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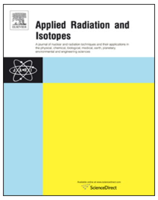

Disintegration rate, gamma-ray emission probabilities and metastable half-life measurements of ^{67}Ga

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HIGHLIGHTS

- A procedure for $4\pi(\text{PC})\beta\text{–}\gamma$ primary standardization of ^{67}Ga is described.
- The experimental extrapolation curve is compared to Monte Carlo simulation.
- Gamma-ray emission probability per decay is determined for nine transitions.
- The 93 keV metastable half-life is determined by three methods.

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ABSTRACT

The procedure for determining the ^{67}Ga disintegration rate by a primary method is described. The proposed triple $4\pi\beta\text{–}\gamma$ coincidence system consists of a thin window gas-flow 4π proportional counter (PC) coupled to a NaI(Tl) scintillator and a HPGe crystal. Independent pulse height and occurrence time information is provided for the three detector outputs by means of a Software Coincidence System. Separate spectrometry measurements with a *n*-type reversed electrode coaxial Ge detector (REGe) were performed for obtaining gamma-ray emission probabilities per decay. Accurate values of disintegration rate, gamma-ray emission probabilities and the metastable half-life were achieved.

1. Introduction

Recently, the Nuclear Metrology Laboratory (Laboratório de Metrologia Nuclear – LMN) at the Nuclear and Energy Research Institute (Instituto de Pesquisas Energéticas e Nucleares – IPEN), in São Paulo, has developed a Software Coincidence System (Toledo et al., 2007, Brito et al., 2012) for primary radionuclide standardization, with emphasis on radionuclides applied to Nuclear Medicine. One of these radionuclides is ^{67}Ga which has been standardized previously by means of a conventional coincidence counting system at the LMN (Attie et al., 1998). The main difficulty in performing primary calibration by a coincidence method for this radionuclide is the presence of a 9.0 μs metastable state associated with a high conversion electron coefficient (Mougeot and Chechev, 2011). This feature usually requires a set of measurements with several different system dead times and variation of beta detection efficiency for each selected dead time.

The proposed triple $4\pi\beta\text{–}\gamma$ coincidence system consists of a thin window gas-flow proportional counter (PC) in 4π geometry coupled to a NaI(Tl) scintillator and a HPGe crystal. The system includes the Software Coincidence System in which pulse height and occurrence time information is provided for the three detector outputs by means of software managed data acquisition system, written in LabView (Toledo et al., 2007). The advantages of this system includes: high efficiency for low energy gamma-rays, such as the ^{67}Ga 93.3 keV metastable gamma transition, by means of the PC thin window and the NaI(Tl) detector, as well as simultaneous HPGe high resolution gamma-ray measurements.

The Software Coincidence System also allows off-line selection of system dead time and beta discrimination level by software. As a result, full extrapolation curves for several selected dead time values and different gamma-ray windows can be obtained from a single measurement. In addition, these extrapolated curves can be compared to simulated curves calculated by the Monte Carlo code ESQUEMA (Dias et al., 2006, 2013). In the present study, accurate values for ^{67}Ga disintegration rate, gamma-ray emission probabilities per decay and the metastable half-life were achieved.

2. Methodology

2.1. Decay scheme

The radionuclide ^{67}Ga disintegrates 100% by electron capture with 3.2613(5) day half-life to the excited states and ground level

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of ^{67}Zn (Mougeot and Chechev, 2011). The first excited level is a metastable state with 9.0 μs half-life and the corresponding 93 keV gamma transition has a high conversion coefficient which amounts to 0.854(12). The other most intense gamma transitions are prompt and have energies corresponding to 91.2, 184.5, 208.9, 300.2 and 393.5 keV. The gamma-ray emission probabilities per decay are known to 1.3–11.3% uncertainties (Mougeot and Chechev, 2011). Therefore, lower uncertainty is desirable for gamma-ray spectrometric measurements.

2.2. 4$\pi\beta$–γ coincidence measurements

The 4πβ–γ coincidence system consists of a thin window gas-flow PC in 4π geometry for detecting X-rays, Auger electrons, as well as prompt and delayed internal conversion electrons. This PC is coupled to a NaI(Tl) scintillator 50.8 mm long, × 50.8 mm in diameter, and to a 20% relative efficiency HPGe coaxial crystal, model EGC20 Intertechnique, 50.2 mm long, 51.2 mm in diameter, for gamma-ray detection. A thin aluminum window is provided at the PC counter in order to allow low energy gamma-rays and X-ray measurements in the NaI(Tl) detector. The detector system geometry has been plotted by code VISED, included in MCNP5 software package (ORNL, 2006) and is shown in Fig. 1. The NaI(Tl) scintillator is positioned above the 4π detector and the HPGe spectrometer is placed below. The lead shield is the gray region. The surrounding circle corresponds to the escape sphere in Monte Carlo calculation performed by MCNPX, as described in Section 2.7.

The coincidence equations applied to ^{67}Ga can be found in the literature (e.g. Lewis et al., 1973; Attie et al., 1998). In the present paper, the PC detection efficiency has been changed by off-line analysis of pulse height spectrum applying the Software Coincidence System, as described in Section 2.4. The gamma-ray spectrum window and the system dead time were also imposed by software, after the experiment has been completed. From these data the extrapolation curves were achieved. Corrections for dead time and accidental coincidences were applied according to formulae taken from the literature (Smith, 1978).

In the present experiment non-extendable dead times, defined off-line by software, were used. This procedure may affect activity measurements performed with radionuclides which decay by metastable transitions such as ^{67}Ga. Therefore, as pointed out by Lewis and Funck (Lewis et al., 1972; Funck, 1987), a correction must be applied to the observed PC channel counting rates in order to avoid detection of a daughter event which normally would occur within the dead time of its parent but falls within the dead time of another event. For the present measurement conditions this correction amounted (0.58 ± 0.12)%. Modifications in the analysis program are foreseen in order to apply extendable dead time methodology and compare with the present results.

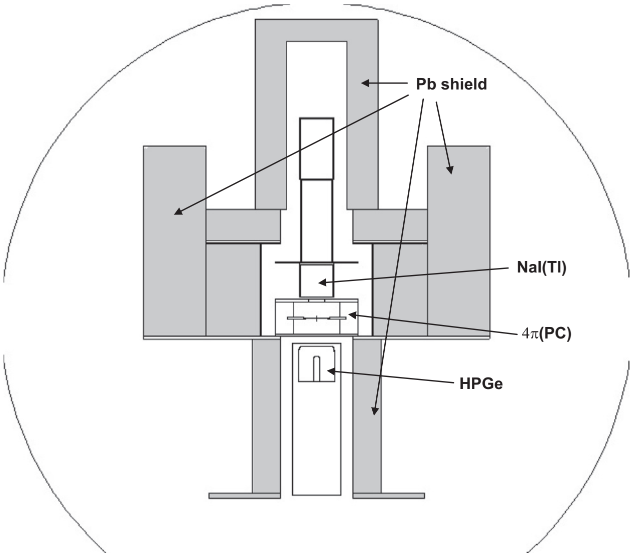

Fig. 1. Schematic diagram of the LMN coincidence system for radionuclide standardization plotted by code VISED (ORNL, 2006). The NaI(Tl) scintillator is positioned above the 4π detector and the HPGe spectrometer is placed below. Lead shield is the gray region. The surrounding circle corresponds to the escape sphere in MCNPX Monte Carlo calculation.

2.3. Sample preparation

The ^{67}GaCl solution was supplied by the IPEN Radiopharmaceutical Center, and eluted with physiological saline solution. After this procedure, the radioactive solution was diluted in distilled water and the radioactive sources were prepared by dropping known aliquots on 20 μg cm^{-2} thick Collodion substrate, previously coated with 10 μg cm^{-2} gold layer on both sides to turn the film conductive. The sources were held by means of a stainless steel ring 0.1 mm thick and 2.0 and 4.0 cm internal and external diameters, respectively. The source masses were determined by the pycnometer technique (Campion, 1975). A seeding agent (Cyastat SM) was used to improve the deposit uniformity; the sources were dried in a warm (45 °C) nitrogen jet (Wyllie et al., 1970). A set of five sources were prepared with masses ranging from 20 to 47 mg. These masses were determined with an uncertainty of ± 20 μg by means of a Sartorius MC 21S digital balance.

2.4. Software Coincidence System

A full description of the data acquisition system is given elsewhere (Toledo et al., 2007). Independent pulse height and occurrence time information is provided for the three detector outputs by means of a data acquisition system composed of a NI-6132 card, associated with a LabView acquisition program (National Instruments, 2012) and a coincidence analysis program. Independent ADC's coupled to up to four channels features a 14-bit maximum resolution, at a 2.5 MS/s rate.

This Software Coincidence System allows off-line selection of several acquisition parameters after the measurement has been completed. During the data analysis, it is possible to choose different system dead times, gamma-ray windows, pulse height resolution (up to 16 k channels) and PC discrimination levels. As a result, several extrapolation curves can be determined from a single measurement, each one corresponding to a given set of acquisition parameters. The activity calculations were performed by codes developed at the LMN (Brancaccio et al., 2009; Dias, 2010).

2.5. Metastable half-life measurements

The half-life of the ^{67}Ga 93 keV metastable transition has been determined from the time distributions between PC prompt and PC delayed events; PC prompt and NaI(Tl) delayed events, and PC prompt and HPGe delayed events. Each of these time distributions are composed of two regions: the first one is near the prompt events, where the decay of the metastable transition is noticeable and extends up to about ten half-lives (~ 90 μs). Beyond this time there is a flat region corresponding to accidental coincidences. Therefore, the time distribution can be given by the following:

$$N(t) = N_{acc} + N_m\, e^{-\lambda t} \qquad (1)$$

where $N(t)$, N_{acc} and N_m are the total, accidental and metastable counting rates, respectively; λ is the metastable decay constant and t is the time difference between prompt and delayed events.

The nonlinear least square fit between $N(t)$ and t yields the values of N_{acc}, N_m and λ. In the present work code ORIGIN (Microcal, 1995) version 4.0 was used for obtaining these fitting parameters. Since $N(t)$ correspond to count rates, that follow the Poisson distribution, the fitting was performed applying a weighing factor proportional to the inverse of $N(t)$ and assuming no correlations between each pair of points.

The possible influence of finite time resolution of the prompt pulses on the measured half-life has been investigated. Additional broadening of the time distribution, similar to prompt pulses, has been applied to the decay data and no difference has been found in the results. Another effect is the time shift due to decay of delayed pulses within the time channel bin, however, it cancels out because the half-life is measured considering time differences between channels along the time distribution.

The PC pulse rise time is longer when compared to NaI and HPGe detectors. As a result, there is a time shift of $+0.49\ \mu s$ between the PC and the other two detectors, which appears in the time distribution. However, this time shift is constant for all bin channels, therefore, it does not affect the metastable half-life measurement.

2.6. Monte Carlo calculations

Monte Carlo calculations applying code ESQUEMA (Dias et al., 2006, 2013) were performed for obtaining theoretical results to be compared with the 4πβ–γ experimental activity values. This code takes into account all materials and geometric details of the experimental detection system as well as all necessary decay scheme parameters. The theoretical deposited energy spectra for electrons and photons were calculated by the code MCNPX (ORNL, 2006) for the three detectors in the coincidence system and used as input data for code ESQUEMA. This code calculated the three detector output spectra, as well as coincidence spectra, for each experimental condition, yielding a simulated extrapolation curve for each set of acquisition parameters. The present version of code ESQUEMA does not take into account metastable transitions, therefore, the comparison between calculated and experimental extrapolation curves was performed in the limit where the dead time goes to infinity and the extrapolated value corresponds to the source activity.

In order to obtain the radioactive source activity, the simulated extrapolation curve was fitted with the experimental one by minimizing the following chi-square value:

$$\chi^2 = (\vec{y}_{\mathrm{exp}} - N_0\, \vec{y}_{MC})^T\, V_y^{-1}\, (\vec{y}_{\mathrm{exp}} - N_0\, \vec{y}_{MC}) \qquad (2)$$

where

$\vec{y}_{\mathrm{exp}}$ is the experimental vector of $N\beta N\gamma/N_c$;
$\vec{y}_{MC}$ is the $N\beta N\gamma/N_c$ vector calculated by Monte Carlo for unitary activity;
N_0 is the radioactive source activity;
V_y is the total covariance matrix, including both experimental and calculated uncertainties; and
T stands for matrix transposition.

A series of simulated values was calculated for a wide range of beta efficiency parameter in small bin intervals. The theoretical value to be used in Eq. (2) was determined by linear interpolation, for the same corresponding experimental beta efficiency.

2.7. Gamma-ray emission probabilities per decay measurements

The gamma-ray spectrometer consists of a REGe coaxial detector Model GR1520 Canberra, 45.5 mm long, 46.5 mm in diameter and 15% relative efficiency. This detector has a 0.5 mm thick Be window and yielded 1.9 keV FWHM resolution at 1332 keV. The amplifier time constant was set to 2 μs and the spectra were stored in an 8192 multichannel analyzer. Standard sources of ^{60}Co, ^{133}Ba, ^{152} Eu, ^{166m}Ho and ^{241}Am, prepared on Collodion films and calibrated in a 4πβ−γ coincidence system, were used for obtaining the REGe peak efficiency as a function of the gamma-ray energy. The decay data adopted for the calibration were taken from the International Atomic Energy Agency recommended data set (IAEA, 2007). The radioactive sources were positioned on a Plexiglas holder 17.9 cm away from the crystal front face, in order to minimize the cascade summing corrections, which were calculated by means of the Monte Carlo code COINCIG (Dias et al., 2002). An accurate pulser was introduced in the gamma-ray spectrum close to the right edge, in order to perform dead time and pile-up corrections. The area of each peak was evaluated by summing all MCA counts in the interval $[C - 2\delta, C+2\delta]$, where C is the peak centroid and δ is the FWHM (Full Width at Half Maximum). The net counts were calculated by considering the background in a region of width δ at both sides of the gamma-ray peak. A fifth degree polynomial in log–log scale was fitted between the REGe peak efficiency and the gamma-ray energy, including 25 pairs of data points and covering the energy range between 59 and 1408 keV. The same procedure has been followed for measuring the ^{67}Ga sources with the REGe spectrometer for all gamma lines except the (91+93) keV doublet. In this case, two Gaussian functions superimposed on a third degree polynomial background were used for determining the areas under the peaks. For this purpose a nonlinear least square fitting applying code ORIGIN (Microcal, 1995) was performed.

A set of five ^{67}Ga sources was measured in the 4π(PC)–γ coincidence system and in the REGe spectrometer as well. The probabilities per decay for five gamma-ray energies, namely: 93.30, 184.58, 208.95, 300.22 and 393.53 keV were determined experimentally for each radioactive source.

In order to take into account all partial errors and correlations involved, the following least square fitting equations were applied:

$$\vec{y}_{\mathrm{exp}} = D\ \vec{p} \qquad (3)$$

$$V_p = (D^T V_y^{-1} D)^{-1} \qquad (4)$$

$$\vec{p} = V_p D V_y^{-1} \vec{y}_{\mathrm{exp}} \qquad (5)$$

where

$\vec{y}_{\mathrm{exp}}$ is the vector of experimental results for the probability per decay; dimension 25 × 1;

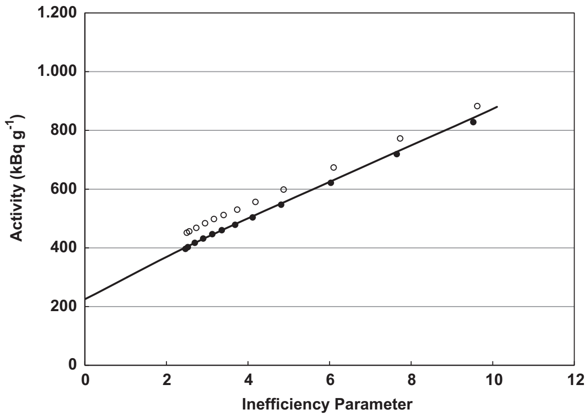

Fig. 2. Experimental and simulated extrapolation curves for two different dead times: 3 and 99 μs for one of the ^{67}Ga sources. The white marks (above) correspond to 3.0 μs and black marks (below) to 99 μs. The continuous line corresponds to the Monte Carlo calculation for infinity dead time.

D is the design matrix for the fitting; dimension 5×25;
$\vec{p}$ is parameter vector of the solution; dimension 5×1;
V_y is the covariance matrix of the vector; dimension 25×25;
V_p is the covariance matrix of the vector; dimension 5×5; and
T stands for matrix transposition.

Table 1
Results of activity determined for each ^{67}Ga source at infinite dead time, regarded as equivalent to 99 μs.

^{67}Ga Source	Activity (kBq g^{-1})	Combined uncertainty (%)
1	222.07	0.66
2	223.57	0.63
3	218.99	0.88
4	221.42	0.74
5	221.69	0.57
Mean	221.83	0.33

Table 2
Uncertainty budget, considering all partial errors involved in Eq.(2).

Source of uncertainty in the activity	Uncertainty (u=1) (%)
Mass	0.10
Radioactive decay	0.02
Beta counting statistics (per data point)	0.03
Gama counting statistics (per data point)	0.32
Coincidence counting statistics (per data point)	0.78
Non-extendable dead time correction	0.12
Combined uncertainty – fitting (all data points)	0.66

The design matrix D is given by the following:

$$D = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{6}$$

The vector $\vec{p}$ gives the weighted average values of the probability per decay for the five gamma-lines listed above, taking into account all partial errors and correlations involved.

The gamma-ray emission probability per decay for the weaker lines, namely: 494.17, 703.11, 794.38 and 887.69 keV, were determined experimentally by means of an additional higher activity (~730 kBq) uncalibrated ^{67}Ga source, prepared on Collodion film and measured at the REGe spectrometer. In this case, the probabilities per decay have been determined in a relative way, considering the absolute results of the present work for the following gamma lines: 184.58, 208.95, 300.22 and 393.53 keV. Each absolute result yielded a set of emission probabilities for the weaker gamma lines. The final result was the weighted average of the values obtained from the four absolute measurements.

3. Results

Fig. 2 shows the experimental and simulated extrapolation curves for two different dead times: 3.0 and 99 μs for one of the ^{67}Ga sources. The white marks (above) correspond to 3.0 μs and black marks (below) to 99 μs. The continuous line corresponds to the Monte Carlo calculation for infinity dead time. Similar curves were obtained for the other four radioactive sources.

From the fitting value, calculated by means of Eq. (2), the source activity $\boldsymbol{N_0}$ was determined for each ^{67}Ga source at infinite dead time (regarded as equivalent to 99 μs) and the results are

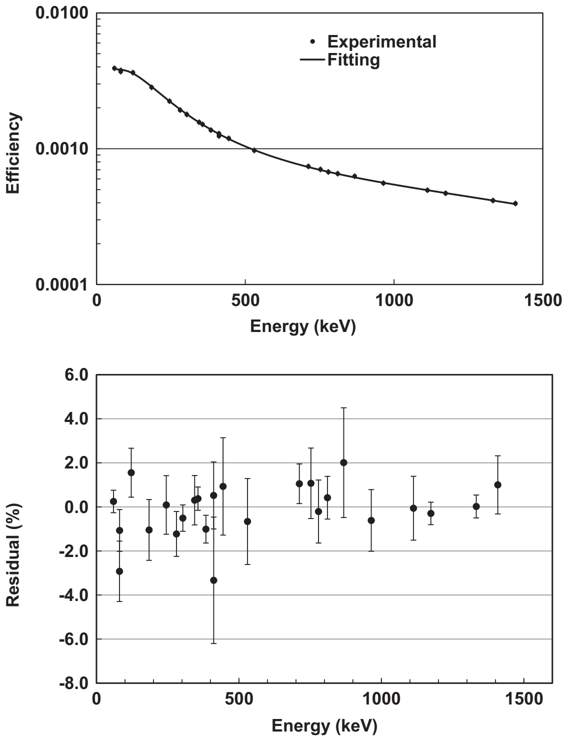

Fig. 3. Results for the REGe gamma-ray efficiency. Above is the experimental peak efficiency, as a function of the gamma-ray energy. The black marks correspond to experimental points and the continuous line to fitting values. Below are the percent residuals between experimental and fitted REGe efficiency values. The covered gamma-ray energy interval is between 59 and 1408 keV.

Table 3
Efficiency parameters of the polynomial fitting. The values correspond to a fifth degree polynomial in log–log scale.

Fitting parameters	Value
a_0	$2.3653E+02$
a_1	$-2.2806E+02$
a_2	$8.4489E+01$
a_3	$-1.5361E+01$
a_4	$1.3699E+00$
a_5	$-4.8071E-02$
χ^2	1.68

Table 4
Results of the gamma-ray probability per decay (×100) for ^{67}Ga and comparison with the literature.

Gamma-ray energy (keV)	Present work	Meyer (1990)	Yalçin and Kurucu (2005)	Bobin et al. (2007)	Mougeot and Chechev (2011)
Gamma-ray probability per decay (×100)					
93.31	37.71(32)	36.6(14)	38.8(17)	38.61(35)	38.1(7)
184.58	20.95(16)	21.7(9)	21.4(9)	21.13(10)	20.96(44)
208.95	2.375(19)	2.4(1)	2.46(11)	2.396(13)	2.37(5)
300.22	16.78(10)	16.6(4)	16.6(7)	16.74(8)	16.60(37)
393.53	4.628(30)	4.5(1)	4.6(2)	4.462(25)	4.59(10)
494.17	0.0672(7)	0.07(1)	–	0.0657(33)	0.0666(29)
703.11	0.01299(22)	0.010(1)	–	–	0.0113(9)
794.38	0.0530(5)	0.053(3)	–	0.0565(24)	0.0528(17)
887.69	0.1493(14)	0.149(5)	–	0.1522(35)	0.1492(38)

presented in Table 1, together with the corresponding combined uncertainty ($u=1$). The uncertainty budget for a typical source, considering all partial errors involved in Eq. (2), is shown in Table 2. The overall uncertainty in each individual source activity ranged from 0.57 to 0.88% and the main contribution comes from statistics in the coincidence counting rate. The weighted mean activity for all ^{67}Ga sources resulted 221.83(74) kBq g^{-1}, corresponding to 0.33% overall uncertainty, as shown in Table 1.

The REGe efficiency curve obtained for the gamma-ray probability per decay measurements and the residuals between experimental and fitted values are shown in Fig. 3. No appreciable bias can be noted. The fitting parameters are presented in Table 3. The reduced chi-square resulted 1.68 and the overall uncertainty in the interpolated efficiency was in the range between 0.37% and 0.61%. After normalization by the square root of the chi-square value, the uncertainties in the efficiencies became from 0.48% to 0.79%

The results of the gamma-ray probability per decay are shown in Table 4, together with the combined uncertainty ($u=1$). The main uncertainty contribution comes from the efficiency curve. The comparison with the literature is also shown in this table. In general, there is a good agreement with other authors and especially with the recent evaluation by Mougeot and Chechev, 2011, except the 703.11 keV transition which is the least intense and the present result is 14% higher. In most cases the uncertainty achieved by the present work is lower than those from the literature. The value shown for 93 keV gamma line was calculated by unfolding the doublet with two Gaussian functions on a third degree polynomial set as the background. The uncertainty obtained for the 91 keV gamma line was not considered satisfactory, due to overlapping with the 93 keV peak, and was excluded. New measurements are being planned with a planar HPGe which has better energy resolution.

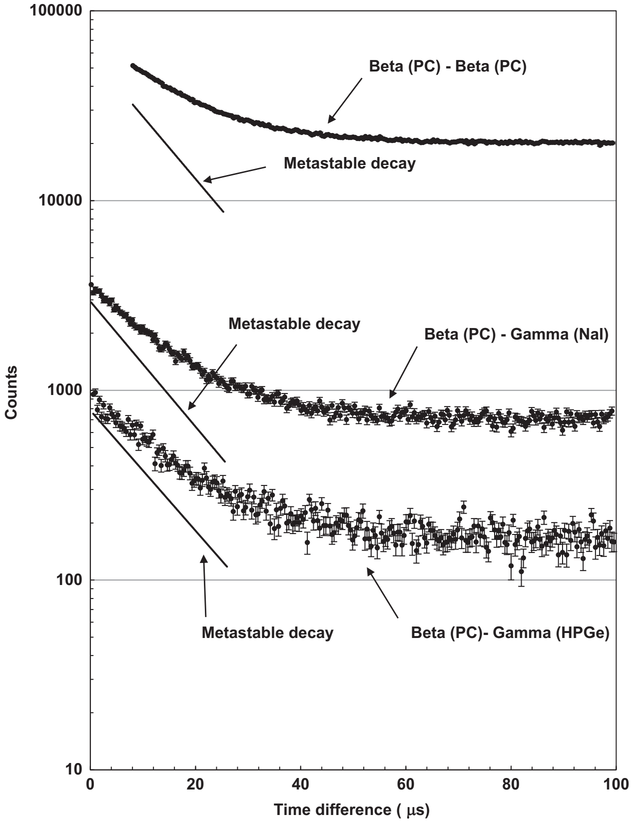

Fig. 4. Time distributions between: beta (PC)–beta (PC); beta (PC)–gamma (NaI) and beta (PC)–gamma (HPGe). The straight lines correspond to 93 keV metastable decay for each time distribution.

Fig. 4 shows the time distribution in three different measuring conditions: (a) between PC prompt events and PC delayed events (conversion electrons from the 93 keV transition); (b) between PC and NaI(Tl) delayed events (gamma discrimination window set at 93 keV total absorption peak) and (c) between PC and HPGe delayed events (gamma discrimination window set at 93 keV total absorption peak). As expected, the statistical fluctuation increases from cases (a) to (c) due to the variation in the counting rates at each detector. In the (b) and (c) cases it was possible to measure time differences down to approximately 1.0 µs. However, in case (a) the time difference measurements could only start above 8.0 µs because of the large time distribution width between the PC prompt events. The continuous straight lines correspond to the metastable decay contributions, calculated by means of the fitted parameters obtained from Eq. (1).

Table 5 shows the results of metastable half-life for the three different measuring conditions. Each result is the average of all five radioactive sources. The weighted average for the three measuring conditions is 9.157(21) µs. This result can be compared to the most recent measurements taken from the literature. There is a good agreement with the values from other authors, except with the value from Hwang et al. (1996) which is 1.7% lower. The uncertainty in the ^{67}Ga metastable half-life obtained in the present work is substantially lower because of the use of PC–PC coincidences which could achieve much better counting statistics due to the high detector efficiency.

4. Conclusions

The methodology applied to the ^{67}Ga activity determination was performed successfully, achieving an average uncertainty of 0.33% ($u=1$). The Monte Carlo calculation by means of Eq. (2) was essential to achieve this uncertainty. The gamma-ray emission probability per decay has been measured with low uncertainty for nine transitions and in most cases yielded good agreement and lower uncertainties when compared with the literature. The measured metastable half-life is 9.157(21) µs, in good agreement with most data from the literature and with a lower uncertainty. All uncertainties were treated rigorously, applying the covariance matrix methodology.

Table 5
Results of the ^{67}Ga 93 keV metastable half-life (in µs) for three different measuring conditions: (a) between PC prompt events and PC delayed events; (b) between PC prompt events and NaI(Tl) delayed events; (c) between PC prompt events and HPGe delayed events, and (d) between NaI(Tl) counter (300 keV prompt events) and PC delayed events. The other columns correspond to values taken from the literature.

Method	Present work	Attie et al. (1998)	Hwang et al. (1996)	Roodbergen et al. (1975)
Metastable half-life (µs)				
PC–PC	9.144(23)			
PC–NaI	9.22(6)			
PC–HPGe	9.22(12)			
Mean	9.157(21)	9.34(20)	9.01(3)	9.1(4)

Further measurements are foreseen to measure the gamma-ray emission probability per decay for the 91 keV transition.

In the present experiment non-extendable dead time was used. It is planned to compare these results with extendable dead time methodology, by improving the activity calculation codes to include this feature.

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References

Attie, M.R.P., Koskinas, M.F., Dias, M.S., Fonseca, K.A., 1998. Absolute disintegration rate measurements of Ga-67. Appl. Radiat. Isot. 49, 1175.

Bobin, C., Bouchard, J., Hamon, C., Iroulart, M.G., Plagnard, J., 2007. Standardization of ^{67}Ga using a 4π(LS)β–γ anti-coincidence system. Appl. Radiat. Isot. 65, 757–763.

Brancaccio, F., Dias, M.S., Toledo, F., 2009. Development of an analysis methodology applied to 4πβ–γ software coincidence data acquisition system. In: Proceedings of the 2009 International Nuclear Atlantic Conference (INAC 2009), Rio de Janeiro, RJ, Brazil, September 27 to October 2.

Brito, B., Koskinas, M.F., Litvak, F., Toledo, F., Dias, M.S., 2012. Standardization of 99mTc by means of a software coincidence system. Appl. Radiat. Isot. 70, 2097–2102.

Campion, P.J., 1975. Procedures for Accurately Diluting and Dispensing Radioactive Solutions. Monographie BIPM – 1. Bureau International des Poids et Mesures, Sèvres,, France.

Dias, M.S., 2010. SCTAC: A Code for Activity Calculation Based on Software Coincidence Counting measurements. Internal Report, IPEN-CNEN/SP.

Dias, M.S., Takeda, M.N., Koskinas, M.F., 2002. Cascade summing corrections for REGe spectrometers by the Monte Carlo method. Appl. Radiat. Isot. 56, 105–109.

Dias, M.S., Takeda, M.N., Koskinas, M.F., 2006. Application of Monte Carlo simulation to the prediction of extrapolation curves in the coincidence technique. Appl. Radiat. Isot. 64, 1186–1192.

Dias, M.S., Takeda, M.N., Toledo, F., Brancaccio, F., Tongu, M.L.O., Koskinas, M.F., 2013. Improvements in the Monte Carlo code for simulating 4πβ(PC)–γ coincidence system measurements. Nucl. Instrum. Methods Phys. Res. A 698, 177–184.

Funck, E., 1987. The influence of the half-life of a metastable state on the dead-time correction for nonextending dead times in single detector systems. Nucl. Instrum. Methods Phys. Res. A 254, 604–610.

Hwang, H.Y., Lee, C.B., Park, T.S., Kim, H.J., 1996. A new method for isomer lifetime measurement. Nucl. Instrum. Methods Phys. Res. A 383, 447–450.

IAEA, 2007. Update of X-ray and Gamma Ray Decay Data Standards for Detector Calibration and other Applications. Vol. 1: Recommended Decay Data, High Energy Gamma Ray Standards and Angular Correlation Coefficients. International Atomic Energy Agency, Vienna.

Lewis, V.E., Woods, M.J., Goodier, I.W., 1972. The calibration of the 1383A ionisation chamber for ^{67}Ga. Int. J. Appl. Radiat. Isot. 23, 279–283.

Lewis, V.E., Smith, D., Williams, A., 1973. Correlation counting applied to the determination of absolute disintegration rates for nuclides with delayed states. Metrologia 9, 14–20.

Meyer, R.A., 1990. Fizika (Zagreb) 22, 153. Cited by: Mougeot, X, Chechev, V. P., 2011. LNHB – Laboratoire National Henri Becquerel Recommended Data – Table de Radionucléides – ^{67}Ga. Accessed at ⟨http://www.nucleide.org/DDEP_WG/DDEPdata.htm⟩.

Microcal, 1995. Microcal ORIGIN Version 4.0. Copyright 1991–1995. Microcal Software Inc.

Mougeot, X, Chechev, V.P., 2011. LNHB – Laboratoire National Henri Becquerel Recommended Data – Table de Radionucléides – ^{67}Ga. Accessed at ⟨http://www.nucleide.org/DDEP_WG/DDEPdata.htm⟩.

National Instruments, 2012. ⟨http://www.ni.com/labview/pt/⟩ (accessed June 2012).

ORNL, 2006. Monte Carlo N-Particle Transport Code System, MCNP5, RSICC Computer Code Collection. Oak Ridge National Laboratory.

Roodbergen, S., Visser, H., Molendijk, W., Bedet, H.S., Verheul, H., 1975. Transition probabilities in the Ni-Zn region. Z. Phys. A: Hadrons Nuclei A 275, 45–50.

Smith, D., 1978. Improved correction formulae for coincidence counting. Nucl. Instrum. Methods 152, 505–519.

Toledo, F., Brancaccio, F., Dias, M.S., 2007. Design of electronic system with simultaneous registering of pulse amplitude and event time applied to the 4πβ–γ coincidence method. In: Proceedings of the 2007 International Nuclear Atlantic Conference (INAC 2007), Santos, SP, Brazil, September 30 to October 5.

Wyllie, H.A., Johnson, E.P., Lowenthal, G.C., 1970. A procedure for stirring aliquots of radioactive solutions when making thin 4π counting sources. Int. J. Appl. Radiat. Isot. 21, 497.

Yalçin, P., Kurucu, Y., 2005. Emission probabilities of K X- and γ-rays following 51Cr and ^{67}Ga decay. Appl. Radiat. Isot. 62, 63–67.