**Author(s):** Alanssari, M.; Frekers, D.; Eronen, Tommi; Canete, Laetitia; Hakala, Jani; Holl, M.; Jokinen, Ari; Kankainen, Anu; Koponen, Jukka; Moore, Iain; Nesterenko, Dmitrii; Pohjalainen, Ilkka; Reinikainen, Juuso; Rinta-Antila, Sami; Voss, Annika

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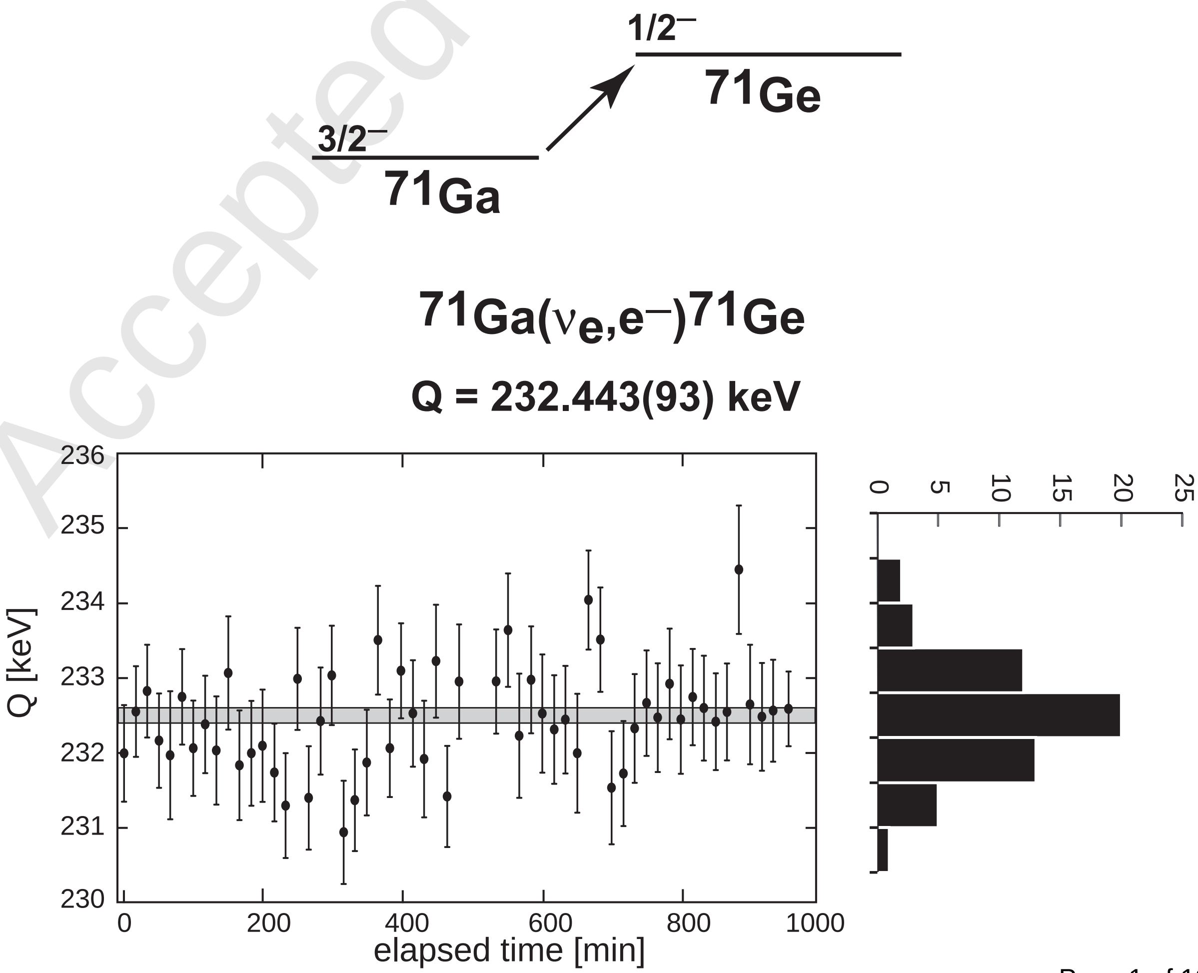
1/2–
71Ge
3/2–
71Ga
71Ga(νe,e–)71Ge
Q = 232.443(93) keV
Q [keV]
elapsed time [min]

Highlights

- Precision measurement of the $^{71}$Ga($\nu_e$,$e^-$)$^{71}$Ge reaction Q value to 232.443 keV with an accuracy of 93 eV performed.
- Hypothesis of the SAGE/GALLEX neutrino calibration discrepancy being due to an incorrect Q value discarded.
- Solar neutrino capture rate on $^{71}$Ga re-evaluated to 122.8 SNU

# Precision $^{71}$Ga – $^{71}$Ge mass-difference measurement

M. Alanssari[a], D. Frekers[a,*], T. Eronen[b], L. Canete[b], J. Hakala[b], M. Holl[a], A. Jokinen[b], A. Kankainen[b], J. Koponen[b], I. D. Moore[b], D. A. Nesterenko[b], I. Pohjalainen[b], J. Reinikainen[b], S. Rinta-Antila[b], A. Voss[b]

[a] *Institut für Kernphysik, Westfälische Wilhelms-Universität, D-48149 Münster, Germany*
[b] *University of Jyvaskyla, Department of Physics, FI-40014, Finland*

**Abstract**

The $^{71}$Ga$(\nu_e, e^-)^{71}$Ge reaction $Q$ value has been measured with the JYFLTRAP mass spectrometer at the IGISOL facility of the University of Jyväskylä to $Q = 232.443(93)$ keV. This value agrees with previous measurements, though it features a much higher accuracy. The Q value is being discussed in the context of the solar neutrino capture rate in $^{71}$Ga.

*Keywords:* mass measurements, Q value for solar-neutrino capture rates

## 1. Introduction

The $^{71}$Ga$(\nu_e, e^-)^{71}$Ge reaction $Q$ value is a key parameter for the evaluation of the solar-neutrino capture rate in the SAGE and GALLEX experiments [1, 2] and thereby also for the evaluation of the fraction of neutrinos undergoing a flavor change during their passage from Sun to Earth. Recently the solar-neutrino capture rate (in solar neutrino units SNU) was re-evaluated in a neutrino-nonoscillation scenario to $122.4 \pm 3.5$ SNU [3]. It decreased compared to a previously accepted value of $132 \pm 18$ SNU [4, 5], and since the measured neutrino rate from the combined experiments GALLEX (incl. GNO) and SAGE was 66.2 SNU, the electron neutrino survival fraction for the same reason increased from 50% to 54%. The new SNU value was the result of a re-evaluation of the $^{71}$Ga$(\nu_e, e^-)^{71}$Ge cross section using the Gamow-Teller strength $B$(GT) values from high-resolution $^{71}$Ga$(^3$He$, t)^{71}$Ge

*Corresponding author
*Email address:* Frekers@Uni-Muenster.de (D. Frekers )

charge-exchange data [3]. However, the $B(\mathrm{GT})$ values were calibrated against the $^{71}$Ge electron-capture $ft$ value, and since the $ft$ value carries a quadratic dependence on the $^{71}$Ge decay $Q$ value (i.e. $ft \propto Q^2$), the latter needs to be known with a precision preferentially better than 1%. We note that a lowering of the $Q$ value would bring the SNU value up.

The $Q$ value had also attracted attention when the SAGE and GALLEX detectors were calibrated with neutrinos from reactor-produced $^{51}$Cr and $^{37}$Ar sources and the ratio between the measured and expected neutrino capture rates on $^{71}$Ga came out to be 13% too low at a $2.5\,\sigma$ level [6], thus spurring speculations about the existence of a non-standard neutrino [7, 8, 9, 10]. It was, however, also conjectured that this could have been a result of an incorrect $Q$ value for the $^{71}$Ga neutrino-capture calculations [11], for which so far 232.69 keV had been taken (see Ref. [12] and references therein). It was furthermore argued that a precision measurement of the $^{71}\mathrm{Ge} - {}^{71}\mathrm{Ga}$ mass difference, e.g., by using an ion trap, had never been carried out. An experiment was eventually performed at the ISAC facility at TRIUMF using the TITAN ion-trap and mass-measuring setup [13], and it provided a value of $233.5 \pm 1.2$ keV [11]. This new value did not resolve the observed neutrino calibration discrepancies, because reaching consistency at a minimum $1\sigma$ level would have required an increase of the $Q$ value to at least 240 keV. Also a re-evaluation of the capture rate to the excited states in $^{71}$Ge by the neutrinos from the $^{51}$Cr and $^{37}$Ar sources showed that the discrepancy remained robust or even got slightly amplified [14, 15].

The $Q$-value measurements reported in Ref. [11] exhibited, however, unknown systematic uncertainties. The quoted Birge ratio [16] came out to be significantly larger than unity, thereby indicating a non-statistical error contribution. In the final error evaluation these non-statistical components were accounted for by an increased error value, however, the origin of those remained largely unknown.

In this note we report on a new precision measurement of the $^{71}\mathrm{Ge} - {}^{71}\mathrm{Ga}$ mass difference using the JYFLTRAP mass spectrometer at the IGISOL facility of the University of Jyväskylä. This new measurement essentially confirms previous $Q$-value determinations, however at much higher precision.

## 2. Experimental Details

The measurements were performed at the IGISOL facility [17, 18] of the University of Jyväskylä. A 10 MeV proton beam with an intensity of $\approx 2$ $\mu$A was directed onto a gallium(III)-sulfide $Ga_2S_3$ target. The $^{71}$Ge isotopes were produced via a $(p,n)$ reaction on $^{71}$Ga, and both isobaric ion species $^{71}Ge^+$ and $^{71}Ga^+$ were released from the target.

The ions were thermalized in the IGISOL gas cell and transported by means of gas flow and the sextupole ion guide to the high-vacuum region, where they were accelerated with a 30 kV potential and mass-number selected with a dipole magnet. The $A/q = 71$ ions were injected into the radio-frequency quadrupole cooler and buncher [19], and then transferred to the JYFLTRAP system [20]. The JYFLTRAP features two cylindrical Penning traps in a 7 T magnetic field. The first trap is the purification trap filled with helium buffer gas at low pressure (i.e., in the range of $10^{-5}$ mb). The second trap is the precision mass-measuring trap, where the cyclotron frequency of the ion is determined by the time-of-flight ion-cyclotron-resonance technique (TOF-ICR) [21].

As the mass difference between the $^{71}$Ge and $^{71}$Ga is expected to be $\approx 232$ keV, the cyclotron-frequency difference can be evaluated to be $\approx 5.3$ Hz. A full isobar separation was achieved by employing the buffer-gas-cooling [23] and Ramsey-cleaning techniques [24]. A Ramsey-excitation pattern of 25–750–25 ms (on–off–on) was then employed for the TOF-ICR measurement (see Fig. 1). Further details are described in Refs. [25, 26].

By switching between the ion species $^{71}Ge^+$ and $^{71}Ga^+$, data from 565 interleaved cycles were acquired, where each scanning cycle took about a minute to complete. In the analysis typically 10 cycles were summed before a fit to the time-of-flight data was performed and the cyclotron frequencies $\nu_c^{(i)}$ of the pair with ionic masses $m_i$ and the frequency ratio $R$,

$$R = \nu_c^{\mathrm{Ga}}/\nu_c^{\mathrm{Ge}}, \qquad \nu_c^{(i)} = \frac{1}{2\pi}\frac{eB}{m_i}, \tag{1}$$

were evaluated. By this mode of operation magnetic field fluctuations, which are measured to be $8.18(19) \times 10^{-12}$/min [27], need not be considered, and since the two ion species constitute an $A/q$ doublet, systematic effects resulting from field imperfections cancel in the frequency ratio [28]. Furthermore, no systematic frequency shifts were seen when the data were analyzed using a count-class analysis as described in Ref. [29]. In the final analysis only events with 1-5 ions per bunch were considered. The $Q$ value is then determined as:

$$Q_{21} = M_2 - M_1 = (R-1)(M_1 - m_e) + \Delta B_{21}, \tag{2}$$

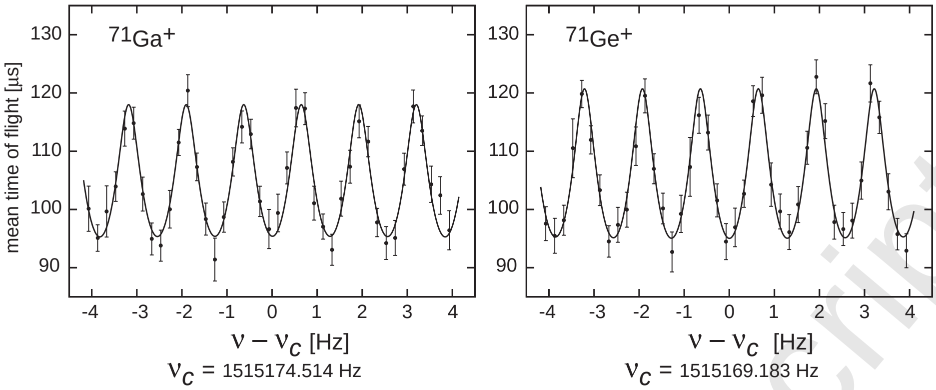


Figure 1: Time-of-flight spectra for the $^{71}$Ge$^{+}$,$^{71}$Ga$^{+}$ pair using a Ramsey-excitation pattern (25 on–750 off –25 on) ms. The solid lines represent a fit to the data using the theoretical line shape as described in Ref. [22].

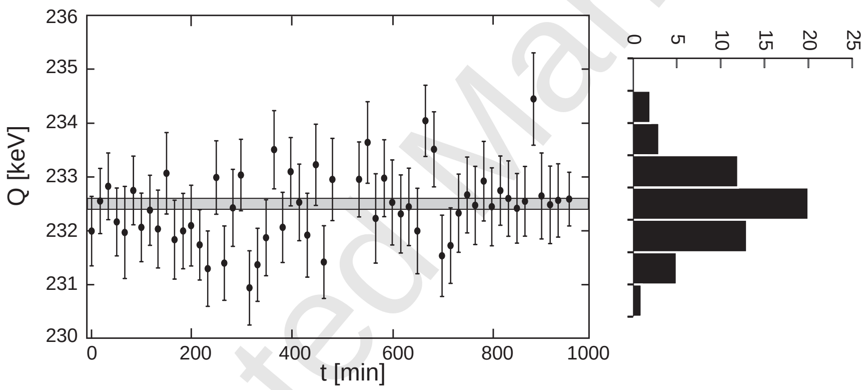


Figure 2: Sequence of the $^{71}$Ge$-^{71}$Ga mass difference measurements as a function of the elapsed time. The distribution of 56 individual data points indicates a near perfect normal distribution with a Birge ratio of 0.95. The bin size for this distribution was ±300 eV.

where $m_e$ is the electron mass and $M_2$, $M_1$ are atomic masses of $^{71}$Ge and $^{71}$Ga, respectively, and the electron binding-energy difference $\Delta B_{21} = -1.9$ eV [30]. Figure 2 shows the sequences of the $Q$-value measurements as a function of the elapsed time for the $A = 71$ pair together with the distribution of the individual measurements. The final results are given in Table 1, which also contains the Birge ratio [16] for the measurement showing that the statistical error of 93 eV for the final $Q$ value may even be overrated by $\approx 6\%$.

Table 1: Measured cyclotron-frequency ratio (here: $R-1$) for the $^{71}$Ga /$^{71}$Ge isobars, the deduced $Q$ value and the Birge ratio for the measurements appearing in Fig. 2.

| isobaric pair ($M_1/M_2$) | $R-1$ ($10^{-9}$) | Q (keV) | Birge ratio |
|---|---|---|---|
| $^{71}$Ga /$^{71}$Ge | $3518.40 \pm 1.49$ | $232.443 \pm 0.093$ | 0.94 |

## 3. Results and Conclusion

The mass difference between the isobaric doublet $^{71}$Ge and $^{71}$Ga has been measured at the IGISOL/JYFLTRAP facility to 232.44 keV with an uncertainty of 93 eV. We note that the high precision is a result of (i) being able to simultaneously produce the two isobaric mass states and (ii) of exploiting the high mass-separation power of the JYFLTRAP system, realized by a combination of buffer-gas cooling and Ramsey cleaning.

The present $^{71}$Ga$(\nu_e, e^-)^{71}$Ge reaction $Q$ value is consistent with the previous ion-trap measurement of $233.5 \pm 1.2$ keV quoted in Ref. [11] and the value $232.64 \pm 0.22$ keV of the Atomic Mass Evaluation 2012 [31]. However, the present 93 eV uncertainty, which is more than an order of magnitude less than the one from the previous ion-trap measurement, further diminishes hopes for a simple explanation of the $^{71}$Ga neutrino-capture rate discrepancy, like having made incorrect nuclear physics input assumptions.

From a new evaluation of the $ft$ value [32] [$ft$ = 22341(62)] the solar neutrino-capture rate quoted in Ref. [3] remains robust at a slightly increased value of $122.8 \pm 3.6$ SNU.

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