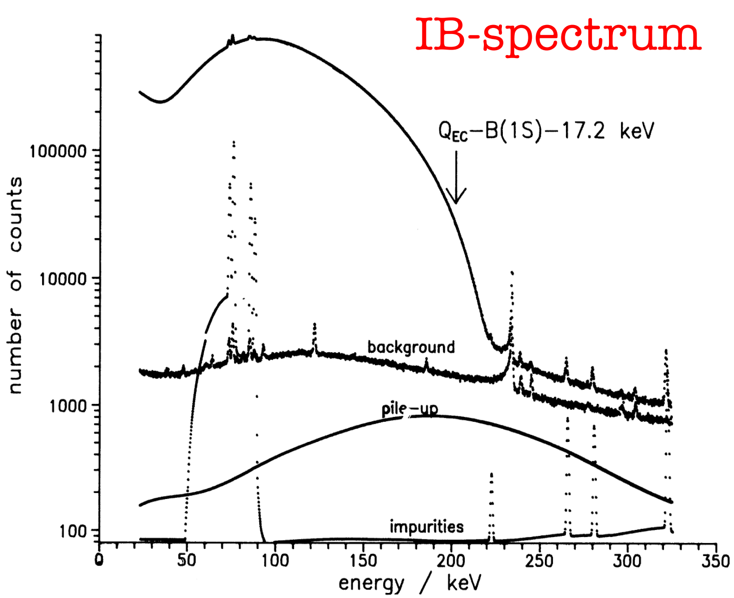


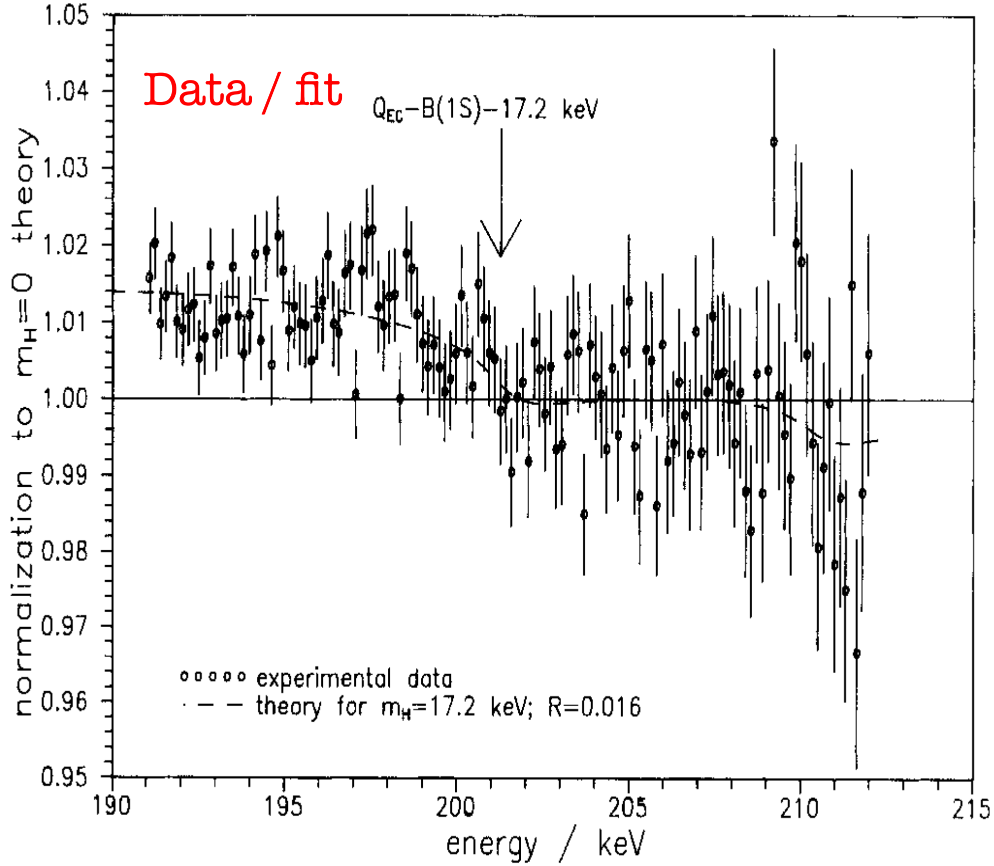


Q_{EC}-value: 232.1 ± 0.1 keV

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

Also in context of the 17 keV neutrino; positive report!!





Q_{EC}-value: 229.0 ± 0.5 keV

^{71}Ge Q_{EC}-value measurement at TRIUMF's TITAN experiment – <u>NEW approach</u>: 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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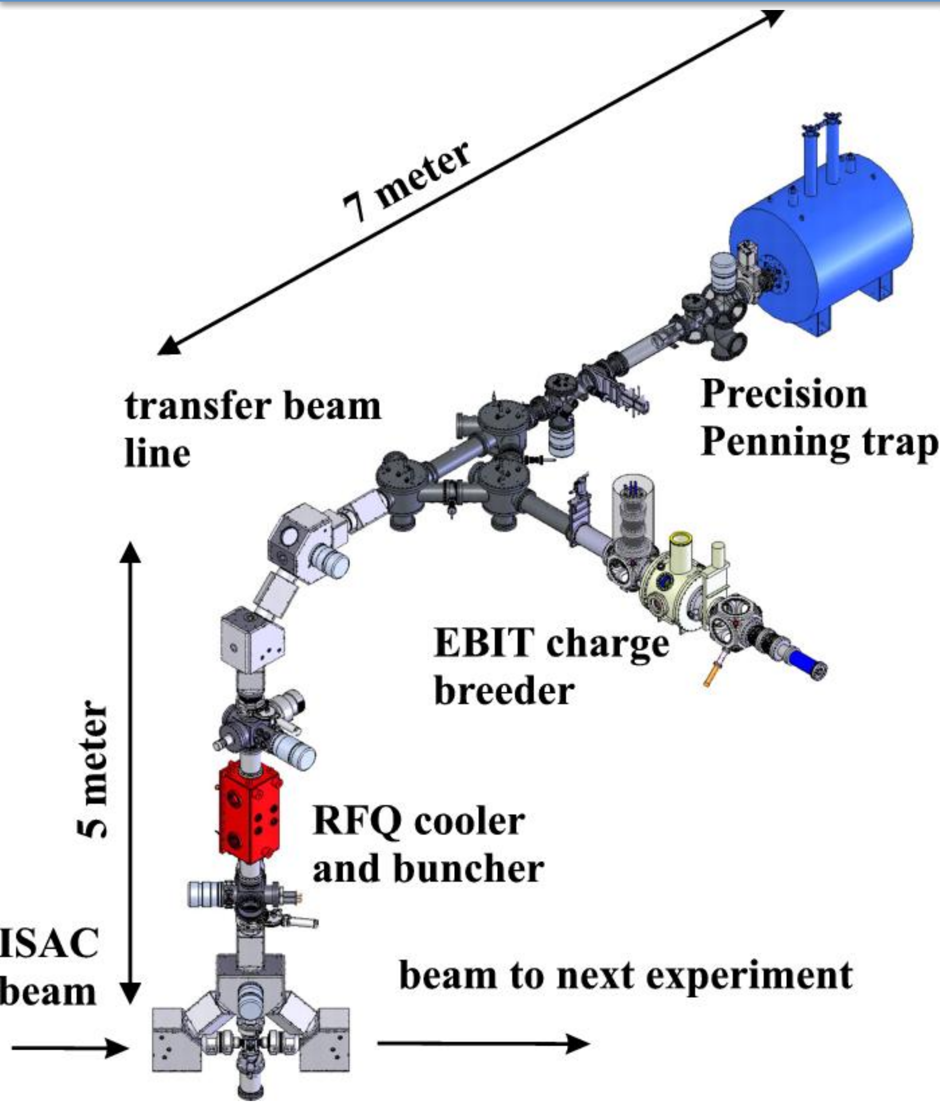
TITAN – TRIUMF's Ion Traps for Atomic and Nuclear science



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)

Beam injection with ≈ 20 keV

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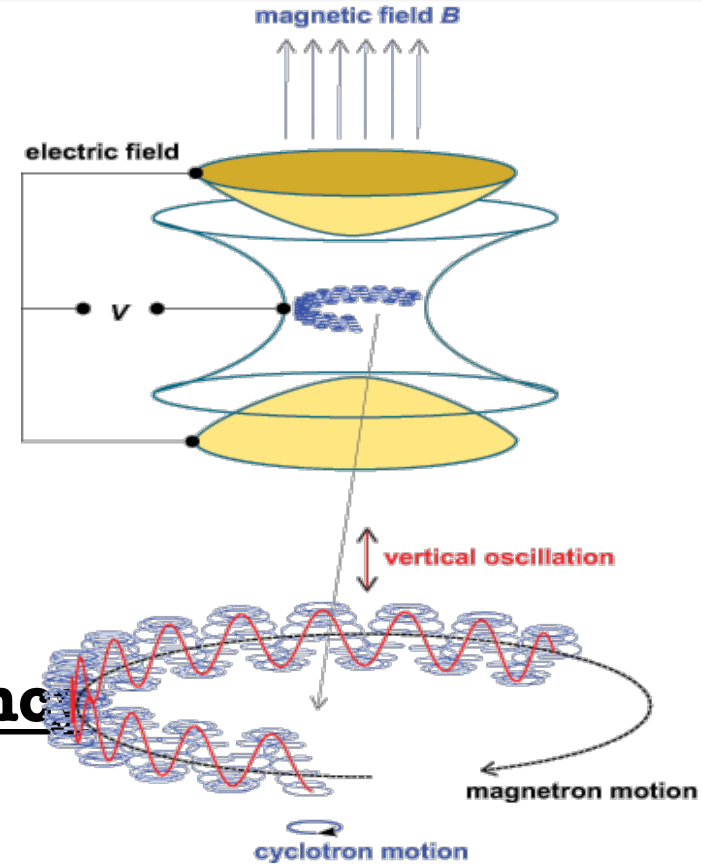
Principle of mass measurement with Penning Traps

1. Single ion injection
2. Confinement by B-field + electrostatic quadrupole field
3. Lorentz force ⇒ oscillation with cyclotron frequency perpendicular to B-field
4. Excitation With $\nu_{RF}=\nu_{C}$
5. Trap opening & transfer of energy to E_{kin} ⇒ TOF-measurement



Ions oscillate with cyclotron frequenc

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

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

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)

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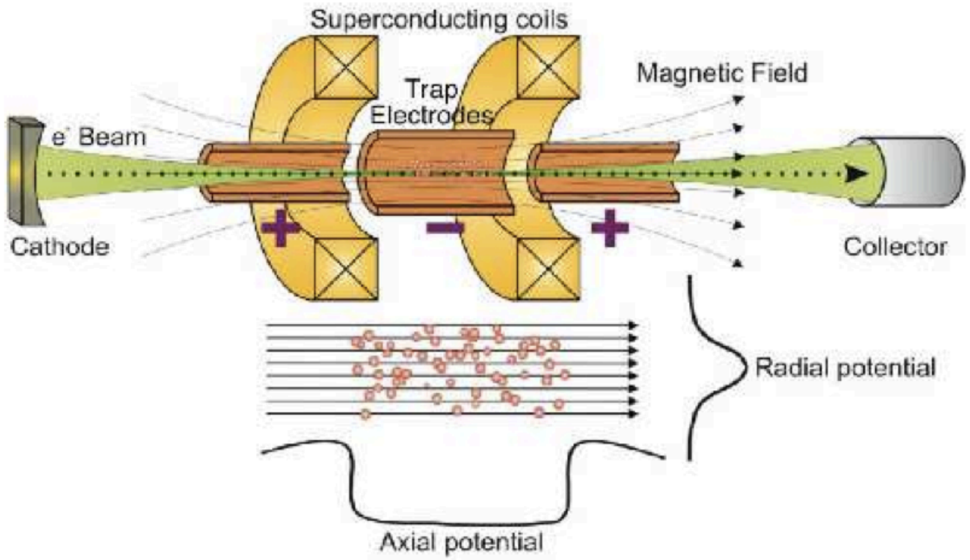
EBIT – Electron-Beam Ion Trap

produces and traps highly charges ions (HCI's) using a high-current (up to 500 mA) e- beam

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



The electron beam is compressed by a magnetic (Helmholtz) field up to 6T

Creation of highly charged ions (HCI's) by multiple electron impact

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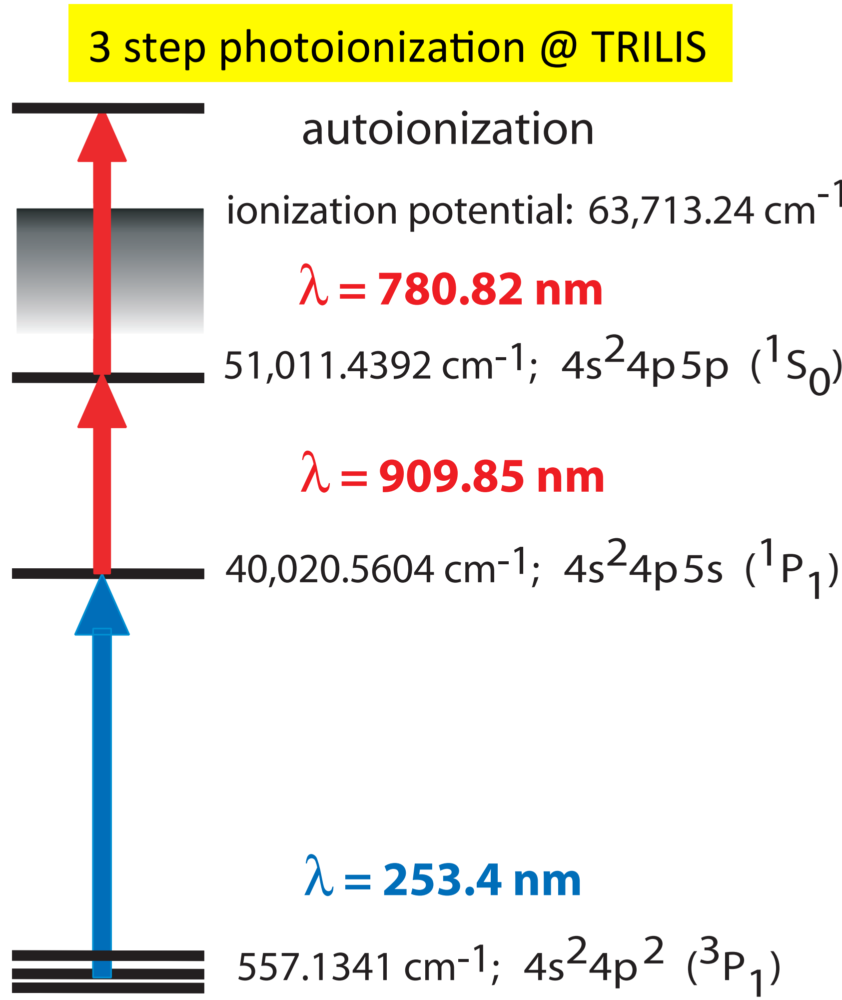
Novel approach: Production of ^{71}Ga and radioactive ^{71}Ge

- Ta-target + 50µA, 500MeV p-beam
  ⇒ produce $^{71}Ga/^{71}Ge$ ($\approx 10^7 - 10^8$ p/s)

- Beam-1: **surf. ion.** ^{71}Ga ($\approx 10^7$ p/s)
- Beam-2: **surf. ion.** ^{71}Ga + **laser ionized** ^{71}Ge ($\approx 10^6$ p/s)
- Beam transport to EBIT
- Charge breeding to **Ne-like** charge states
  ⇒ Beam-1: Ga^{21+}
  ⇒ 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



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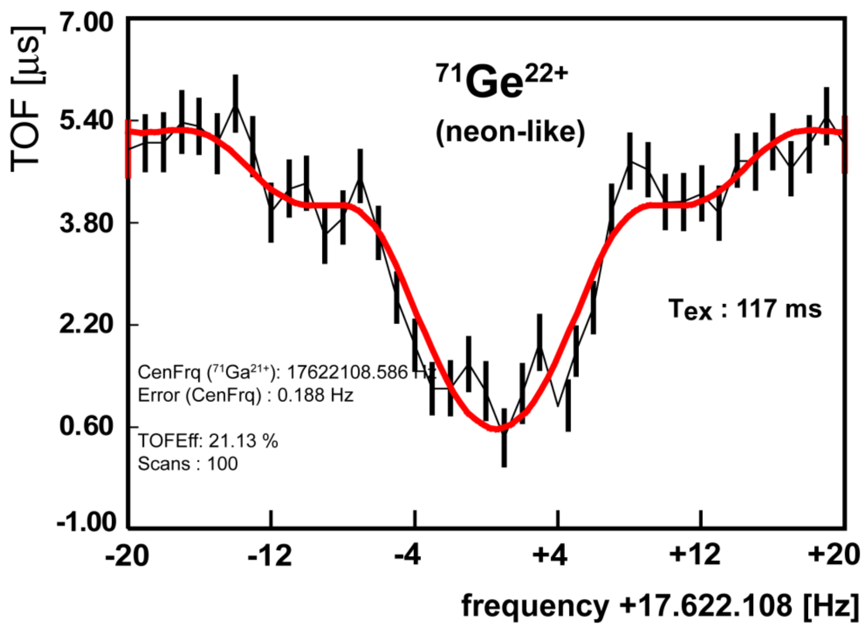
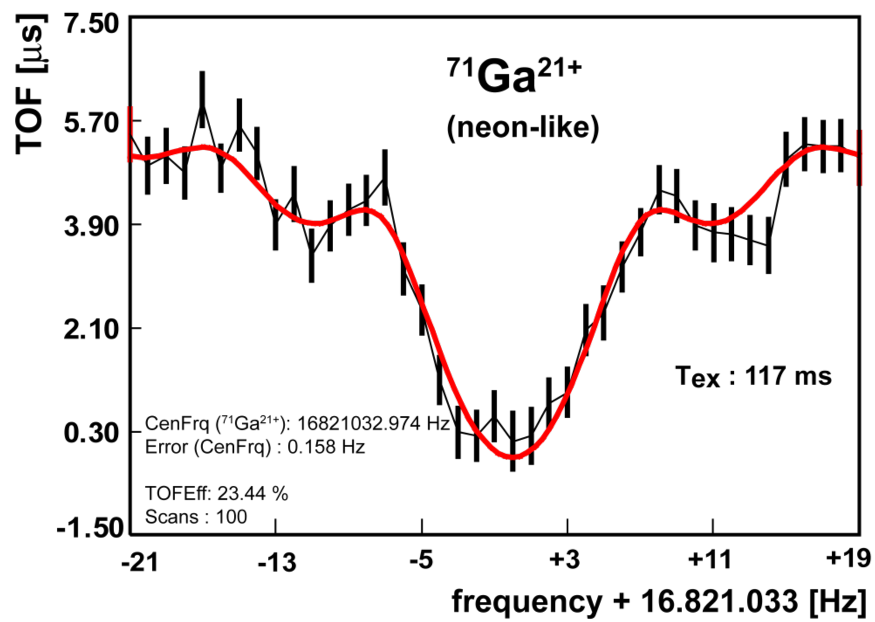
Typical TOF-resonances for ^{71}Ga and ^{71}Ge

Excitation frequency versus the TOF

Minimum of the resonance corresponds to the cyclotron frequency





- **Calculation of atomic mass excess**
- **Stable nucleus (^{71}Ga) as reference (m_2)**

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

→ **Q_{EC}-value**

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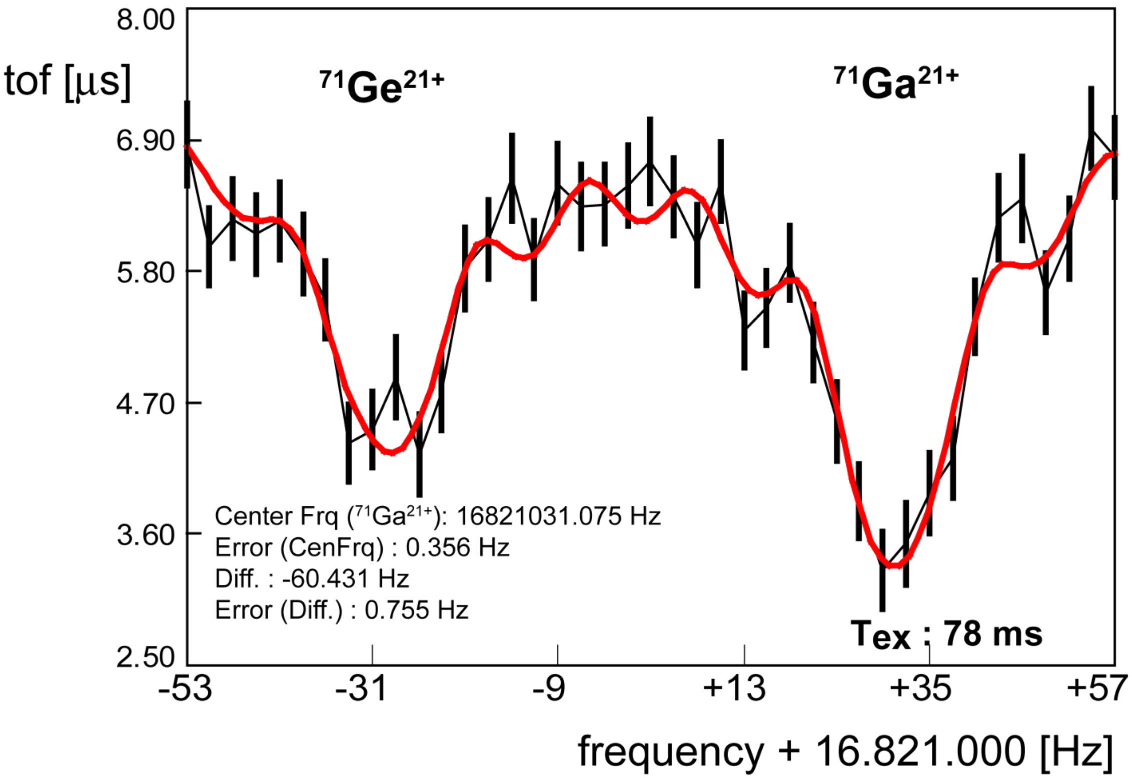
Double resonance

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



Independent measurement; direct measurement of mass difference

Mass difference close to literature value!

⇒ Q_{EC}-value: 234±1keV (Preliminary!)

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Consequences of Q_{EC} -value measurement

- $ft \propto Q_{EC}^2 \cdot T_{1/2}$
  ⇒ phase space factor for $B_2(GT) \approx 14$ % lower
- ⇒ $\sigma_0(^{51}Cr - \nu)$ slightly reduced ⇒ **Only slightly reduced discrepancy**

0.66 **0.18**

$$\sigma\left(^{51}Cr\right) = \sigma_0(^{51}Cr)\left[1 + 0.67\frac{B_1(GT)}{B_0(GT)} + 0.22\frac{B_2(GT)}{B_0(GT)}\right]$$

Contribution from excited states: 6.3 %

Conclusion:

Nuclear physics aspect of the ν x-section investigated

Contribution from excited states: 7.2 % ± 2.0 % (5.1 % by Bahcall)

⇒ slightly amplifies the discrepancy

2. Q_{EC} is close to J. Bahcall value & reduces @ most contrib. from exct. states from 7.2 % to 6.3 %

3. New calculations of phase space factors

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

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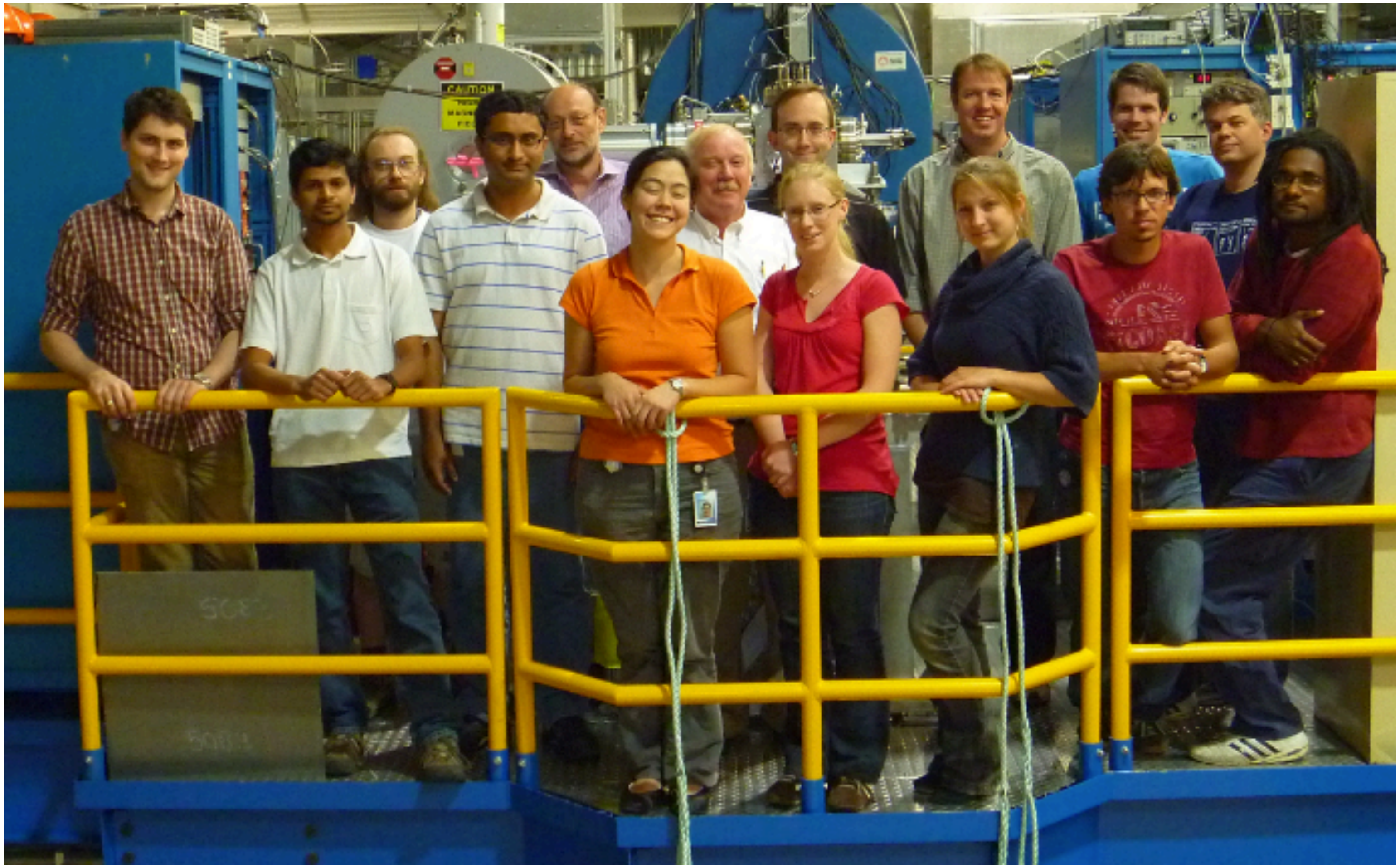

THANK YOU FOR YOUR ATTENTION!