Eur. Phys. J. A (2018) **54**: 93
DOI 10.1140/epja/i2018-12532-4

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Gamma-ray branching ratios in the decay of ^{49}Cr

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Received: 17 January 2018 / Revised: 23 April 2018

Communicated by A. Jokinen

Abstract. The γ-decay branching ratios of ^{49}V have been studied in the β/EC decay of ^{49}Cr. The γ-ray spectrum has been measured with a 70% relative efficiency co-axial germanium detector calibrated in efficiency with a precision of about 0.5%. The primary result is the measurement of the relative branching ratios of the three main γ rays in the decay of ^{49}Cr. Large discrepancies were found with a previous experimental work. The ^{49}Cr sample was produced by proton impact on a ZrO$_2$ target and collected at the ISOLDE facility of CERN and enabled us to re-evaluate the decay scheme of ^{49}Cr. The new data allow the use of this nucleus for future high-precision calibration work.

1 Introduction

Over the last 10 years, we have calibrated with high precision the efficiency of a single-crystal germanium detector [1], (70% relative efficiency) primarily in order to measure with high precision the β-decay branching ratios of super-allowed $0^+ \rightarrow 0^+$ β decays. These decays are the most precise means to determine the weak-interaction vector coupling constant g_V and, together with the muon weak-decay coupling constant, the quark-mixing matrix element V_{ud}. To determine these quantities, the decay Q value, the half-life and the super-allowed $0^+ \rightarrow 0^+$ branching ratio have to be measured with high precision up to better than 0.1%. In the past [2], $0^+ \rightarrow 0^+$ β decays have been measured for a series of nuclei with isospin projection $T_z = 0$ and allowed a precision of the order of 0.1% to be reached for these quantities. However, as the most important theoretical input to determine g_V and V_{ud}, the isospin breaking correction, is strongly nuclear-model dependent, it was questioned whether the overall precision achieved for g_V and V_{ud} was correct. Therefore, efforts were undertaken over the past years to increase the body of primary data and in particular to add $T_z = -1$ nuclei, for which the isospin correction is significantly higher and thus easier to evaluate. However, unlike the $T_z = 0$ nuclei for which the non-analogue β decay branches, *i.e.* all branches other than the $0^+ \rightarrow 0^+$ decay branch, are quite small (well below 1%), the more exotic $T_z = -1$ nuclei have non-analogue branches of the order of up to almost 100%. The challenge for these measurements is therefore to determine the super-allowed branching ratio with a precision of 0.1%. These branching ratios are measured with germanium detectors which have thus to be calibrated in efficiency with that same precision. Two detectors exist presently that reach this degree of precision [1,3,4].

At present, only for few of these $T_z = -1$ nuclei all quantities have been measured with satisfactory, though limited precision: ^{10}C, ^{14}O, ^{22}Mg, ^{34}Ar, ^{38}Ca. Other nuclei for which efforts are presently under way are ^{18}Ne, ^{26}Si, ^{30}S, and ^{42}Ti [2], to mention only the lighter nuclei. The energies of the γ rays for which the branching ratios have to be measured span a wide range from about 70 keV (^{22}Mg) to 3.2 MeV (^{38}Ca).

Measurements with standard radioactive calibration sources as well as with short-lived sources produced either at ISOLDE, CERN or at the TANDEM of IPN Orsay (see [1] for details) were used to calibrate the efficiency of our germanium detector over an energy range from about 30 keV to more than 4 MeV. However, when the paper of this calibration was published [1] there were too few data points available in the low-energy part of the calibration curve to ensure that also below 100 keV the calibration was as good as at higher energy. Therefore, instead of giving a precision of the efficiency of 0.15% as for energies

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above 100 keV, we opted for a conservative precision of only 0.5%.

In the mean time, we have improved our knowledge of the efficiency below 100 keV with new measurements of ^{48}Cr, ^{109}Cd and ^{169}Yb and improved simulations and analyses of other nuclei. This work will be published soon. One of the sources we wanted to use was a ^{49}Cr source produced on-line at ISOLDE. This isotope is a very good candidate for such a low-energy calibration, because it has strong γ rays at 62.3 keV, 90.6 keV, and 152.9 keV. Therefore, this source can be used to link the region where the calibration was already well established (*i.e.*, above 100 keV) to the region below 100 keV.

The decay of ^{49}Cr was studied several times in the literature. The first measurements date back to 1942 [5] and 1944 [6]. Both authors determined the half-life of ^{49}Cr (41.9(3) min. and 45(5)min.) and positron and γ-ray energies by absorption techniques after chemical separation of the chromium activity. Crasemann *et al.* [7] used also a chemical procedure to separate chromium from other activities after the bombardment of titanium foils with 40 MeV α particles. To measure the positron spectrum, these authors used a "thick lens beta spectrograph". From the Fermi-Kurie plots, they determined three decay components and a half-life of 41.7(5) min. Nussbaum *et al.* [8] were the first to correctly identify the low-energy γ rays measured with scintillation detectors, however, the branching ratios determined appeared later wrong. Baskova *et al.* [9] and Barker *et al.* [10] determined the correct low-energy γ-ray energies, but got branching ratios grossly deviating between the two works and in particular with the later higher-precision work.

Cheung *et al.* [11] were the first to use germanium detectors to study the different decay branches of ^{49}Cr. They studied this decay after production of the chromium activity by a $^{51}\mathrm{V(p, 3n)}$ reaction. The authors found that the "result differed notably from previously reported values". Okon *et al.* [12] determined the high γ-ray energies from the decay of ^{49}Cr. However, these results appeared to be in contradiction with the work of Tabor *et al.* [13] who determined energies and branching ratios for γ rays from 60 keV to 2.2 MeV. Finally, Jackson *et al.* [14] determined the same quantities and found again differences with Okon and co-workers. All these experiments [11–14] were performed with germanium detectors giving access to precise energies and branching ratios.

Burrows [15] evaluated the literature data on ^{49}Cr decay and determined in particular the relative γ-ray branching ratios of this nucleus. According to this evaluation these branching ratios were rather well known.

However, in the process of the analysis of our ^{49}Cr data, it turned out that our new data are in strong disagreement with the latest and most precise literature data [14]. An error about a factor of 20 greater than our calibration uncertainty would be needed to bring the relative branching ratios determined in the present work in agreement with the most precise literature data. In contrast, our data are in reasonable agreement with older and less precise data [11–13].

The purpose of the present paper is to correct the relative γ-ray branching ratios for the decay of ^{49}Cr and to establish a new complete decay scheme of this nucleus by combining literature data with our present data. So in some sense, instead of using the data from this source to continue the calibration of the germanium detector, we use the germanium detector with its present precision to measure the γ rays from the ^{49}Cr source and improve its decay scheme.

2 Experiment

A single ^{49}Cr ($T_{1/2} = 42.3(1)$ min) sample was produced at ISOLDE from a $\mathrm{ZrO_2}$ target bombarded with a 1.6 μA proton beam, coupled to a VD5 plasma ion source. Activity was accumulated for 5 minutes on a PVC target with a diameter of 2.2 cm and a thickness of 5 mm. During this time a total of 4.5×10^9 atoms was accumulated on the disk corresponding to a current of approximately 2 pA. Due to the mass separation of the beam with the ISOLDE GPS, only mass $A = 49$ ions or molecules could reach the PVC target. The elements vanadium and scandium are known to be very refractory and do not defuse easily out of a target. In addition, ^{49}Sc (99.94%) and ^{49}V (100%) decay basically only to the ground state of their daughter nuclei and do not produce γ rays. ^{49}K, ^{49}Mn and ^{49}Fe, if produced, have too short half-lives to be still present after dismounting the target from the collection chamber and its installation in the measurement set-up (typically 5 min). Therefore, only ^{49}Ca with a half-life of 8.7 min could be potentially present in the sample when the measurement started. With the exception of a γ ray at 143 keV (branching ratio of 0.035%), all γ rays from the decay of this nucleus have energies above 800 keV that do not influence the present measurement. However, none of the ^{49}Ca γ rays were identified up to an energy of 2.2 MeV which allows us to conclude that we dealt with a basically pure ^{49}Cr sample (see fig. 1). This is in agreement with the fact that in the whole spectrum up to 2.2 MeV, only γ ray or pile-up peaks linked either to the decay of ^{49}Cr or to well identified room background could be observed. The overwhelming part of the current came from stable molecules. The daughter nucleus of ^{49}Cr, ^{49}V, has a half-life of 330 d and a 100% decay branch to the ground state of stable ^{49}Ti, so does not contribute to the γ-ray spectrum.

This sample was put in front of the germanium detector (70% relative efficiency, n-type co-axial germanium crystal) after the end of the collection and measured for periods of 30 min and twice 1 h without any significant pause between the measurements. As in all previous measurements, the sample was positioned at 15.0 cm from the entrance window of the detector located in a low-activity area outside the ISOLDE hall. No collimation or shielding was used to have the same peak-to-total ratios and the same experimental conditions as in previous measurements. Background measurements showed that no γ-ray contamination was present in the region of interest. From the number of counts in the 90.6 keV peak for the first

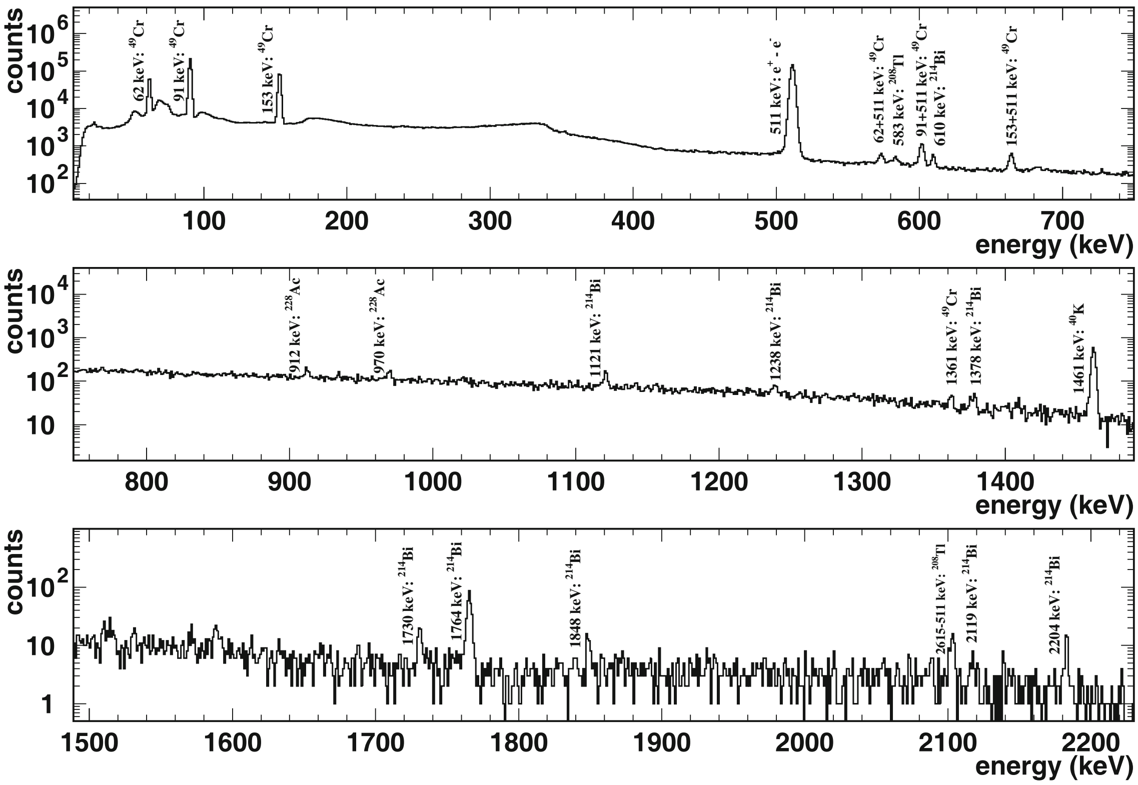

Fig. 1. Experimental γ-ray spectrum as recorded for the present work. The all important γ-ray peaks are identified demonstrating that the source accumulated on the catcher contained only ^{49}Cr. The last peak (2204 keV) is slightly off of its correct energy, as it is at the very end of the ADC where non-linearities are common.

measurement run (1.1×10^6 counts) and the peak efficiency of our detector at 90.6 keV (1%), we determined the activity of the ^{49}Cr sample to be 150 kBq at the beginning of the measurement yielding a ^{49}Cr beam intensity of 500 nuclei per second. This value is close to the expected value with a ZrO_2 target (400 nuclei per second) which can be estimated from the ISOLDE yield data base for the Y_2O_3 target including a loss factor of about 400 between the Y_2O_3 target and the ZrO_2 target. The set-up was identical to the one used for all calibration measurements performed with the germanium detector in ref. [1]. The data acquisition was of listmode type based on the GANIL VME data acquisition. Only energy spectra were acquired.

In the same experiment, samples of ^{48}Cr, ^{24}Na, and ^{38}K were also collected. These data will be used in the continued calibration procedure of our germanium detector and published in an upcoming technical paper.

3 Results

Figure 1 shows the γ-ray spectrum from the decay of ^{49}Cr from the first 30 min run. The spectrum shown up to the ADC limit (about 2.2 MeV) with all significant γ rays identified demonstrates that the source accumulated was indeed clean containing only ^{49}Cr. The three γ-ray peaks at 62.3 keV, 90.6 keV, and 152.9 keV were fitted with a Gaussian and different functions for the background (see [1] for details) including a polynomial of degree two and a smoothed step function. The best fit in terms of χ^2 was used for the integral of the peak and for the statistical error. A systematic error was determined by means of the difference of the best fit with the second best fit. We also varied the range of the background fit window to estimate the influence of this parameter.

The peak integrals were then corrected for the efficiency of our detector for the three energies of 0.1624(83)%, 0.5406(27)%, and 0.2424(12)%. We assumed a global uncertainty of the efficiency of 0.5% for the detector which has been summed quadratically with the uncertainties of the peak integrals (which became basically negligible). This corresponds to the precision quoted in ref. [1]. As in the literature, all branching ratios were then normalised to the branching ratio of the strongest peak at 90.6 keV. We observed also the weak peaks at 1361, 1508, 1514 and 1570 keV from the decay of higher-lying levels in the daughter nucleus ^{49}V. However, they were too weak to determine their intensity with reasonable precision.

Our results are presented in table 1. In the following, we will average our results with the literature data for these relative branching ratios and determine the absolute β-decay feeding probabilities in order to establish a new decay scheme for ^{49}Cr.

Table 1. Relative γ-ray branching ratios from the β decay of ^{49}Cr. Literature data are compared to our results. As we believe that the precision quoted in the work of Jackson *et al.* is most likely by far overestimated, we added in quadrature the uncertainty given in their paper to obtain absolute intensities of 2% also to the relative intensities (see text for more details). This gives rise to the column labelled "modified". The last two columns present the final relative branching ratios used in the rest of the present paper and the χ^2 value from the averaging. All intensities are normalised with respect to the γ-ray intensity of the 90.6 keV line.

γ-ray energy (keV)	Cheung *et al.* [11]	Okon *et al.* [12]	Tabor *et al.* [13]	Jackson *et al.* [14]	Jackson *et al.* "modified"	Present work	Average	χ^2
62.3	340(20)	322(32)	315(38)	308(4)	308(7)	298.8(23)	300(3)	1.55
90.6	1000(60)	1000(100)	1000(50)	1000(2)	1000(21)	1000(5)	1000(5)	–
152.9	500(30)	548(55)	520(24)	570(2)	570(12)	509.7(29)	513(7)	6.13
511.0	3250(200)	3340(334)	3270(160)	3480(70)	3480(99)	–	3393(76)	1.00

4 Discussion and decay scheme

In table 1, we compare our results with data found in the literature. For this comparison, we deliberately omitted older data taken with scintillation detectors (see, *e.g.*, [7, 8, 16]) for which part of the results deviate grossly from the data acquired with germanium detectors.

The results of Jackson *et al.* [14] need to be discussed with some detail. These authors give relative γ-ray branching ratios with a relative precision from 0.2% to 1.3%. In particular, the precision with which the relative branching ratio of the 90.6 keV line is given is at least surprising. In the recent past, two endeavours of germanium efficiency calibration have been undertaken by Hardy and co-workers [3,4] and by our group which reached an absolute precision of the order of 0.15–0.2% and a relative precision slightly better. However, to reach this precision a strict calibration procedure was used lasting several years. In the paper of Jackson *et al.*, not a single indication is given how the authors have potentially reached such a precision. No indications are given what calibration measurements and procedures they used to establish their efficiency curve.

As can be seen from fig. 2, their branching ratio of the 152.9 keV γ transition strongly deviates from our measurement which in turn is compatible with previous results. We suspect that a possible explanation for their large branching ratio of the 152.9 keV γ ray could be problems with pile-up of the 62.3 keV and the 90.6 keV peaks. In order not to reject completely this work we will increase their uncertainty with the uncertainty these authors give in their paper for the absolute branching ratios of 2%. These modified uncertainties give thus rise to the additional column in table 1. In the following, we will use the average relative branching ratios determined with this increased uncertainty as given in the last but one column of the table. The last column gives the χ^2 value for the averaging of the different literature values. It clearly indicates that there is most likely a problem with the relative branching ratio of the 152.9 keV line.

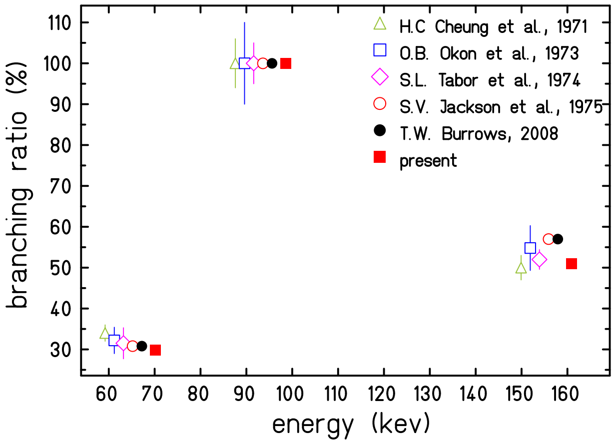

Fig. 2. Comparison of relative branching ratios from the literature with the present results. The literature data are from Cheung *et al.* [11], Okon *et al.* [12], Tabor *et al.* [13], and Jackson *et al.* [14]. Burrows has evaluated the data available in the literature in 2008 [15]. The Jackson *et al.* data are plotted with their original error bars that are smaller than the symbol size.

In order to elaborate the decay scheme of ^{49}Cr, we need now to transform the relative γ-ray branching ratios in absolute branching ratios and correct for internal conversion to determine the β-decay and electron-capture feedings of the different levels. For the internal conversion coefficients (ICCs), we used the BrICC calculations [17] which yield ICCs of 0.0787, 0.0287, and 0.0725 for the electromagnetic transitions at 62.3 keV, 90.6 keV, and 152.9 keV. The use of calculations to determine the internal conversion coefficients is inline with the evaluation work of Burrows [15], where the same calculations were used. Measurements by Nussbaum *et al.* [8] and Menti [18] show at least to some extent large differences with respect to these calculations. The electron capture probabilities are calculated according to Firestone *et al.* [19], page F-33 using tables 1 and 2 of appendix F. We obtain relative values for electron cap-

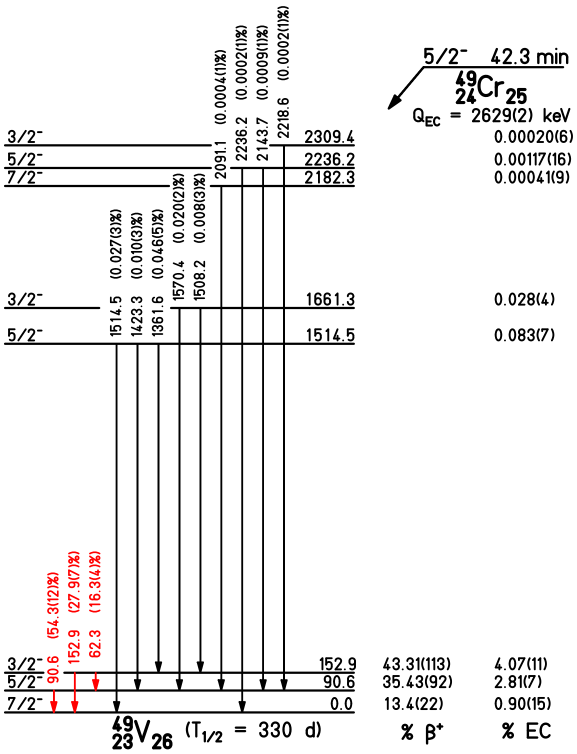

Fig. 3. Decay scheme of ^{49}Cr. The data for the β^+ and electron capture (EC) feeding are from table 2, whereas the γ-ray intensities are from table 1 normalised with a factor of 0.0543(12) in order to get absolute branching ratios. Data in red were measured in the present work.

ture of 6.30%, 7.37% and 8.60% for the β decay to the ground state and to the states at 90.6 and 152.9 keV, respectively.

For β decay to higher-lying levels, we used the data from Burrows [15]. As the Q_{EC} for the β decay to these high-lying levels is rather small, β^+ decay is negligibly small (or even impossible) and the decay proceeds via electron capture. For the high-energy γ rays emitted from these levels, internal conversion is assumed to be negligible (10^{-4} and below). The γ rays considered and their relative branching ratios (in parentheses, normalised to 1000 for the 90.6 keV γ ray) are: 1361.6 keV (0.85(8)), 1423.3 keV (0.19(6)), 1508.3 keV (0.15(6)), 1514.1 keV (0.49(6)), 1570.6 keV (0.37(3)), 2091.1 keV (0.0075(16)), 2143.7 keV (0.0173(26)), 2218.6 keV (0.0036(11)), and 2236.2 keV (0.0042(12)). We assume the same decay pattern as in Jackson *et al.* [14].

The absolute branching ratios are determined by means of the number of counts in the 511 keV γ-ray peak from the literature data (see table 1). The assumption here is that 511 keV γ rays are only produced by β^+ decays to the ground state and the first two excited states. All other decays are due to electron capture and do not produce 511 keV radiation. Thus the relative ground-state feeding can be determined from half the 511 keV counts from which we subtract the β^+ feeding of the first two excited states determined from the γ decays corrected for internal conversion. We obtain a relative ground-state β^+ feeding of 246(40) from which we can calculate the electron capture branching ratio of 17(3). The feedings for the other levels are calculated from the relative γ-ray branching ratios taking into account that some levels decay by two or three decay branches as can be seen in the decay scheme of fig. 3.

Table 2. Relative and absolute β^+ and electron-capture branching ratios for the β decay of ^{49}Cr. The relative numbers are normalised to 1000 γ rays of 90.6 keV. A factor of 0.0543(12) is used to convert the relative branching ratios in absolute ones. For details about the feeding probabilities see text.

Level (keV)	Relative β^+ decay	Relative EC	Absolute β^+ decay	Absolute EC
0.0	246(40)	17(3)	13.4(22)	0.90(15)
90.6	653(08)	52(1)	35.43(92)	2.81(7)
152.9	798(10)	75(1)	43.3(11)	4.07(11)
1514.5	–	1.53(12)	–	0.083(7)
1661.1	–	0.52(7)	–	0.028(4)
2182.3	–	0.0075(16)	–	0.00041(9)
2236.2	–	0.0215(29)	–	0.00117(16)
2309.4	–	0.0036(11)	–	0.00020(6)

Table 2 gives the relative β^+ and electron capture feedings of the different levels in ^{49}V. From the sum of all relative feedings (1842(42)) which have to sum up to 100%, we can finally determine the absolute β^+ and electron-capture branching ratios by multiplying the relative feedings with a factor of 0.0543(12). These absolute branching ratios are also given in table 2.

The results allow us to propose a complete decay scheme for the β decay of ^{49}Cr. This is given in fig. 3.

5 Conclusion

We have measured relative branching ratios for the γ-ray emission in the β decay of ^{49}Cr for the lowest three γ rays. Using relative γ-ray branching ratios for these energies and for other energies from the literature as well as calculated electron capture and internal conversion probabilities enabled us to propose a detailed decay scheme of ^{49}Cr. All decay branches are given with a precision of the order of 1.5%. A better precision is prevented due to the evident discrepancies between the present data and the data from Jackson *et al.* [14].

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