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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

Title: Precision ^{71}Ga – ^{71}Ge mass-difference measurement

Year: 2016

Version:

Please cite the original version:

Alanssari, M., Frekers, D., Eronen, T., Canete, L., Hakala, J., Holl, M., Jokinen, A., Kankainen, A., Koponen, J., Moore, I., Nesterenko, D., Pohjalainen, I., Reinikainen, J., Rinta-Antila, S., & Voss, A. (2016). Precision ^{71}Ga – ^{71}Ge mass-difference measurement. *International Journal of Mass Spectrometry*, 406, 1-3.
<https://doi.org/10.1016/j.ijms.2016.05.019>

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Accepted Manuscript

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PII: S1387-3806(16)30068-9
DOI: <http://dx.doi.org/doi:10.1016/j.ijms.2016.05.019>
Reference: MASPEC 15616

To appear in: *International Journal of Mass Spectrometry*

Received date: 15-3-2016
Revised date: 18-5-2016
Accepted date: 23-5-2016

Please cite this article as: M. Alanssari, D. Frekers, T. Eronen, L. Canete, J. Hakala, M. Holl, A. Jokinen, A. Kankainen, J. Koponen, I.D. Moore, D.A. Nesterenko, I. Pohjalainen, J. Reinikainen, S. Rinta-Antila, A. Voss, Precision ^{71}Ga ndash ^{71}Ge mass-difference measurement, *International Journal of Mass Spectrometry* (2016), <http://dx.doi.org/10.1016/j.ijms.2016.05.019>

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Highlights

- Precision measurement of the $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ 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 $^{71}\text{Ga} - ^{71}\text{Ge}$ mass-difference measurement

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Abstract

The $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ 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 $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ 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 ± 3.5 SNU [3]. It decreased compared to a previously accepted value of 132 ± 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 $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ cross section using the Gamow-Teller strength $B(\text{GT})$ values from high-resolution $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$

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charge-exchange data [3]. However, the $B(\text{GT})$ 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 2.5σ 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 $^{71}\text{Ge} - ^{71}\text{Ga}$ 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 ± 1.2 keV [11]. This new value did not resolve the observed neutrino calibration discrepancies, because reaching consistency at a minimum 1σ 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 $^{71}\text{Ge} - ^{71}\text{Ga}$ 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 $\approx 2 \mu\text{A}$

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 $^{71}\text{Ge}^+$ and $^{71}\text{Ga}^+$ 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 ≈ 232 keV, the cyclotron-frequency difference can be evaluated to be ≈ 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 $^{71}\text{Ge}^+$ and $^{71}\text{Ga}^+$, 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 ,

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

were evaluated. By this mode of operation magnetic field fluctuations, which are measured to be $8.18(19) \times 10^{-12}/\text{min}$ [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:

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

Figure 1: Time-of-flight spectra for the $^{71}\text{Ge}^+, ^{71}\text{Ga}^+$ 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 $^{71}\text{Ge} - ^{71}\text{Ga}$ 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 $^{71}\text{Ga} / ^{71}\text{Ge}$ 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
$^{71}\text{Ga} / ^{71}\text{Ge}$	3518.40 ± 1.49	232.443 ± 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 $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ reaction Q value is consistent with the previous ion-trap measurement of 233.5 ± 1.2 keV quoted in Ref. [11] and the value 232.64 ± 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 ± 3.6 SNU.

4. Acknowledgments

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) under grant FR 601/3-1. M.A. acknowledges the financial support from Al-Nahrain University and the Ministry of Higher Education and Scientific Research of Iraq. The work was further supported by the Academy of Finland under the Finnish Center of Excellence Program 2012-2017 (Nuclear and Accelerator Based Program at JYFL).

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