Q_{EC} value of the superallowed β emitter ^{42}Sc

T. Eronen, J. C. Hardy, L. Canete, A. Jokinen, J. Hakala, A. Kankainen, V. S. Kolhinen, J. Koponen, I. D. Moore, I. M. Murray, H. Penttilä, I. Pohjalainen, O. Poleshchuk, J. Reinikainen, S. Rinta-Antila, N. Soukouti, A. Voss, and J. Äystö

Phys. Rev. C **95**, 025501 — Published 10 February 2017

DOI: 10.1103/PhysRevC.95.025501

Q_{EC}value of the Superallowed β-Emitter ^{42}Sc

T. Eronen,[1,2,*] J. C. Hardy,[2] L. Canete,[1] A. Jokinen,[1] J. Hakala,[1] A. Kankainen,[1] V. S. Kolhinen,[1] J. Koponen,[1] I. D. Moore,[1] I. M. Murray,[1,†] H. Penttilä,[1] I. Pohjalainen,[1] O. Poleshchuk,[1,‡] J. Reinikainen,[1] S. Rinta-Antila,[1] N. Soukouti,[1] A. Voss,[1] and J. Äystö[1]

[1]*Department of Physics, P.O. Box 35 (YFL), FI-40014 University of Jyvaskyla, Finland*
[2]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*

The Q_{EC} value of the superallowed β^+-emitter ^{42}Sc has been measured with the JYFLTRAP Penning-trap mass spectrometer at the University of Jyväskylä to be 6426.350(53) keV. This result is at least a factor of four more precise than all previous measurements, which were also inconsistent with one another. As a byproduct we determine the excitation energy of the 7^+ isomeric state in ^{42}Sc to be 616.762(46) keV, which deviates by 8σ from the previous measurement.

PACS numbers: 21.10.Dr, 23.40.Bw, 27.30.+n, 27.30.+t, 27.30.+z,

I. INTRODUCTION

The measured ft values for superallowed $0^+ \rightarrow 0^+$ β^+ decays between $T = 1$ analog states currently provide the most precise value for V_{ud}, the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, and the most precise test of the unitarity of that matrix. The latest 2014 survey of relevant world data [1] documents 14 $0^+ \rightarrow 0^+$ transitions with ft values known to $\sim$0.1% precision or better. The corrected $\mathcal{F}t$ values for these transitions are all consistent with one another, thus satisfying the conservation of vector current (CVC), and they lead to a value for the sum of squares of the top-row elements of the CKM matrix of 0.99978(55), in excellent agreement with unitarity. This value, together with its uncertainty, already places constraints on physics beyond the Standard Model (see, for example, Ref. [2]), so there is strong motivation to reduce this uncertainty still further.

Of course, with so many measurements contributing to the body of world data, any improvement must necessarily be incremental, with the input parameters being refined one at a time, starting with those least well determined. Here we address the Q_{EC} value of the superallowed transition from ^{42}Sc. In this case there are four existing measurements, but they are sufficiently inconsistent with one another that the uncertainty on their weighted average must be increased by a large scale factor, 3.0 [1]. Thus, though the measurements themselves all have uncertainties of approximately 200 eV, their average has an uncertainty of 300 eV! The measurement reported here has an uncertainty of 53 eV, a substantial improvement over all previous measurements.

*Electronic address: tommi.eronen@jyu.fi
†Current address: RIKEN, Nishina Center for Accelerator Based Science, Wako City, Saitama, Japan
‡Current address: Institute for Nuclear and Radiation Physics, Leuven, Belgium

II. EXPERIMENTAL METHOD

We carried out the Q_{EC}-value measurements at the accelerator laboratory of the University of Jyväskylä, Finland, using the IGISOL radioactive-ion-beam production facility [3] combined with the JYFLTRAP Penning-trap mass separator/spectrometer [4, 5].

Singly charged ^{42}Sc ions were produced with the ^{45}Sc$(p, p\,3n)^{42}$Sc reaction initiated by 48-MeV protons. In addition to the ^{42}Sc 0^+ ground state, the 7^+ isomeric state, ^{42m}Sc, was also populated, more strongly in fact than the ground state at our comparatively high bombarding energy. Also, stable ^{42}Ca ions were produced via the ^{45}Sc$(p, \alpha)^{42}$Ca reaction and likely also via ionization of trace amounts of calcium, which could have been present in the gas-cell structures. Thus, ^{42}Sc, ^{42m}Sc and their β-decay daughter ^{42}Ca were all produced by the same proton beam and were all available for interleaved mass measurements.

We employed the light-ion guide [6] filled with $\sim$200 mbar of helium gas to thermalize and extract the reaction products from the target region. After leaving this ion guide, the ions entered a $\sim$30-cm-long radiofrequency-sextupole transport section [7]; they were then accelerated to 30 keV and coarsely mass-separated by passing them through a dipole magnet having mass resolving power $M/\Delta M \approx 500$. This resolution was sufficient to select $A/q = 42$ ions and reject all the rest.

After being mass-separated the continuous beam of $A/q = 42$ ions was bunched with a gas-filled radiofrequency (RFQ) cooler-buncher [8], and then transferred to the JYFLTRAP Penning-trap mass spectrometer, which consists of two cylindrical Penning traps [4, 5]. In our measurement, the ion bunches from the RFQ were initially transferred to the first of the two Penning traps. This trap was filled with low-pressure ($\approx 10^{-5}$ mbar) helium gas to allow us to use the sideband cleaning technique [9]; it was tuned to have enough mass resolving power to separate ^{42}Sc from the co-produced isomeric state ^{42m}Sc and the stable ^{42}Ca.

The mass measurement itself was performed in the second Penning trap, operating in vacuum ($\approx 10^{-8}$ mbar).

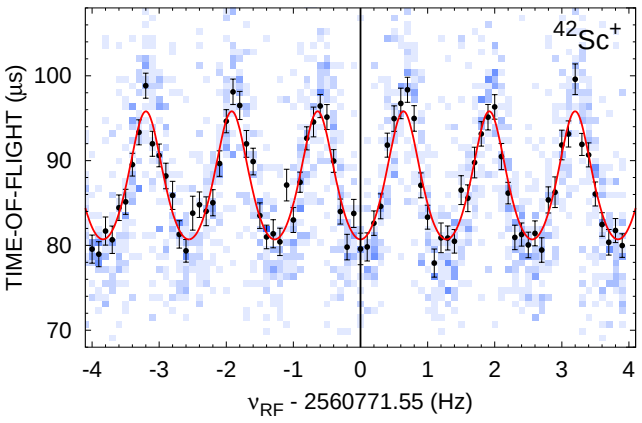

FIG. 1: A sample resonance of ^{42}Sc obtained with a Ramsey-type excitation pattern of 25 ms (on) - 750 ms (off) - 25 ms (on). The blue pixels indicate detected ions: the darker the pixel, the greater the number of ions. Black points with error bars are the average times-of-flight for each frequency. The solid red line is the fit to the average time-of-flight points.

We used the time-of-flight ion-cyclotron resonance (TOF-ICR) technique [10, 11] and employed Ramsey's method of time-separated oscillatory fields to boost the precision [12, 13]. Since the half-life of ^{42}Sc is only about 680 ms, we limited the duration of the excitation pattern to 800 ms.

The main idea in Penning trap mass spectrometry is to measure the cyclotron frequency,

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B, \qquad (1)$$

where m is the mass and q the charge of the ion of interest, which is in the trap's homogeneous magnetic field B. To obtain this frequency, the radial-sideband frequency, $\nu_+ + \nu_-$, is measured. It turns out that this sideband frequency actually equals the cyclotron frequency with high precision, as shown through the invariance theorem [14].

To get the sideband frequency, the ions must be excited in two steps. First, the magnetron-motion amplitude of the ion[1] is increased slightly to about 1 mm by means of a short-duration dipole electric field at a magnetron frequency of about 170 Hz. Second, a quadrupole electric field is used to induce conversion of the ion's magnetron amplitude to its cyclotron motion. The amplitude of this exciting RF field is chosen so that full conversion occurs at the ion's cyclotron frequency, as given by Eq. (1). At other frequencies only partial conversion occurs. We used the Ramsey excitation pattern, 25 ms (on) - 750 ms (off) - 25 ms (on), to produce TOF-ICR resonance curves for each ion species as shown for ^{42}Sc in Fig. 1.

The $Q_{\rm EC}$ value between parent and daughter atoms with mass M_1 and M_2 can be obtained from the relationship

$$Q_{\rm EC} = M_1 - M_2 = (r-1)\,(M_2 - m_e)\,c^2, \qquad (2)$$

where m_e is the mass of the electron and $r = \frac{\nu_{c,2}}{\nu_{c,1}}$ is the ratio of the cyclotron frequencies $\nu_{c,1}$ and $\nu_{c,2}$ measured for M_1 and M_2 respectively. This expression assumes that the ions of both species are singly charged and that the atomic binding energy difference between the two is small, a condition easily satisfied by the calcium-scandium pair, for which the difference is about 0.5 eV.

To minimize systematic uncertainties arising from magnetic-field fluctuations [17] during our measurements, we switch back and forth between parent and daughter ions after one or two complete frequency scans, each one of which takes 1.5 minutes. Since one scan does not contain enough statistics for reliable data fitting, we combine many such interleaved scans to produce two summed resonance curves, one for the parent and one for the daughter. Thus the data from both the parent and the daughter ions are collected under essentially identical field conditions; any field fluctuation having a time scale greater than a few minutes influences both ion species equally and eventually cancels out in the frequency ratio.

Since we measure mass differences between atoms having the same A/q, the mass-dependent systematic uncertainties are also very small [18] provided that the two ion species are measured under similar conditions: for example with the same motional amplitudes. This way, any potential frequency shifts are the same for both species and so cancel out in the frequency ratio.

III. RESULTS, ANALYSIS AND DISCUSSION

We directly measured the $Q_{\rm EC}$ value of the superallowed decay branch from ^{42}Sc: *i.e.* the mass difference between the ground states of ^{42}Sc and ^{42}Ca. In addition, as a consistency check we also measured the mass differences between ^{42m}Sc and ^{42}Sc, and between ^{42m}Sc and ^{42}Ca. More than half of the measurement time (about 17 hours) we dedicated to the $Q_{\rm EC}$ value of the superallowed transition. The remainder went to measuring the Sc isomer-to-ground-state excitation energy (6 hours) and to the Q-value between ^{42m}Sc and ^{42}Ca (9 hours). The results are collected in Table I.

In arriving at these results, we binned the data with several different time-of-flight cuts, ions/bunch and several combinations of fit parameters. No significant deviations were found among the different sets. Most importantly, we did not see any change in frequency as a function of the number of ions in the measurement trap. Thus, we limited the data we used to bunches with 1-2

[1] See for example Ref. [15, 16] for a complete description of ion motions in a Penning trap

TABLE I: Results of the present measurements. The reference masses used in the application of Eq. 2 were taken from Ref. [21]. We derived the final ^{42}Sc $Q_{\rm EC}$ value, shown in bold, by using both the direct measurement and the value obtained by combining the two mass-differences involving the isomeric state.

Ion	Reference	Freq. ratio, r	$Q_{\rm EC}$, $E_{\rm ex}$ (keV)	χ^2/N
^{42}Sc	^{42}Ca	1.000164425(16)	6426.340(60)	0.87
^{42m}Sc	^{42}Ca	1.000180207(19)	7043.138(75)	0.74
^{42m}Sc	^{42}Sc	1.000015778(21)	616.751(82)	0.26
Final ^{42}Sc $Q_{\rm EC}$ value			**6426.350(53)**	

ions detected [19]. This selection included about 90% of all recorded bunches that had at least one detected ion.

As an illustration of our analyzed data, the measured frequencies and frequency ratios for the ^{42}Sc-^{42}Ca pair are plotted in Fig. 2. Each frequency-point for ^{42}Sc consists of 40 scans and for ^{42}Ca it comprises 20 scans, each scan taking about 1.5 minutes. With this binning, about 2000 detected ions were obtained for each resonance. Because of the difference in production rates for the two ion species, we interleaved the scans by repeatedly recording 2 scans for ^{42}Sc followed by 1 scan for ^{42}Ca. The effect of magnetic-field drift, which has recently been measured to be $8.18(19)\times10^{-12}$/min [20], is clearly visible in Fig. 2b but it is certainly negligible over the 4.5-minute period of a single set of interleaved scans. The frequency ratios shown in Fig. 2a show no signs of systematic changes.

The normalized chi-squared values for all three sets of measurements listed in Table I are less than 1, indicating that our statistical uncertainties may be slightly overestimated. We make no adjustment for this, so the uncertainties quoted in the table can be regarded as being rather conservative.

We derived the final ^{42}Sc $Q_{\rm EC}$ value presented in Table I by combining our direct measurement of this quantity, 6426.340(60) keV, with the value we obtained by subtracting the ^{42m}Sc-^{42}Sc mass-difference from the ^{42m}Sc-^{42}Ca difference. The latter result, 6426.387(111) keV, is less precise than the former but is statistically consistent with it. The weighted average, our final result, is 6426.350(53) keV. This is about four times more precise than the result we obtained in 2006 [23]. Mostly the better accuracy is explained by our use of the Ramsey method and additionally by our achieving a better vacuum in the precision trap, which allowed us to employ a somewhat longer excitation time.

The four previous determinations of the ^{42}Sc $Q_{\rm EC}$ value all used different approaches. The first is derived from a combination of two reaction $Q_{\rm EC}$ values, ^{41}Ca$(n,\gamma)^{42}$Ca and ^{41}Ca$(p,\gamma)^{42}$Sc [22], which yields the result 6425.84(17) keV [1]. The second is a direct measurement with the JYFLTRAP Penning trap, giving 6426.13(23) keV [23]. The third and fourth derive from "doublet" $Q_{\rm EC}$-value measurements, in which the difference between two superallowed $Q_{\rm EC}$ values was measured [24]: the ^{42}Sc-^{26m}Al difference in one case, and ^{42}Sc-^{54}Co in the other. To make comparison with the other ^{42}Sc results transparent, we combine the difference measurements with Penning trap measurements of the $Q_{\rm EC}$ values of ^{26m}Al [23] and ^{54}Co [25] respectively to yield ^{42}Sc $Q_{\rm EC}$-value results of 6426.33(24) keV and 6427.34(22) keV.

These four values are displayed, together with our new measurement of the ^{42}Sc $Q_{\rm EC}$ value in Fig. 3. Also shown is the weighted average of previous results as it appears in the 2014 survey of world data [1]. It is noteworthy that our new, more precise measurement agrees rather well with the central value of the survey average. Individually though, only two of the previous measurements agree satisfactorily with the new result: Our 2006 Penning-trap measurement [23] and the 1987 doublet measurement (^{42}Sc-^{26m}Al) by Koslowsky *et al.* [24] combined with our 2006 Penning-trap measurement of the ^{26m}Al $Q_{\rm EC}$ value [23]. The 1989 Kikstra *et al.* reaction measurement [22] is three of its standard deviations away from the new value, and the second Koslowski doublet (^{42}Sc-^{54}Co) result [24] deviates by more than four of its standard deviations (in the opposite direction). There is no obvious explanation for these discrepancies except to note that, in pre-Penning-trap times 30 years ago, reaction measurements

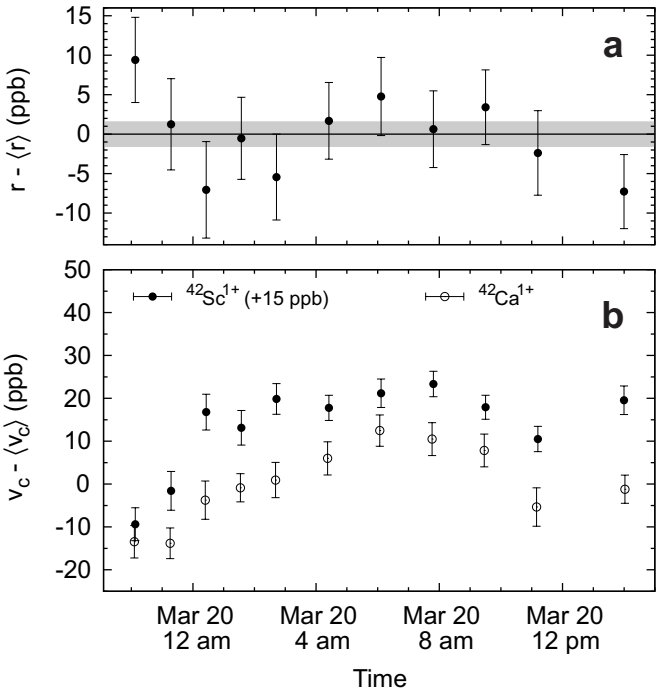

FIG. 2: The fitted cyclotron frequencies for the ^{42}Sc—^{42}Ca set (panel b) showing deviations from the average frequency. The ^{42}Sc resonances have been offset by 15 ppb for clarity. Each frequency point for ^{42}Sc includes 40 scans and for ^{42}Ca 20 scans, which have been interleaved. Panel a shows the deviation of the individual frequency ratios, from the average frequency ratio.

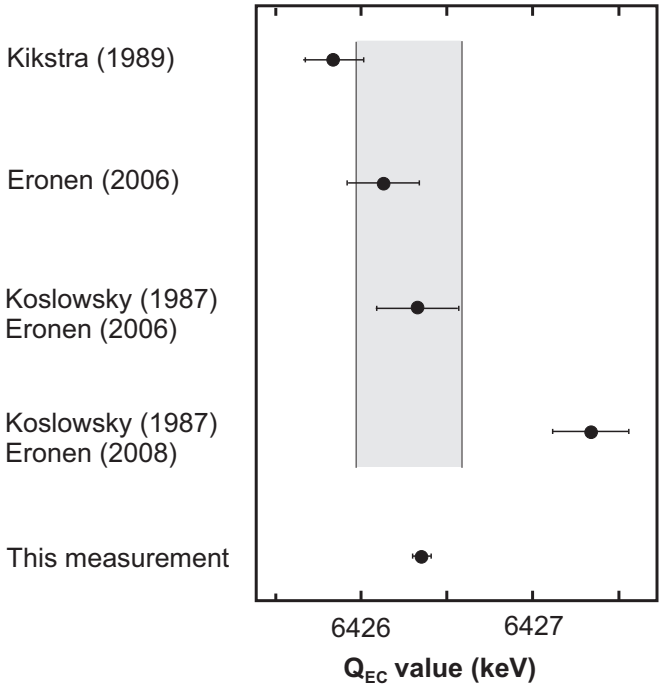

FIG. 3: Comparison of our new ^{42}Sc $Q_{\rm EC}$-value measurement with previous determinations. The grey band shows the previous average value, with its uncertainty, as is appears in the 2014 survey of world data [1]. The experimental references are Kikstra (1989) [22], Eronen (2006) [23], Koslowsky (1987) [24] and Eronen (2008) [25].

quoted to 200-eV precision required heroic efforts, which evidently were not always completely successful.

The excitation energy of the 7^+ isomeric state in ^{42}Sc is an interesting byproduct of our measurement. We determine its value directly to be 616.751(53) keV and indirectly to be 616.798(96) keV, a result we obtain by subtracting the ^{42}Sc-^{42}Ca mass-difference from the ^{42m}Sc-^{42}Ca difference. The weighted average of these two consistent values is 616.762(46) keV. This value agrees with our 2006 measurement [23] but is significantly more precise.

Since there is no known electromagnetic decay of the isomer to the ground state, its excitation energy has only been measured with comparable precision once before: in a study of four resonances produced by the ^{41}Ca(p,γ)^{42}Sc reaction [22], from which the isomer's excitation energy was deduced from sums and differences of the energies of cascading γ rays populating the isomer and the ground state. That measurement gave the excitation energy of the isomer to be 616.280(60) keV, a result that differs from ours by 482 eV, or 8σ. It is worth noting that this previous result by Kikstra *et al.*[22] comes from the same 1989 publication as the discrepant $Q_{\rm EC}$ value that appears at the top of Fig. 3; the discrepancy with our result in that case was 510 eV. It is unproductive to speculate on what might have gone amiss with that 30-year-old experiment.

IV. CONCLUSIONS

The error budgets for all the $\mathcal{F}t$ values for the precisely measured superallowed transitions are illustrated in Fig. 3 of the 2014 survey [1]. For the ^{42}Sc transition, the contributions from the $Q_{\rm EC}$ value and the half-life are very similar, the former being 0.026% and the latter 0.037%. If taken at face value, our new result would reduce the $Q_{\rm EC}$-value contribution by a factor of 5 to 0.005%. However, taken in the context of world data, the uncertainty on the weighted average will be about a factor of two larger than that, since the discrepant $Q_{\rm EC}$-value results from the past will still have an impact. Even so, our new result has substantially reduced the contribution from $Q_{\rm EC}$ to the ^{42}Sc ft-value uncertainty to a level about a factor of 4 lower than the contribution from the half-life.

Although this measurement in itself does not significantly reduce the uncertainty on the ^{42}Sc ft value, it opens the door for a much larger improvement if the ^{42}Sc half-life can be measured more precisely. Since a number of the superallowed-transition half-lives have already been measured to $\sim$0.01% precision, this should not be an insurmountable challenge.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-FG03-93ER40773, by the Welch Foundation under Grant No. A-1397, and by the Academy of Finland under the Finnish Centre of Excellence Programme 2012-2017 (Nuclear and Accelerator Based Physics Research at JYFL). A.K. and L.C. acknowledge the support from the Academy of Finland under project No. 275389.

[1] J. C. Hardy and I. S. Towner, Phys. Rev. C **91**, 025501 (2015).
[2] M. González-Alonso and J. M. Camalich, ArXiv e-prints 1605.07114v1 (2016).
[3] I.D. Moore *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **317**, 208 (2013).
[4] V. S. Kolhinen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **317, Part B**, 506 (2013).
[5] T. Eronen *et al.*, Eur. Phys. J. A **48**, 46 (2012).
[6] J. Huikari *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **222**, 632 (2004).
[7] P. Karvonen *et al.*, Nucl. Instrum. Methods Phys. Res.,

Sect. B **266**, 4794 (2008).
[8] A. Nieminen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **469**, 244 (2001).
[9] G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
[10] G. Gräff, H. Kalinowsky, and J. Traut, Z. Phys. A **297**, 35 (1980).
[11] M. König *et al.*, Int. J. Mass Spectrom. Ion Process. **142**, 95 (1995).
[12] M. Kretzschmar, Int. J. Mass Spectrom. **264**, 122 (2007).
[13] S. George *et al.*, Int. J. Mass Spectrom. **264**, 110 (2007).
[14] G. Gabrielse, Phys. Rev. Lett. **102**, 172501 (2009).
[15] L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986).
[16] J. Ketter *et al.*, Int. J. Mass Spectrom. **358**, 1 (2014).
[17] J. Hakala *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **266**, 4628 (2008).
[18] C. Roux *et al.*, Eur. Phys. J. D **67**, 1 (2013).
[19] A. Kellerbauer *et al.*, Eur. Phys. J. D **22**, 53 (2003).
[20] L. Canete *et al.*, Eur. Phys. J. A **52**, 124 (2016).
[21] G. Audi *et al.*, Chinese Physics C **36**, 1157 (2012).
[22] S. W. Kikstra *et al.*, Nucl. Phys. A **496**, 429 (1989).
[23] T. Eronen *et al.*, Phys. Rev. Lett. **97**, 232501 (2006).
[24] V. T. Koslowsky *et al.*, Nucl. Phys. A **472**, 419 (1987).
[25] T. Eronen *et al.*, Phys. Rev. Lett. **100**, 132502 (2008).