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Positron and γ -ray intensities in the decay of ^{45}Ti

Abstract: To evaluate the PET-imaging properties of the promising positron emitter ^{45}Ti , its β^+ - and γ -ray intensities were measured. Use of the cation-exchange resin DOWEX 50W \times 8 (H^+ -form) enabled the isolation of radiochemically pure, no-carrier-added ^{45}Ti from “bulk” scandium after proton bombardment. Thin, no-carrier-added ^{45}Ti samples were prepared. The combination of γ -ray and X-ray spectrometry with $\gamma\gamma$ -coincidence counting allowed for the first time the experimental determination of the positron intensity as $(85.67 \pm 2.23)\%$ and the absolute intensity of the 720.22 keV γ -ray as $(0.1171 \pm 0.0057)\%$.

Keywords: Nuclear data, ion exchange chromatography, gamma-ray spectrometry, X-ray spectrometry, gamma-gamma-coincidence-measurement, positron emitter ^{45}Ti .

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1 Introduction

During the last decades the impact of imaging techniques on life sciences and medicine has grown enormously. Molecular imaging concepts, especially in combination with positron emission tomography (PET), experienced a remarkable evolution [1]. The general concept of radio-labelled molecules as PET-tracers in biological systems enables the undisturbed *in vivo* investigation of molecular processes. The principal applicability of a radiotracer for functional molecular imaging is dependent on the exact knowledge of the decay properties of the radionuclide used; in particular the positron emission intensity, positron energy, corresponding gamma radiation and, of course, half-life [2]. Especially the latter has to match the kinetics of the (patho-)physiological processes to be examined and is therefore essential for choosing the “right” radionuclide. The positron intensity is the percentage of decays by positron emission. The accompanying γ -radiation

should be as low as possible, especially with energies higher than *ca.* 400 keV, in order to reduce measurement imprecision due to high background, coincidence errors and so on. Furthermore, the positron energy directly affects the spatial resolution of the PET-image [3].

The well-known, so-called “organic” or standard, positron emitters ^{11}C , ^{15}O and ^{18}F are not suitable for some applications. Especially the half-lives of those nuclides are too short for studying slow physiological or pharmacological processes. Consequently non-standard PET nuclides with longer half-lives like ^{89}Zr , ^{64}Cu , $^{44\text{g}}\text{Sc}$ or ^{73}Se are required [4–6]. Although those radionuclides also need to comply with the general conditions mentioned above, most of the non-standard positron emitters do not. In addition, the nuclear decay data of many of those PET nuclides appear to be rather imprecise and therefore need to be re-measured [7, 8]. A promising, so far less regarded radionuclide which seems to satisfy the requirements for *in vivo* imaging is titanium-45. It decays *via ca.* 85% β^+ and *ca.* 15% EC to ^{45}Sc having a half-life of 184.8 min. Furthermore, the maximum positron energy of 1040.4 keV is rather low and the strongest γ -ray features a low intensity of less than 1% [9].

In spite of these promising qualities, only few research groups attempted its application in life sciences so far. First experiments with ^{45}Ti labelled compounds were carried out in the 1980s by Ishiwata *et al.* [10] and Kawamura *et al.* [11]. Using *ex vivo* experiments they showed the suitability for medical applications and were able to perform first investigations on the biodistribution of ^{45}Ti -acetate. In 1991, the same group demonstrated the general applicability of ^{45}Ti for *in vivo* studies [12]. Våvere *et al.* [13] could show that the image quality using ^{45}Ti is comparable to that using fluorine-18.

The general interest in titanium compounds has grown over the past several years, because titanium(IV)-complexes exhibited pharmaceutical potential. For instance, titanocen dichloride has undergone clinical trials as anticancer drug [14, 15]. According to the work of Becker *et al.* [16] metalloproteins are ambitious targets for therapy and diagnosis of tumour growth or neurodegenerative diseases like stroke. In biological studies Våvere and Welch [17] investigated the biodistribution of ^{45}Ti -transferrin by animal PET on tumour-bearing mice. The tumour could be delineated clearly from the surrounding tissue. Merrill *et al.* [18] had proposed already in 1978 that

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^{45}Ti would be an ideal radionuclide for toxicological and biological investigations of environmental pollutants.

Even though ^{45}Ti is known from its first documented production by Allen *et al.* [19] in 1941, the corresponding γ -radiation was not discovered till 1960 by Ishii and Takahashi [20]. In 1965 Gföller and Flammersfeld [21] determined the four most intense γ -rays connected with its decay. Porter *et al.* [22] re-measured the values in 1966, followed by Zuk *et al.* [23] in the early 1970's whose results are considered as standard till today. However, due to limited or unknown sample purity and fragmentary measurement protocols, the reliability of the data of all three studies remains unclear. Additionally, all three show a few drawbacks in their experimental techniques especially concerning the crucial preparation of thin samples for the measurement of the emitted radiation.

With respect to the possible use of ^{45}Ti for medical imaging a precise experimental determination of its important decay parameters is necessary. Therefore, pure, no-carrier-added (n.c.a.) ^{45}Ti was produced by proton induced nuclear reactions on natural scandium and subsequently radiochemically isolated. Combining different measurement techniques allowed the first experimental determination of the γ -ray intensities and the positron emission ratio of ^{45}Ti with high precision.

2 Experimental

The positron branching and the γ -ray intensities of titanium-45 were measured using thin, radionuclidically pure samples. The experimental details are given below.

2.1 Materials

Small ingots of natural scandium, supplied by Koch-Light Laboratories Ltd. (Haverhill, UK) and SeltenErdmetalle24 (Göppingen, Germany), were used for the irradiation experiments. The chemical purities of those scandium batches amounted to $\geq 96\%$ and $\geq 99.99\%$, respectively. As degrader and monitor foils in the irradiation experiments, high purity metal foils of Al and Cu ($\geq 99\%$), supplied by Goodfellow GmbH (Bad Nauheim, Germany), were used. Concentrated hydrochloric acid (p.a.) was acquired from Merck KGaA (Darmstadt, Germany) as was the H^+ -form Dowex 50W \times 8 (100–200 mesh) ion exchange resin. The $^{22}\text{NaCl}$ -solution was supplied by PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany). The reference activities of ^{152}Eu , ^{226}Ra , ^{60}Co , ^{133}Ba , ^{241}Am for the calibration of the HPGe-detectors

were purchased from PTB and Amersham Ltd (Amersham, UK).

2.2 Production of n.c.a. ^{45}Ti

Titanium-45 was produced via the nuclear reaction $^{45}\text{Sc}(p, n)^{45}\text{Ti}$ at the BC 1710 cyclotron of the Forschungszentrum Jülich. The ingots of natural Sc were rolled to gain coarse foils of about 200 μm thickness which could be inserted into a standard stacked-foil target holder. Aluminium foils were used as degraders to adjust the proton energies to 12–10 MeV. The irradiation time was 10 to 45 min with a proton-flux of 0.5 and 1.0 μA . The evaluated cross section data of the $^{\text{nat}}\text{Cu}(p, x)^{62}\text{Zn}$, $^{\text{nat}}\text{Cu}(p, x)^{63}\text{Zn}$ and $^{\text{nat}}\text{Cu}(p, x)^{65}\text{Zn}$ reactions were used to monitor the projectile energy [24] and the beam current [25]. In total 15 irradiations were performed.

After irradiation the scandium targets were dissolved in 2–3 mL of carefully heated 4 M HCl until a clear colourless solution was obtained. The ^{45}Ti produced was separated from the bulk scandium via ion chromatography using the resin Dowex 50W \times 8 which was pre-conditioned with 4 M HCl. The co-produced $^{44\text{m}+g}\text{Sc}$ was used as radioindicator in the separation process. Radionuclidic purity of the separated radiotitanium was ascertained by γ -ray spectrometry. In total 45 fractions, each of a volume of 20 mL, were taken in order to screen the whole separation process (see Figure 1). Based on this elution diagram the 3 to 5 fractions with the highest amount of ^{45}Ti , which did not show any traces of $^{44\text{m}+g}\text{Sc}$, were combined and concentrated for the subsequent investigations.

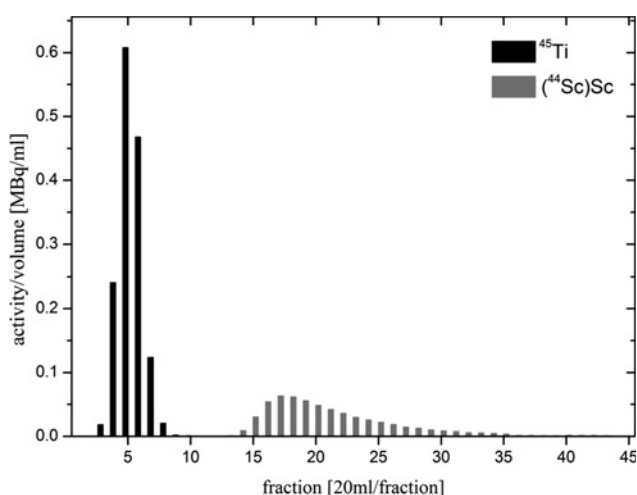


Fig. 1: Radiochromatogram of cation exchange separation of ^{45}Ti and $^{44\text{m}+g}\text{Sc}$ on Dowex 50W \times 8 resin with 4 M HCl.

2.3 Production of n.c.a. ^{44}Ti

For the investigation of the $^{45}\text{Sc}(p, 2n)^{44}\text{Ti}$ nuclear reaction, two thick foils of natural scandium were irradiated with projectile energies of 16.7–13.4 MeV at the BC 1710 for 9.5 h resulting in a total proton-fluence of 16.2 mC on the target. After disassembling the irradiated target the scandium was pestled and carefully dissolved under light heating and stirring. The solution was concentrated for 12 h until 5 mL of a clear, yellow solution was obtained. The ^{44}Ti was separated from bulk scandium as described above for ^{45}Ti . The fractions containing ^{44}Ti were combined and concentrated to 1 mL solution. In this case, however, a second chromatographic step was performed to eliminate remaining scandium traces from the solution. In total 5 kBq of n.c.a. ^{44}Ti in HCl acidic solution could be obtained.

2.4 Measurement of radioactivity

For measurement of the produced radioactivity, samples were prepared from the acidic ^{45}Ti -solution. Single drops of 0.5 μL volume were applied on a 0.1 mm thin backing of glass, based on the method described by Van der Eijk [26]. Each drop was dried under a heat lamp to gain a thin sample of a diameter less than 1 mm. Depending on the amount of radioactivity aimed for in the sample, this procedure was repeated and a corresponding number of drops were added. Samples which were intended to be measured with HPGe-spectrometry or $\gamma\gamma$ -coincidence counting were covered with a second identical thin glass plate. For X-ray-spectrometry the samples were not covered at all, whereas for β -counting a sheet of Mylar foil was required as coping. The combination of these detection systems has been elaborated and shown to be suitable for measurement of the positron intensity in earlier studies in our institute [27, 28].

2.5 Preparation of calibration standards

With respect to the requirements of calibration of the measurement devices utilized, standard sources of equivalent geometry and comparable chemical quality had to be prepared. These calibration sources were fabricated in the same manner as described for the ^{45}Ti -samples above. The X-ray-detector was calibrated with ^{44}Ti -samples which were prepared accordingly using the produced ^{44}Ti solution (see above). The coincidence counting array was cali-

brated using samples of defined n.c.a. ^{22}Na activity made from the $^{22}\text{NaCl}$ solution (PTB).

2.5.1 $\gamma\gamma$ -Coincidence counting

The coincidence counting was performed at the division of nuclear chemistry of the University of Cologne which is equipped with a dedicated low level counting room (background of 0.006 cps). Two 7.6×12.7 cm NaI(Tl)-detectors operating in coincidence recorded only events in the shaping area around 511 keV which were measured simultaneously within a shaping time of 0.1 μs by both detectors. Each detector was equipped with the necessary electronics and its own power supply. The samples were centrally arranged at a distance of 22.8 mm to each detector. The counting efficiency for this set-up was about 4%. A holder made of acrylic resin (Lucite) enclosing the respective sample assured the annihilation of the emitted positrons within a volume of 7 mm diameter.

2.5.2 γ -Ray spectrometry

The γ -ray spectrometry of the samples was carried out using five different HPGe-detectors from Ortec®. All spectra were analysed using the program GammaVision 6.01.

Different detector-source geometries were used with distances between 10 cm and 50 cm. The samples were measured for 20 min to 180 min. Selected samples of each batch were measured repeatedly for plotting decay curves

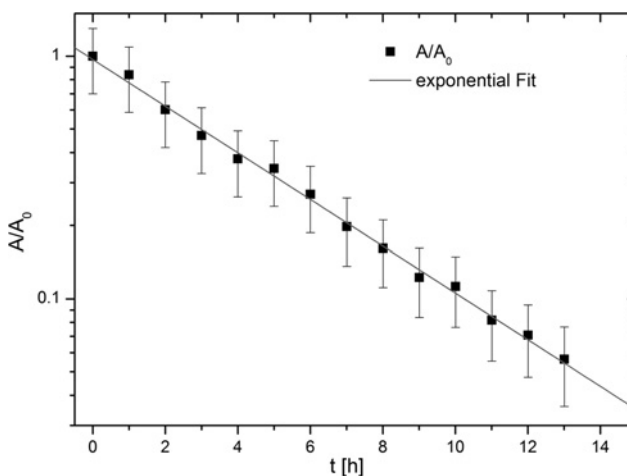


Fig. 2: Decay curve of radiochemically separated ^{45}Ti . The experimental half-life deduced from the slope of the curve fit is $-(178.4 \pm 8.1)$ min.

in order to verify isotopic purity. An exemplary decay curve is shown in Figure 2.

Concerning the analysis of the 511 keV annihilation peak, manual determination of the peak area was done by defining an appropriate region of interest in the spectrum. Likewise manual area determinations were applied in case of very small γ -ray peaks.

2.6 X-Ray spectrometry

For the measurement of the low-energy $K_{\alpha 2, \alpha 1}$ and $K_{\beta 3, \beta 1}$ X-rays (4.09 and 4.46 keV) of Sc, which are emitted in the decay of ^{45}Ti , a germanium detector type GL0210P from Canberra was used. Covered with a thin Be-foil and an active area of 200 mm² it is especially suitable for low energy X-ray spectrometry. The spectra were also analysed with GammaVision 6.01. For these quasi-weightless samples the self-absorption correction could be neglected. The samples were measured in 3 or 5 cm distance.

2.7 Positron counting

Direct counting of the emitted positrons was done using a Type 7402A gas counter from Berthold EG&G. An argon/methane mixture (P-10 gas) was used as counting gas, and the detected β^+ -emissions were recorded using a multi-logger (LB 5310, Berthold EG&G). The calibration was performed using standard sources produced by NEN (New England Nuclear) on the one hand as well as ^{22}Na sources, which were prepared analogously to the procedure described above.

3 Results and discussion

The experiments performed allowed the isolation of radionuclidically pure no-carrier-added samples of the potential PET nuclide ^{45}Ti out of irradiated bulk scandium. The preparation of thin samples of minimal mass allowed to record X-ray spectra of this isotope for the first time.

With the exception of the annihilation peak all the relevant peaks in the spectrum of pure ^{45}Ti are difficult to observe due to their low intensities. Samples containing other radionuclidic side-products, for example $^{44\text{m}+g}\text{Sc}$, cause background radiation which could easily cover these weak photo peaks. Similar problems may arise if the dead-time of the detector is too high, because the peak-to-Compton ratio would decline. Most importantly, no β^+ -emitting radionuclidic impurities may be present,

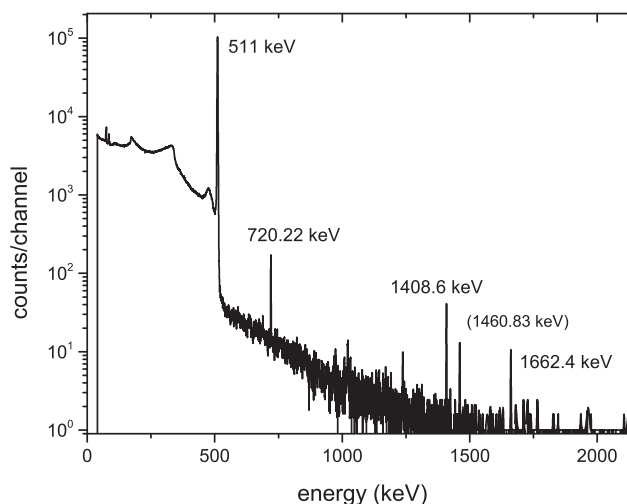


Fig. 3: Exemplary γ -ray spectrum of a pure ^{45}Ti sample showing the corresponding photopeaks and background.

which would interfere with the analysis of the annihilation peak. Thus, the preparation of radiochemically and radioisotopically pure samples of n.c.a. ^{45}Ti was essential. Figure 3 shows the γ -ray spectrum of a radiochemically purified sample. The spectrum was recorded over three hours with a distance of 50 cm between the sample and the detector.

To produce reliable results, the samples were measured with different techniques; hence several requirements had to be taken into account for the preparation of multimodal probes. By choosing the right projectile energy range during irradiation, most of the impurities could be avoided. Table 1 gives an overview of the nuclear reactions relevant for this study.

In our experiments natural scandium was irradiated with 12–10 MeV protons for several reasons:

- The energy is below the threshold of 12.7 MeV of the $^{45}\text{Sc}(p, 2n)^{44}\text{Ti}$ nuclear reaction [30], which would lead to a radioisotopic impurity that could not be separated chemically and would interfere with the X-ray measurement and the $\gamma\gamma$ -coincidence counting (see Table 1).

Table 1: Thresholds of proton-induced nuclear reactions involved in the production of ^{45}Ti [29].

Nuclear reaction	Threshold [MeV]
$^{45}\text{Sc}(p, n)^{45}\text{Ti}$	2.9
$^{45}\text{Sc}(p, d)^{44g}\text{Sc}$	9.3
$^{45}\text{Sc}(p, np)^{44g}\text{Sc}$	11.6
$^{45}\text{Sc}(p, 2n)^{44}\text{Ti}$	12.7

- A sufficient amount of $^{44\text{m}+g}\text{Sc}$ is co-produced to serve as indicator in the radiochemical separation of n.c.a. ^{45}Ti from bulk scandium allowing an accurate control of the product quality.
- A high amount of radioactivity can be produced via the $^{45}\text{Sc}(p, n)^{45}\text{Ti}$ nuclear reaction because the energy range covers the maximum of the excitation function; but is narrow enough to require only little target material.

Concerning the measurements, it was important to employ the right amount of radioactivity suiting the requirements of all used counting techniques. Samples with a minor amount of activity could not be measured properly with γ -ray and X-ray-spectrometry. On the other hand, a radioactivity too high would cause large uncertainties due to dead-time effects in $\gamma\gamma$ -coincidence measurements and to some degree in X-ray spectrometry. Furthermore, the whole cycle of measurements took several half-lives of ^{45}Ti . Thus, the sequence of conducted measurements needed to be well planned.

The accurate radiochemical preparation of the ^{45}Ti samples allowed the combined spectrometric investigation of each sample using $\gamma\gamma$ -coincidence counting and X-ray spectrometry for the determination of the positron emission intensity of ^{45}Ti . An additional analysis via β -counting was done for at least one sample in each experiment.

A typical X-ray spectrum of a ^{45}Ti -sample is shown in Figure 4. The peak area was analysed using the known emission probability of the $K_{\alpha 2, \alpha 1}$ and $K_{\beta 3, \beta 1}$ X-rays of scandium during the decay of ^{45}Ti [9]. The absolute activity of a sample was calculated using Eq. (1).

$$A_{\text{abs}}(T) = \frac{C_x \frac{\lambda t}{(1-e^{-\lambda t})}}{I_x \varepsilon_x} e^{-\lambda T} \quad (1)$$

where A_{abs} : absolute activity at time T ; C_x : counting rate of analysed peak in X-ray spectrum; λ : decay constant; I_x : emission probability of X-rays; ε : efficiency of the detector; T : elapsed time since reference time, i.e. since preparation of the sample; t : time of measurement.

After determining the precise radioactivity at the end of bombardment (EOB) the absolute positron emission probability in % was calculated using Eq. (2).

$$I_{\beta^+} = \frac{C_{\gamma\gamma}(T) \frac{\lambda t}{(1-e^{-\lambda t})}}{A_{\text{abs}}(T) \varepsilon_{\gamma\gamma}} \cdot 100[\%] \quad (2)$$

where A_{abs} : absolute activity at time T ; $C_{\gamma\gamma}$: counting rate of $\gamma\gamma$ -coincidence measurement; λ : decay constant; I_{β^+} :

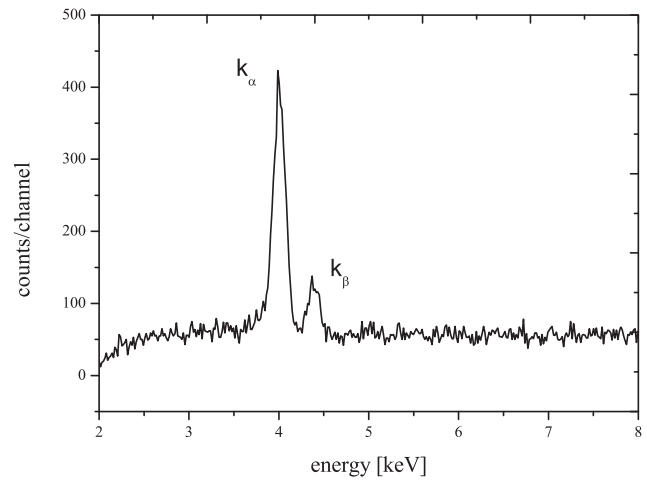


Fig. 4: A typical X-ray spectrum of ^{45}Ti , measured at 3 cm distance with a germanium detector type GL0210P from Canberra.

emission probability of positrons; $\varepsilon_{\gamma\gamma}$: efficiency of the coincidence array; T : elapsed time since reference time, i.e. since preparation of the sample; t : time of measurement.

Based on the comprehensive X-ray and $\gamma\gamma$ -coincidence measurements the total β^+ -intensity of ^{45}Ti was determined as $(85.7 \pm 2.2)\%$. This result was cross-checked by direct β -counting and confirmed with 5.2% uncertainty.

According to the decay scheme of ^{45}Ti , the peaks detected in the spectra at 720.22 keV, 1237.07 keV, 1408.6 keV and 1662.4 keV could easily be assigned to the excitation levels of ^{45}Sc . The analytical parameters given by Gföller and Flammersfeld [21] were followed to compute the emission probabilities of the γ -rays relative to the β^+ -decay to the ground state of ^{45}Sc .

The measured absolute radioactivity corresponding to those γ -rays and the 511 keV annihilation peak were compared. These data were used in Eq. (3) to obtain the γ -ray intensity of the 720.22 keV transition.

$$I_{720.22} = \frac{\gamma_{720.22}}{\beta^+} I_{45\text{Ti}, \beta^+} \quad (3)$$

where $\gamma_{720.22}$: corrected counting rate of the 720.22 keV line; β^+ : corrected counting rate of the annihilation peak; $I_{45\text{Ti}, \beta^+}$: emission probability of positrons during the decay of ^{45}Ti .

The intensities of the other relevant γ -rays were calculated using the counting rates calculated with Eq. (4).

$$I_i = \frac{\gamma_i}{\gamma_{720.22}} I_{720.22} \quad (4)$$

where $\gamma_{720.22}$: absolute counting rate of the 720.22 keV line; γ_i : absolute counting rate of the peak at energy i ;

$I_{720.22}$: intensity of the peak at 720.22 keV relative to the annihilation peak; I_i : intensity of peak at Energy i ($i = 1237.07, 1408.6$ and 1662.4 keV).

The results of all γ -ray intensities are summarized in Table 2. The weighted value depends on the statistical quality of the corresponding measurement.

3.1 Discussion and conclusion

The numerical value of the β^+ -intensity published by Porter *et al.* [22] and Zuk *et al.* [23] is $(84.80 \pm 0.13)\%$ and is based on theoretical values of Zweifel [31]. However, this result had not been experimentally confirmed up to now. The β^+ -decay intensity measured in this work amounts to $(85.7 \pm 2.2)\%$ and thus exhibits an excellent agreement of experimental and theoretical data.

The study succeeded in the experimental determination of the intensities of the four strongest γ -rays emitted during the decay of ^{45}Ti . Even the most intensive γ -ray at 720.22 keV was found to be very weak, as the emission probability amounted only to $(0.1171 \pm 0.0057)\%$. The intensities of the γ -rays 1237.07, 1408.6 and 1662.4 keV were found to be smaller as was expected, having values of $(0.0161 \pm 0.005)\%$, $(0.0696 \pm 0.0067)\%$ and $(0.00299 \pm 0.0039)\%$, respectively. The comparison of these data with the γ -ray intensities shown in Table 2, published by the three research groups mentioned above [21–23], shows the best agreement with the values given by Zuk *et al.* [23], although the new results are about 30% lower. Within given uncertainties the data of Porter *et al.* and Zuk *et al.* show good agreement to each other, whereas those of Gföller and Flammersfeld are significantly higher.

To evaluate these different data sets, the earlier works have to be examined in detail. All three older studies show at least a few drawbacks in their experimental set-up. The work of Porter *et al.* [22] and Gföller and Flammersfeld [21] have in common, that most of the γ -ray spectrometry was done with NaI(Tl)-scintillation crystals. This type of de-

tector possesses a superior counting efficiency, but lacks both a good energy resolution and a high peak to Compton ratio. Secondly and more important: the radiochemical preparation of the samples used in all previous investigations was insufficient, being neither small nor thin, as would be needed to avoid absorption and geometry effects in the measurements, and moreover the radioisotopic purity was not ensured. The samples were either prepared from carrier-added material, with radioactive impurities, or not even chemically purified at all. These drawbacks had necessarily a severe impact on the results of all three studies.

The relative γ -ray intensity is defined by the ratio of an observed γ -ray to the strongest one in the spectrum. In the case of ^{45}Ti that latter peak is the 511 keV annihilation γ -ray of the positron decay. The 720.22 keV γ -ray is the next strongest photopeak in the spectrum. The intensities of all further γ -rays emitted during the decay of ^{45}Ti are computed relative to these peaks (see Eq. 4). To obtain the absolute intensity of a certain γ -ray, the percentage of the peak corresponding to the 720.22 keV γ -ray and the annihilation peak have to be ascertained (see Eq. 3). The older works used theoretical estimations for the positron emission and the electron capture. Only Porter *et al.* measured the conversion electrons directly [22]. Table 3 gives an overview of the relative γ -ray intensities identified in this work as well as in the literature.

The radionuclidic purity of the samples was crucial for the investigation of the ^{45}Ti decay process, as any positron emitting contamination would have directly or indirectly affected the determination of the radioactivity. Within the confidence limits the relative emission intensities given in the older investigations agree rather well with our new results in spite of the mentioned obstacles. Regarding the absolute emission probabilities the data differ significantly. This is a result of the calculations described above and refers to the ratio of $I_{\text{Ti},\beta^+}^{45}$ and the corrected counting rate of the annihilation photons (see Eq. 3).

Table 2: Absolute γ -ray intensities of ^{45}Ti in comparison with literature data. All data given are multiplied by 10^5 .

γ -ray energy [keV]	Zuk <i>et al.</i> [23]	Porter <i>et al.</i> [22]	Gföller and Flammersfeld [21]	This work
720.22 ± 0.17	154 ± 12	149 ± 35	400 ± 40	117 ± 5
1237.07 ± 0.20	11.8 ± 1.3	16 ± 6	50 ± 20	16 ± 5
1408.6 ± 0.5	85.4 ± 9.1	112 ± 30	270 ± 30	70 ± 7
1662.4 ± 0.6	40.7 ± 4.3	< 40	80 ± 10	30 ± 4

Table 3: Relative γ -ray intensities of ^{45}Ti in comparison to literature data. All data are relative to the intensity of 720.22 keV peak which was assumed to be 100%.

γ -ray energy [keV]	γ -ray intensities			
	Zuk <i>et al.</i> [23]	Porter <i>et al.</i> [22]	Gföller and Flammersfeld [21]	This work
1237.07 ± 0.20	7.7 ± 1.0	10.7 ± 4.8	12.5 ± 5.2	13.7 ± 4.3
1408.6 ± 0.5	55.5 ± 7.3	75.2 ± 26.8	67.5 ± 10.1	59.4 ± 6.4
1662.4 ± 0.6	26.4 ± 3.5	—	20 ± 3.2	25.5 ± 3.6

Due to the high purity, careful sample preparation of n.c.a. material and the comprehensive measurement of beta, γ -ray and annihilation photon emission performed in this work, our new values are reproducible and appear to be more reliable.

In conclusion, the complementary use of different measurement techniques together with a pure radiochemical separation allowed to render the intensities of the four strongest γ -rays of the isotope ^{45}Ti more precisely and to ascertain experimentally the total positron emission probability as $(85.7 \pm 2.2)\%$.

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