# Precision Penning-trap measurement to investigate the role of the $^{51}$Cr($e^-$,$\nu_e$)$^{51}$V $Q$ value in the gallium anomaly

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(Received 23 October 2013; revised manuscript received 24 January 2014; published 18 April 2014)

A direct $Q$-value measurement has been made at TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) for the $^{51}$Cr($e^-$,$\nu_e$)$^{51}$V reaction. This electron capture (EC) reaction was used in calibration measurements at the solar neutrino experiments SAGE and GALLEX, and the observed event rate differed from predictions creating the so-called gallium anomaly. Using isotopes delivered by the Isotope Separator and Accelerator (ISAC) facility at TRIUMF and charge breeding them to charge states 5+ and 6+, a $Q$ value of 751.86(55) keV was determined. This represents a 1.3$\sigma$ deviation from the result in the Atomic Mass Evaluation 2012 (AME12) and the value used in the calculated event rate. This deviation is found to be insignificant in context of the gallium anomaly, thus confirming that the predicted event rate has not been overestimated as the result of an erroneous $^{51}$Cr EC $Q$ value. Additionally, the absolute masses of each $^{51}$Cr and $^{51}$V have been independently determined and are in agreement with the AME12 values.

DOI: 10.1103/PhysRevC.89.044318 PACS number(s): 21.10.Dr, 26.65.+t, 37.10.Ty, 82.80.Qx

## I. INTRODUCTION

Precision experiments at radioactive beam facilities [1] have made a significant impact on the fields of particle and nuclear physics. With the goal of identifying yet undetermined properties of the neutrino, high-precision measurements of branching ratios, half-lives, and $Q$ values have guided the construction of next-generation experiments and refined theoretical models, advancing the field of neutrino physics. Penning-trap mass spectrometry is at the precision frontier for performing direct $Q$-value measurements [2,3], providing accurate results that have included shifts from reaction-based measurements of more than five standard deviations (5$\sigma$) [4–7]. It has contributed to the search for neutrinoless $\beta\beta$ decay [8], resonant-enhanced double-electron capture [9], and the determination of the absolute mass scale of the electron neutrino [7,10]. Such experiments, described in detail in Ref. [11], have affirmed the value of Penning-trap measurements in the broad context of neutrino physics research.

A persistent discrepancy in the field of neutrino physics is the gallium anomaly, resulting from the calibration measurements that were performed at the solar neutrino experiments SAGE and GALLEX. Both SAGE and GALLEX made use of the $^{71}$Ga($\nu_e$,$e^-$)$^{71}$Ge neutrino-capture reaction to detect solar neutrinos, and the results confirmed the solar-neutrino deficiency with the more abundant, lower energy, $p$-$p$ solar neutrinos [12]. Calibration measurements were performed using terrestrial neutrinos from $^{51}$Cr electron capture (EC) at GALLEX and both $^{51}$Cr and $^{37}$Ar EC at SAGE, which "demonstrated the absence of any significant unexpected systematic errors" [13] in the solar neutrino measurements. Despite this, the observed event [14] rate with these terrestrial sources revealed a 13(5)% deficit when compared to the rate predicted by theory [12] and became known as the gallium anomaly.

Missing knowledge of the underlying nuclear structure involved in the calibration reactions is thought to be a possible cause of the discrepancy. Other possible explanations include a statistical fluctuation with 5% probability, miscalculated efficiencies, or physics of unknown origin [14]. A recent white paper [15] explores the gallium anomaly in the context of sterile neutrinos and notes that it could be accounted for by a $\Delta m^2 \approx 1$ eV$^2$ sterile neutrino. Precision measurements have been made on the nuclear structure of the detector materials, confirming the $^{71}$Ga($\nu_e$,$e^-$)$^{71}$Ge $Q$ value of 233.5(1.2) keV [16] and re-evaluating the contribution of the $^{71}$Ge excited states to the neutrino capture cross section for a total of 7.2 $\pm$ 2.0% [17]. These results have eliminated any uncertainty in the nuclear structure of the detector materials at the level required to resolve the gallium anomaly. However, uncertainty in the neutrino source material remains. The $^{51}$Cr($e^-$,$\nu_e$)$^{51}$V $Q$ value of 752.63(24) keV, as reported in the Atomic Mass Evaluation 2012 (AME12) [18], is dominated by the result of a single reaction-based measurement [19]. Accurate knowledge of this value is of great importance as it

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determines the probability that a neutrino will be captured into an excited state in $^{71}$Ge. If the value in the AME12 is artificially inflated by 14 keV or more, then the predicted event rate would have falsely included neutrino capture into the 499.9-keV excited state and been overestimated by $4.5 \pm 0.4\%$ [17].

This potential correction to the gallium anomaly has motivated an independent check of the $^{51}$Cr($e^-$,$\nu_e$)$^{51}$V $Q$ value using TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) [20]. TITAN, located at the Isotope Separator and Acelerator (ISAC) facility [21] at TRIUMF, has demonstrated high-precision mass measurements and direct $Q$-value measurements with both singly and highly charged ions ranging from nuclear structure on the light halo nuclides $^{6,8}$He$^+$ [22], $^{11}$Li$^+$ [23], and $^{11}$Be$^+$ [24], to standard-model tests with $^{74}$Rb$^{8+}$ [25], and neutrino physics with $^{71}$Ga$^{22+}$ and $^{71}$Ge$^{22+}$ [16]. These measurements have covered the shortest half-life and most exotic nuclide measured in a Penning trap as well as new charge-breeding techniques, making TITAN and ISAC a well-established pairing for the independent check of the $^{51}$Cr($e^-$,$\nu_e$)$^{51}$V $Q$ value.

## II. EXPERIMENTAL SETUP

TITAN consists of three ion traps dedicated to the preparation and manipulation of short-lived ions for high-precision mass measurements: a radio-frequency quadrupole (RFQ) [26] linear Paul trap, an electron beam ion trap (EBIT) [27,28], and a precision measurement Penning trap (MPET) [29]. A detailed overview of the TITAN facility can be found in Ref [30].

The $^{51}$Cr and $^{51}$V nuclides were produced by impinging a 480-MeV, 10-$\mu$A proton beam from the TRIUMF main cyclotron on a $UO_2$ target at ISAC. The beam was ionized by a forced-electron-beam-induced arc discharge ion source [31] and extracted from the target station as a 30-keV continuous ion beam. After passing through a dipole mass separator (resolving power of $R \approx 3000$) the ion beam was delivered to the TITAN RFQ, where it was accumulated, cooled by a helium buffer gas, and bunched prior to extraction. The bunches were then sent to the EBIT for rapid charge breeding through successive electron-impact ionization by an electron beam with current $I_e = 89$ mA and energy $E_e = 2.55$ keV. Charge-breeding times of 2 and 3 ms were used to optimize the number of ions in charge states 5+ and 6+, respectively. Ions of a single charge state were then selected by their time of flight (TOF) for injection into the MPET by a Bradbury Nielsen gate [32]. Additionally, $^{39}$K ions were delivered from the TITAN off-line ion source intermittently between $^{51}$Cr and $^{51}$V measurements and measured in the 4+ charge state to obtain a similar $m/q$ ratio. Once trapped inside the MPET, the ions were manipulated with rf excitations via the time-of-flight ion-cyclotron-resonance (TOF-ICR) technique [33].

An example of the resulting resonance spectrum, centered at the cyclotron frequency, is shown in Fig. 1 for $^{51}$Cr$^{5+}$ and an excitation time of $T_{RF} = 160$ ms. The cyclotron frequency is obtained by fitting the theoretical line shape [33] to the data, and it is related to the mass $m$ of the ion according to $\nu_c = \frac{1}{2\pi}\frac{q}{m}eB$. Here, $qe$ is the charge of an ion in a charge state

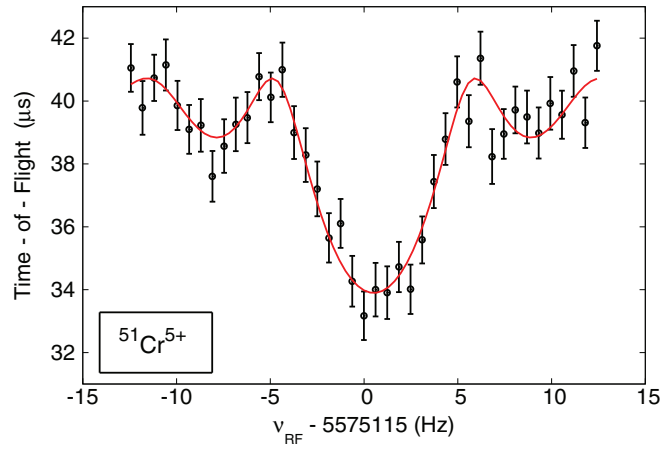


FIG. 1. (Color online) A TOF-ICR resonance of $^{51}$Cr$^{5+}$ for $T_{RF} = 160$ ms. The solid line is a fit of the theoretical line shape [33] to the data.

$q$, and $B$ is the strength of the magnetic field in the MPET. The attainable precision for a frequency measurement using this technique [34] scales as

$$\frac{\delta\nu_c}{\nu_c} \propto \frac{1}{\nu_c\, T_{RF}\, \sqrt{N_{\text{ions}}}}, \tag{1}$$

where $T_{RF}$ is the excitation time and $N_{\text{ions}}$ is the number of detected ions. The linear increase of the cyclotron frequency with the charge state thus provides improved precision for a given measurement. Due to the simultaneous delivery of $^{51}$Cr and $^{51}$V, dipole cleaning [35] was required to remove known contaminant ions from the trap before implementing the TOF-ICR excitation. Dipole excitations were applied for 36 ms on ions in charge state 5+ and 30 ms on ions in charge state 6+.

## III. ANALYSIS AND RESULTS

Frequency measurements on the five species of interest, $^{51}$Cr$^{5,6+}$, $^{51}$V$^{5,6+}$, and $^{39}$K$^{4+}$, were performed in alternation. A reference ion species was chosen, here $^{51}$V, and the frequency measurements of this reference ion were linearly interpolated to account for first-order drifts in the magnetic field [29]. The ratio of this interpolated frequency $\tilde{\nu}_c(^{51}\text{V}^{q_\text{V}+})$ and the frequency of the ion of interest $\nu_c(^{51}\text{Cr}^{q_\text{Cr}+})$ is then independent of the MPET magnetic field and independent of a reference mass, and it is the primary result of our experiment:

$$R = \frac{\tilde{\nu}_c(^{51}\text{V}^{q_\text{V}+})}{\nu_c(^{51}\text{Cr}^{q_\text{Cr}+})} = \frac{m(^{51}\text{Cr}^{q_\text{Cr}+})}{m(^{51}\text{V}^{q_\text{V}+})}\frac{q_\text{V}}{q_\text{Cr}}\ . \tag{2}$$

The $Q$ value is calculated directly from the weighted average of all measured ratios $\overline{R}$, and is given by

$$\begin{aligned} Q = {} & \left(\overline{R}\tfrac{q_\text{Cr}}{q_\text{V}} - 1\right) M_\text{V} - (\overline{R} - 1)\, q_\text{Cr}\, m_e \\ & + \overline{R}\ \tfrac{q_\text{Cr}}{q_\text{V}}\ B_e(^{51}\text{V}^{q_\text{V}+}) - B_e(^{51}\text{Cr}^{q_\text{Cr}+}), \end{aligned} \tag{3}$$

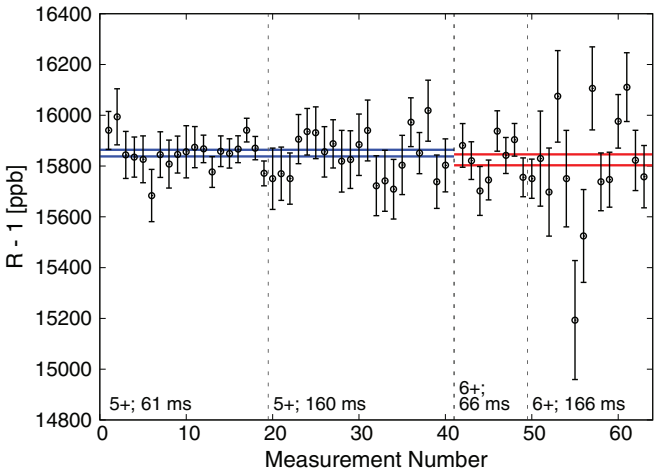


FIG. 2. (Color online) Cyclotron frequency ratios between $^{51}V^{q+}$ and $^{51}Cr^{q+}$ for different excitation times and charge states. Each point represents the ratio resulting from a single $^{51}Cr^{q+}$ resonance and its neighboring $^{51}V^{q+}$ resonances. The blue (left) [red (right)] lines show the $1\sigma$ error band for all 5+ [6+] ratio measurements.

where $M_V$ is the atomic mass of $^{51}V$, $m_e$ is the electron mass, and $B_e$ is the sum of atomic binding energies for all electrons missing from the specified highly charged ion. Since the ratio contains the ionic masses, the analysis was carried out on 5+ and 6+ charge states independently. The reference mass of $^{51}V$ was obtained from the AME12 mass excess of $-52203.69(88)$ keV [36], and the binding energies were taken from Ref. [37], with estimated uncertainties in the 10-eV range. The uncertainty of the $Q$ value was thus obtained from propagation of errors, and the only significant contribution comes from uncertainty of the ratio $\delta R$.

The achieved statistical precision for the final ratio was $\delta R^{5+}_{\rm stat} = 12.7$ ppb and $\delta R^{6+}_{\rm stat} = 21.5$ ppb, which was added in quadrature to any systematic effects. Many of the $m/q$ dependent systematic uncertainties common to Penning-trap mass spectrometry, including spatial magnetic field inhomogeneities, harmonic distortions of the electrode structure, misalignment between magnetic field and trap axes, and relativistic effects, became negligible [29] by measuring the ratio in an $m/q$ doublet (i.e., $^{51}Cr^{5+}$ with $^{51}V^{5+}$, and $^{51}Cr^{6+}$ with $^{51}V^{6+}$). Along with fluctuations in the trapping potential, these are all sub-ppb effects, and significantly smaller than $\delta R_{\rm stat}$. Magnetic field drifts, which have been measured at 0.04(11) ppb per hour [38], were also neglected as the spacing between reference measurements was only 30 to 90 min. The data was also analyzed with mixed charge-state pairings (i.e., $^{51}Cr^{5+}$ with $^{51}V^{6+}$, and $^{51}Cr^{6+}$ with $^{51}V^{5+}$), and variation in $m/q$ produced $Q$ values all within $1\sigma$ agreement. This consistency suggests that there are no $m/q$-dependent shifts that were unaccounted for in the analysis at the desired level of precision.

TABLE I. Results for the Penning-trap $Q$-value determination for the $^{51}Cr(e^-,\nu_e)^{51}V$ reaction. Both the measured frequency ratio and the resulting $Q$ value are reported with their total uncertainties.

| Ion | Ref. | $R = \tilde{\nu}_c^{\rm V} / \nu_c^{\rm Cr}$ | $Q$ value (keV) |
|---|---|---|---|
| $^{51}Cr^{5+}$ | $^{51}V^{5+}$ | 1.000015851(14) | 752.14(64) |
| $^{51}Cr^{6+}$ | $^{51}V^{6+}$ | 1.000015827(23) | 751.05(108) |
| | | Average $Q$ value: | 751.86(55) |

Systematic shifts in the measured cyclotron frequency could also have been caused by the presence of contaminant ions in the MPET [39]. Although dipole cleaning was implemented on either $^{51}Cr$ or $^{51}V$, there was a risk of nonunity efficiency in the dipole cleaning, charge exchange with residual gas, and unidentified contamination. With a typical measurement consisting of 0–2 detected ions on average, possible shifts were accounted for by performing a count-class analysis [40] on all data sets. Measurements with only 1–2 detected ions after extraction from the MPET were also analyzed without count-class analysis, and the results were within $1\sigma$ agreement. Finally, a small systematic uncertainty of $\delta R^{5+}_{\rm sys} = 4.7$ ppb and $\delta R^{6+}_{\rm sys} = 7.4$ ppb was introduced by neglecting time correlations [41] between neighboring ratios. The resulting total uncertainty is thus $\delta R^{5+} = 13.6$ ppb and $\delta R^{6+} = 22.5$ ppb.

The results of all ratio measurements are shown in Fig. 2 for the two charge states and various excitation times: 61, 66, 160, and 166 ms. The final weighted average of the ratios and the resulting $Q$ value are summarized in Table I. The resulting $Q$ value from all data sets is 751.86(55) keV. Furthermore, the absolute masses of $^{51}Cr$ and $^{51}V$ were measured using the $^{39}K^{4+}$ ion as a reference (see Table II). All results are within $1\sigma$ agreement with the AME12 values and improve the precision in the AME12 by factors of 1.6 and 1.8 for $^{51}Cr$ and $^{51}V$ respectively. The $Q$ value was also taken from the absolute mass difference and the result agrees with the direct $Q$-value measurement.

## IV. CONCLUSION

The first direct $Q$-value measurement of the $^{51}Cr(e^-,\nu_e)^{51}V$ reaction was performed at TITAN, yielding $Q_{EC} = 751.86(55)$ keV. The result is in reasonable agreement with the reaction-based measurements summarized in the AME12, differing by $1.3\sigma$. The neutrino energy used in the calculations of the predicted event rate for the calibration experiments

TABLE II. Mass excesses of $^{51}Cr$ and $^{51}V$. The ratio $R(q) = \tilde{\nu}_c^{\rm ref}/\nu_c^{\rm ion}$ was measured in two charge states and the average mass excess $\overline{ME}$ of the neutral atom is tabulated. The results are compared to the AME12 [18].

| Ion | Ref. | $R(q=5)$ | $R(q=6)$ | $\overline{ME}_{\rm TITAN}$ | $ME_{\rm AME}$ | $\Delta_{\rm TITAN-AME}$ |
|---|---|---|---|---|---|---|
| $^{51}Cr^{q+}$ | $^{39}K^{4+}$ | 1.045996804(16) | 0.871654613(20) | −51451.71(61) | −51451.05(88) | −0.66(107) |
| $^{51}V^{q+}$ | $^{39}K^{4+}$ | 1.045980222(15) | 0.871640810(17) | −52203.69(54) | −52203.69(88) | 0.00(103) |

at SAGE and GALLEX has thus been verified at this level. As a consequence, the accessible states of $^{71}$Ge in the neutrino capture reaction will remain unchanged in the calculations, and the predicted event rate from the $^{51}$Cr neutrino source has not been overestimated as a result of an erroneous $^{51}$Cr EC $Q$ value. When combined with the results of measurements on the $^{71}$Ga neutrino capture reaction, these precision measurements have eliminated uncertainty in the nuclear structure that could have been responsible for the gallium anomaly, leaving other possibilities including new physics and the sterile neutrino hypothesis to explore.

## ACKNOWLEDGMENTS

The authors express their gratitude to the TRIUMF technical staff, the ISAC beam delivery group, and M. Good for their contributions in realizing this experiment. This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the National Research Council of Canada. The authors acknowledge financial support for T.D.M. from the NSERC CGS-M program, A.T.G. from the NSERC CGS-D, A.L. and D.F. from the Deutsche Forschungsgemeinschaft (DFG) under grant FR 601/3-1, and V.V.S. from the Studienstiftung des Deutschen Volkes.

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