Q-Value for the Fermi Beta-Decay of $^{46}$V

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Abstract. By comparing the Q-values for the $^{46}$Ti($^3$He,t)$^{46}$V and $^{47}$Ti($^3$He,t)$^{47}$V reactions to the isobaric analog states the Q-value for the superallowed Fermi-decay of $^{46}$V has been determined as $Q_{EC}(^{46}$V) = (7052.11 ± 0.27) keV. The result is compatible with the values from two recent direct mass measurements but is at variance with the previously most precise reaction Q-value. As additional input quantity we have determined the neutron separation energy $S_0(^{47}$Ti) = (8880.51 ± 0.25) keV.

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1 Introduction

For the determination of the first element $V_{ud}$ of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, that describes the mixing of different quark flavours, the beta transition rates between even-A isobaric analogue states (IAS) with spin I=0, called superallowed Fermi-transitions, yield the most precise values up to now [1]. The values from neutron or pion decay are not competitive yet [2]. For nine T=1 pairs with mother nuclei from $^{10}$C to $^{54}$Co the relevant quantities half-life, branching ratio and decay energy, that enters into the phase space factor with the fifth power, have been measured with great precision and yield with the appropriate corrections a decay strength which is constant within the uncertainties of a few 10^{-4}. With the same level of precision the hypothesis of the Conserved Vector Current (CVC) in weak nuclear decays is proven. From the average beta-decay strength the value of $V_{ud} = 0.97408 ± 0.00026$ has been deduced [3] and with this value and the recently improved value of $V_{us}$ and of $V_{ub}$ the unitarity relation for the first row of the CKM matrix is now well fulfilled with $\sum_{\nu=d,s,b}|V_{\nu u}|^2 = 0.9998 ± 0.0010$.

These new measurements on $V_{ud}$ in Kaon decays have now removed the "violation" of the unitarity, which had persisted for many years (e.g. [4]). Nevertheless, it is essential to determine the nuclear physics quantities, experimental and theoretical, in independent ways, to remove systematic errors in $V_{ud}$. The beta-decay Q-values were traditionally determined using nuclear reaction Q-values. In recent years the precision of direct mass measurements using Penning traps has improved that much, that mass differences of radioactive ions can be determined with the required accuracy. Recently the decay energy of $^{46}$V, one of these Fermi-emitters, has been measured by direct mass measurements of $^{46}$V and $^{47}$V in the Canadi-an Penning Trap [5] at Argonne Nat. Lab. as well as in the JYFLTRAP [6] at the University of Jyväskylä. Their result is at variance with the 1977 result obtained by Vonach et al. [7] with a Q value measurement of the $^{46}$Ti($^3$He,t)$^{46}$V reaction. Savard et al. argue that all seven Q-values of Vonach et al. are erroneous and discard them in the averages of input data. Hardy et al. [8] have undertaken a detailed re-analysis of $(n,\gamma)$ and $(p,\gamma)$ data in order to search for systematic differences between reaction Q-values and mass differences. Since reaction Q-value measurements seem to be regarded with scepticism, we repeated the $^{46}$Ti($^3$He,t)$^{46}$V measurement to clarify, whether there is a principal problem.

2 Experimental Details

We used essentially the same experimental components as Vonach et al. [7], the Munich Tandem accelerator and the high resolution Q3D spectrograph [9]. But instead of

| target isotope | nat | 46 | 46/47 | 47 | 48 |
|---------------|-----|----|-------|----|----|
| 46            | 8.3 | 70.8 | 38.7 | 2.5 | 0.2 |
| 47            | 7.4 | 3.2 | 37.5 | 76.1 | 0.3 |
| 48            | 73.7 | 23.0 | 19.0 | 19.0 | 99.1 |
| 49            | 5.4 | 1.6 | 1.5 | 1.3 | 0.2 |
| 50            | 5.2 | 1.4 | 1.3 | 1.1 | 0.2 |

Table 1. Isotopic composition (in atom %) of the targets used.
calibrating the ion energies with an over 100 m long time-of-flight system [7], that is not operational any more, we used the same reaction on another Ti isotope within the same target as a calibration. This method may proof to be reliable also in other cases, since most systematic uncertainties are avoided.

An intense beam from the ECR like ion source [10] was accelerated in the Munich MP tandem accelerator to an energy of 27 MeV. Typical beam currents of 3He\(^+\) ions on target were 0.8 \(\mu\)A. The beam energy was chosen as a compromise for optimum energy resolution. To minimize the specific energy loss a high energy would be favoured. On the other hand the relative energy resolution achieved with a magnetic spectrograph is constant and therefore calls for a low ion energy. The triton energy from the \(^{46}\text{Ti}(^3\text{He},t)^{47}\text{V}\) reaction was (as in [7]) measured with the Munich Q3D magnetic spectrograph, that provides a superb intrinsic resolution of about 2 \(\cdot\)10^{-4}. In the focal plane the tritons were identified and their position was measured by a proportional counter with individual readout of 256 cathode strips [11]. The \(^{46}\text{Ti}(^3\text{He},t)^{46}\text{V}\) Q-value was calibrated against that of the \(^{47}\text{Ti}(^3\text{He},t)^{47}\text{V}\) reaction to the IAS in the \(T=3/2\) multiplet of \(A=47\). The difference of these Q-values is just equal to the difference in Coulomb displacement energies (CDE) for the isotopes and thus small (\(\approx 30\) keV). To become independent of effects of beam position on the target and on different beam energies and energy losses we measured both reactions simultaneously in one single target. The target was produced by evaporating 20 \(\mu\)g/cm\(^2\) of a mixture of enriched \(^{49}\text{Ti}\) and \(^{47}\text{Ti}\) onto a 4 \(\mu\)g/cm\(^2\) carbon backing. The isotopic composition of this mixed and other reference targets is given in table 1.

The Q3D was positioned at 0°: for the L=0 transitions of interest the cross section has a maximum and the energy of the tritons is to first order independent of the angle. The angular acceptance was restricted to \(\pm 2.3°\). This causes a maximum energy shift of 2.5 keV and thus a low energy tail. Since the magnetic rigidity of 27 MeV \(^{3}\text{He}^+\) is only 58% of that for 20 MeV \(^{3}\text{H}^+\), the background from scattered beam particles in the focal plane detector was tolerable.

To measure the particle position in the focal plane, we used a multiwire gas proportional counter [11]. A precise position information is obtained from the charges influenced on 3 to 7 of 255 cathode strips with a periodicity of 3.5 mm. Every strip is provided with a preamplifier and shaper. The digitized charge signals are read out for every event and in the offline analysis fitted to a Gaussian to yield a position information with an intrinsic accuracy better than 0.1 mm, corresponding to 10^{-5} in energy. For particle identification the energy loss signal of the proportional wire is used and a plastic scintillator yields the residual energy.

### 3 Results and Discussion

Fig. 1 shows the relevant part of the spectrum. The excitation of the IAS of all stable Ti isotopes is visible with intensities consistent with the respective isotopic content of the target and the expected neutron number dependence of the cross section \(\sigma \propto (N-Z)/A^2\) [12]. The width of the peaks (FWHM) corresponds to 5.4 keV, whereas the resonance curves in the direct mass measurements [5] [6], inspite of the tremendous relative resolution, have a width of about 30 keV and 50 keV (FWHM) respectively. To determine the energy difference between the \(^{46}\text{V}\) and \(^{47}\text{V}\) peaks we need only the slope of the energy calibration which we obtained from the \(^{26}\text{Mg}(^3\text{He},t)^{26}\text{Al}\) reaction under exactly the same conditions. The spectrum is shown in Fig. 2. With states between 2.5 and 3.8 MeV of excitation.
the quadratic relation between position and triton energy was fitted and the slope of the calibration was obtained with an uncertainty of less than 0.2%.

Thus we obtain a difference in triton energies for the \(^{3}\text{He},t\) reactions on \(^{46}\text{Ti}\) and \(^{47}\text{Ti}\) of 28.27(16) keV. This results in a Q-value difference of \(\Delta Q(46,47) = (28.73 \pm 0.16)\) keV due to the different recoil energies of the heavy reaction products. The error consists of the uncertainty in the fitted peak positions and that of the energy calibration. It has to be noted that in contrast to the measurement of Ref. [7] systematic uncertainties like change in beam energy and position of beam or target do not have to be considered, because of the simultaneous measurement. For completeness we also give the triton energy difference of the pair \(^{46}\text{Ti}\) and \(^{48}\text{Ti}\) as 20.28(0.20) keV. The Q-value difference then is \(\Delta Q(46,48) = (-18.57 \pm 0.20)\) keV.

One possible source of systematic errors could be due to unobserved lines underneath the IAS. Therefore we also investigated the \(^{3}\text{He},t\) reactions on enriched \(^{47}\text{Ti}\) and \(^{48}\text{Ti}\) targets. The spectra are shown in Fig. 3 together with that of the mixed \(^{46,47}\text{Ti}\) target. The spectra are all consistent with the expectation from the known isotopic impurities. Even if there would be a \(^{47}\text{V}\) or \(^{48}\text{V}\) line hidden under the \(^{46}\text{V}\) peak, it could at most have a 0.8 % contribution and could shift the \(^{46}\text{V}\) line by at most 80 eV. Thus we can neglect such an influence.

We also considered differential nonlinearities in the position determination. Since the particle position is derived from a number of 3 - 7 cathode strips, such an effect is conceivable. This was investigated by producing a white spectrum with scattered particles from a thick target. Indeed a modulation of intensity was observed when determining the position of a particle from the centroid of the pulse height distribution, which could shift a line by at most 140 eV. This effects can easily be understood as caused by the threshold on individual strip signals. But our analyzed spectra were produced by applying an event-by-event fitting of the peak position. With that procedure no modulation of the white spectrum was observed and a peak shift cannot be more than 10 eV.

The main uncertainty of the reference Q-value for the \(^{47}\text{Ti}(^{3}\text{He},t)^{47}\text{V}\) reaction in the mass table [15] is due to the neutron separation energy \(S_n\) of \(^{47}\text{Ti}\) with \(S_n = 8880.29\) (0.29) keV. Therefore we measured the \(^{46,48}\text{Ti}(d,p)^{47,49}\text{Ti}\) reactions at deuteron energy of 14 MeV with an enriched \(^{46}\text{Ti}\) target that still contains 23% of \(^{48}\text{Ti}\). The spectrum is shown as Fig. 4. Thus the Q-value difference between the \(^{46,48}\text{Ti}(d,p)^{47,49}\text{Ti}\) reactions was determined with lines at excitation energies around 2.2 MeV in \(^{47}\text{Ti}\) and 1.5 MeV in \(^{49}\text{Ti}\) to be \((S_n(^{47}\text{Ti}) - S_n(^{49}\text{Ti})) = (738.15 \pm 0.25)\) keV. The uncertainty is mainly due to the uncertainty of the states in \(^{47}\text{Ti}\) (\(\approx 0.2\) keV) [16] and their scatter around our calibration of about 0.30 keV (rms). With the averaged value \(S_n(^{49}\text{Ti}) = (8142.358 \pm 0.013)\) keV [13,15] we obtain \(S_n(^{47}\text{Ti}) = (8880.51 \pm 0.25)\) keV. This is in good agreement with the literature value [15] that already contains the new neutron capture value \(8880.50(0.30)\) keV [15]. Since all earlier data have much larger errors we omit them and use the weighted average of the latter and our result: \(S_n(^{47}\text{Ti}) = (8880.51 \pm 0.19)\) keV.

From Esch et al. [10] we have both the excitation energy of the IAS in \(^{47}\text{V}\), \(E_x = (4150.35 \pm 0.11)\) keV, and the proton separation energy \(S_p(^{47}\text{V}) = (5167.57 \pm 0.07)\) keV. The latter value needs a little adjustment, because it had been measured with a \(^{46}\text{Ti}(p,\gamma)^{47}\text{V}\) resonance relative to a resonance in the \(^{27}\text{Al}(p,\gamma)^{28}\text{Si}\) reaction. That resonance energy has been remeasured since and Hardy et al. [8] use a new average for the proton energy \(E_p = 991.780(60)\) keV instead of \(E_p = 991.880(40)\) keV used in [10]. Therefore we use the value \(S_p(^{47}\text{V}) = (5167.67 \pm 0.09)\) keV.
used a novel method by calibrating simultaneously with the same reaction on another target isotope and exciting the IAS. Thus most of the systematic errors are avoided. The method in principle can be applied to other Q-values of superallowed $\beta$ emitters. However at the moment there is no other case for which both the ground state Q-value and the energy of the IAS of another isotope is known with sufficient precision.

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References

1. I. Towner, J.C. Hardy, Phys. Rev. C 77 (2008) 025501
2. C. Amsler et al., Phys. Lett. B 667 (2008) 1
3. T. Eronen et al., Phys. Rev. Lett. 100 (2008) 132502
4. J.C. Hardy, I. Towner, Phys. Rev. C 71 (2005) 055501
5. G. Savard et al., Phys. Rev. Lett. 95 (2005) 102501
6. T. Eronen et al., Phys. Rev. Lett. 96 (2006) 132502
7. H. Vonach et al., Nucl. Phys. A 278 (1977) 199
8. J.C. Hardy, I. Towner, G. Savard, Int. J. of Mass Spectrometry 251 (2006) 95
9. M. Löffler, H.J. Scherer, H. Vonach, Nucl. Instr. Meth. A 111 (1973) 1
10. R. Hertenberger et al., Nucl. Instr. Meth. A 536 (2005) 266
11. H.-F. Wirth et al., Munich Accelerator Lab., Annual Report (2000) 71
12. F.D. Becchetti, D. Dehnhard, T.G. Dzubay, Nucl. Phys. A 168 (1971) 151
13. G. Audi, A.H. Wapstra, C. Thibault, Nucl. Phys. A 729 (2003) 337
14. T.W. Burrows, Nuclear Data Sheets 74 (1995) 1
15. R.B. Firestone, S.F. Mughabghab, G.L. Molnar, in "Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis", IAEA Report 1263 (2007) 45
16. H.P.L. Esch and C. van der Leun, Nucl. Phys. A 454 (1984) 1