Standardization of ^{68}Ga by means of a $4\pi\beta-\gamma$ Software Coincidence System

M. F. Koskinas, F. W. Lacerda, I. M. Yamazaki, F. Toledo, M. N. Takeda and M. S. Dias

***Abstract*– The present work aims the standardization of ^{68}Ga, a positron emitter of short half-life used in PET (Positron Emission Tomography). The ^{68}Ga standardization was performed in a triple $4\pi\beta-\gamma$ coincidence system that consists of a thin window gas-flow proportional counter (PC) in 4π geometry coupled to a NaI(Tl) scintillator and a HPGe crystal, for gamma-ray detection. The data acquisition was carried out by means of a Software Coincidence System (SCS) developed at the Nuclear Metrology Laboratory (Laboratório de Metrologia Nuclear – LMN) at the IPEN-CNEN/SP. The final results were obtained from a multiple curve fitting applying a covariance matrix methodology combining experimental results with those determined by the Monte Carlo simulation.**

I. Introduction

The present work is focused on the standardization of ^{68}Ga, a positron emitter. This radionuclide is of great interest in Nuclear Medicine because it is used in PET (Positron Emission Tomography) and also in dose calibrators, which employ ^{18}F sources, due to similar decay characteristics.The ^{68}Ga decays with a half-life of 67.8 min by mixed β^+ and electron capture branches to the excited states of ^{68}Zn, mainly to a 1077 keV gamma transition, as shown in Fig. 1. The standardization was performed by applying the $4\pi\beta-\gamma$ coincidence technique. Data acquisition was carried out by means of a Software Coincidence system (SCS) developed at the LMN of IPEN [1]. The final results were obtained from a multiple curve fitting applying a covariance matrix methodology combining experimental results with those determined by the Monte Carlo simulation performed by code ESQUEMA [9]. This procedure yields a more realistic extrapolation curve, taking into account all characteristics of the decay scheme and the detection system.

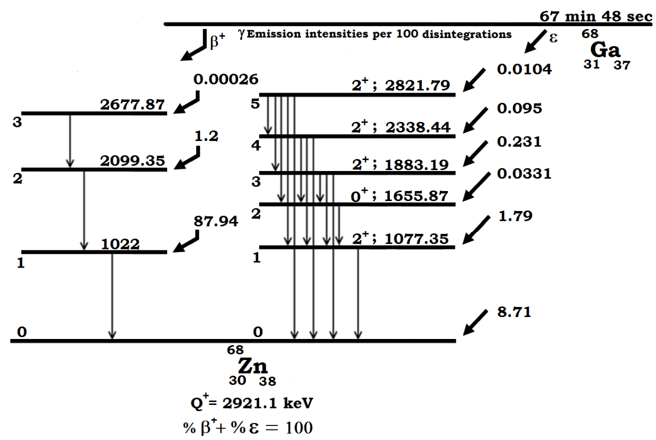

Fig. 1. Decay scheme of ^{68}Ga [3]. All energies are in keV.

II. Methodology

A. Source Preparation

The $^{68}GaCl_3$ solution was obtained by means of a ^{68}Ge generator supplied by the IPEN Radiopharmaceutical Center, followed by elution 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 Collodion substrate, previously coated with 10 μg cm^{-2} gold layer on both sides to make the film conductive. The source masses were determined by the pycnometer technique. A seeding agent (Cyastat SM) was used to improve the deposit uniformity; the sources were dried under a red lamp. A total of 4 sources, with mass ranging from 15 mg to 40 mg, were measured.

B. $4\pi\beta-\gamma$ coincidence measurements

The experimental measurements were performed by a triple $4\pi\beta-\gamma$ coincidence system consisting of a thin window gas-flow proportional counter (PC) in 4π geometry coupled to a 50.1 mm × 25.4 mm NaI(Tl) scintillator and to a 20% relative efficiency HPGe crystal, for gamma-ray detection. Two gamma windows were set for each gamma detector, one at the 511.0 keV positron-annihilation quanta and the other at 1077 keV gamma-ray total absorption energy peaks, respectively. A bi-parametric curve fitting was applied in order to determine the source activity.

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The Software Coincidence System (SCS) was based on a National Instruments PCI-6132 card capable of up to four independent analog inputs, and the signals were processed by means of a LabView Version 8.5 acquisition program. Information on pulse height and time of occurrence were registered for both beta and gamma channels. Fig. 2. shows the electronic diagram.

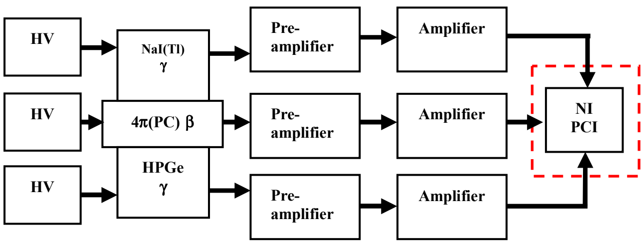

Fig. 2. Schematic of the 4πβ–γ SCS Electronic diagram.

The activity calculation was performed by means of the software coincidence code SCTAC version 6.0, developed at the LMN.

The formulae applied to the coincidence measurement are the following:

$$\frac{N_{4\pi}N_{\gamma}}{N_c} = \frac{N_0\left[a_1\varepsilon_{\beta 1}+a_2\varepsilon_{\beta 2}+b_1\varepsilon_{ec1}+b_2\varepsilon_{ec2}\right]}{(a_1\varepsilon_{\beta 1}+b_1\varepsilon_{ec1})} \qquad (1)$$

$$\left(\frac{N_c}{N_\gamma}\right)_{511} = \frac{\left[a_1\varepsilon_{\beta_1}+a_2\varepsilon_{\beta_2}\right]}{(a_1+a_2)} \qquad (2)$$

and

$$\left(\frac{N_c}{N_\gamma}\right)_{1077} = \frac{\left[a_1\varepsilon_{\beta_1}+b_2\varepsilon_{ec2}\right]}{(a_1+b_2)} \qquad (3)$$

Where: $N_{4\pi}$ is the total counting rate of the PC; the indexes 511 and 1077 refer to 511 keV annihilation quanta and 1077 keV transitions, respectively; N_c is the coincidence rate between each selected gamma-ray and the PC; ε_β and ε_{ec} are the PC efficiencies for positrons and electron capture events, respectively. The a_i and b_i are the branching ratio from beta plus and electron capture, respectively.

Considering: $\alpha_{1077}\cong 0$, $\varepsilon_{\beta\gamma}\cong 0$, $\varepsilon_{\beta_1}\cong\varepsilon_{\beta_2}\equiv\varepsilon_\beta=\varepsilon_1$ and $\varepsilon_{ec1}=\varepsilon_{ec2}=\varepsilon_{ec}$, it follows from equations (2) and (3) that:

Considering: $\left(\frac{N_c}{N_\gamma}\right)_{511}$ $=\varepsilon_1$ the positron detection efficiency, obtained from the measurements at 511 keV gamma channel window, and $\left(\frac{N_c}{N_\gamma}\right)_{1077}$ $=\varepsilon_2$, the mixed efficiency combining positron and electron capture events at the 1077 keV total absorption peak, and applying equations (2) and (4) into equation (1) it follows:

$$\frac{N_{4\pi}}{\varepsilon_1\varepsilon_2} = N_0\left[1+A\frac{(1-\varepsilon_1)}{\varepsilon_1}+B\frac{(1-\varepsilon_2)}{\varepsilon_2}\right] \qquad (4)$$

Where:

$$A=\left[(a_1+a_2)-a_1\frac{(b_1+b_2)}{b_1}\right]$$ and

$$B=\left[\frac{(b_1+b_2)}{b_1}(a_1+b_1)\right].$$

A and *B* are constants determined by least square fitting. The simultaneous extrapolations $(1-\varepsilon_1)\rightarrow 0$ and $(1-\varepsilon_2)\rightarrow 0$ yield the activity N_0. The PC efficiency was changed by moving the PC discrimination lower level.

Corrections for background, dead time and decay were applied and corrections for accidental coincidences were performed by using the Cox-Isham formalism [4], adapted by Smith [5].

C. *Monte Carlo Simulation*

The Monte Carlo code ESQUEMA [2] developed at the LMN. This code makes use of decay scheme parameters, system geometry and radioactive source characteristics. In this way, all detection processes in the coincidence system are simulated, predicting the behavior of the extrapolation curve by the Monte Carlo technique. The detector response curves were obtained by means of the radiation transport code MCNPX [6].

Fig. 3 shows the geometry considered in the simulation obtained by means of code VISED, included in the MCNPX package. All components of the system were considered, which are shown in different colors in the figure. Details of the radioactive source deposit as well as the Collodion substrate were also included in the model.

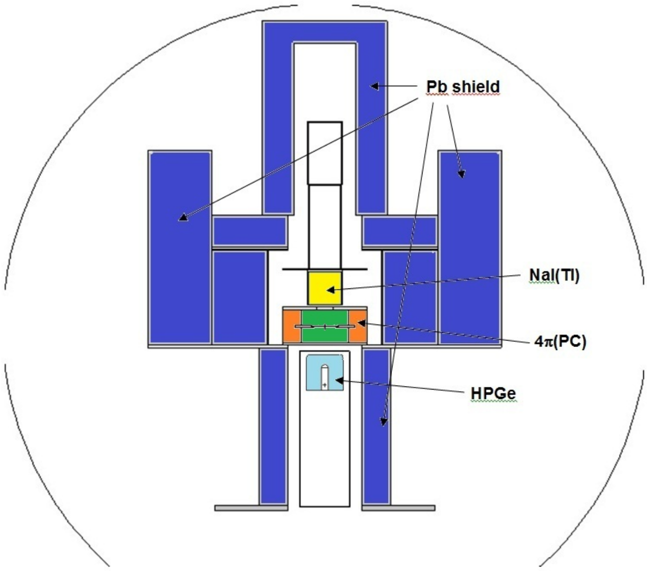

Fig. 3. Geometry of the experimental setup. The NaI(Tl) crystal is shown in yellow and the photomultiplier in white. The HPGe detector is shown in light blue. The orange color represents the proportional detector with the radioactive source in the middle, the green part represent the gas used. The lead shielding that involves the detection system is shown in dark blue.

Code ESQUEMA was used to calculate the deposited energy inside of the detectors and to simulate the variation in the PC efficiency by electronic discrimination.

Fig. 4 shows the ^{68}Ga gamma-ray spectrum from the HPGe simulated by Monte Carlo according to the geometry shown in Fig. 2 in comparison with the experimental spectrum. The gamma window used for the coincidence measurement is indicated by arrows. As can be seen there is a good agreement between these two spectra.

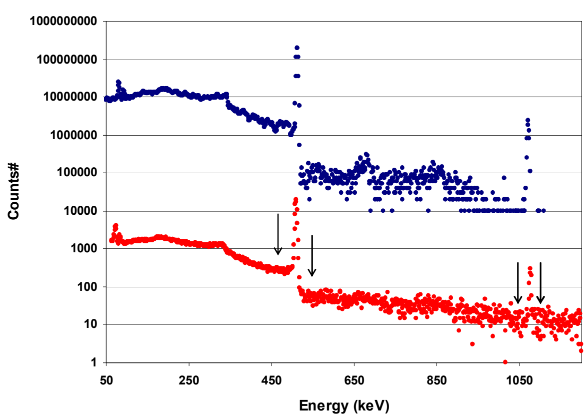

Fig. 4. Experimental HPGe spectrum in red compared with the spectrum predicted by the Monte Carlo simulation, in blue. The gamma window selected is indicated by arrows.

Fig. 5. shows the extrapolation curve predicted by code ESQUEMA for the bi-parametric fitting to the unitary activity, considering the 511 keV annihilation quanta and the 1077 keV total absorption peaks.

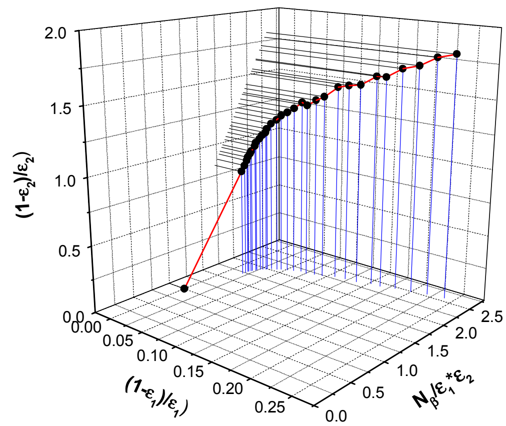

Fig. 5. Predicted extrapolation curve for the bi-parametric fitting to the unitary activity, considering the 511 keV annihilation quanta and the 1077 keV gamma ray windows.

The final activity was obtained by Least Square fitting combining experimental and simulated activity values for each PC pair of efficiencies, ε_β and ε_{ec} , obtained from the two gamma-ray windows. The final result is obtained by minimizing the following Chi-Squared value:

$$\chi^2 = (\vec{y}_{exp} - N_0 \vec{y}_{MC})^T V^{-1} (\vec{y}_{exp} - N_0 \vec{y}_{MC}) \qquad (5)$$

where:

$\vec{y}_{exp}$ is the experimental vector of $N_\beta/\varepsilon_1\varepsilon_2$; $\vec{y}_{MC}$ is the $N_\beta/\varepsilon_1\varepsilon_2$ vector calculated from the Monte Carlo for unitary activity; N_0 is the activity of the radioactive source; V is the total covariance matrix, including both experimental and calculated uncertainties; and T represents matrix transposition.

III. Results and Discussion

The range of beta plus efficiency was from 98 % to 38 % for β^+ (gamma-ray window at 511 keV) and from 60 % to 6 % for mixed β^+ and electron capture events (gamma-ray window at 1077 keV). All uncertainties were included in the fitting [7].

Fig. 6. shows a typical experimental extrapolation curve for the bi-parametric fitting, considering the gamma-channel windows at the 511 keV and at the 1077 keV total absorption peaks.

The gap between the extrapolated value and the first experimental data point can be explained considering that the maximum efficiency for electron capture events is low because of the low Auger electron emission probability and low PC detection efficiency for ^{68}Zn X-rays. This effect can be also observed in the simulated curve, shown in Fig. 4.

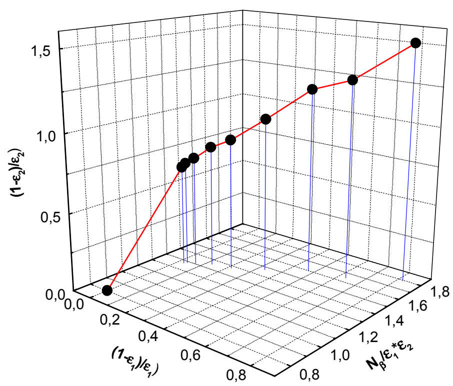

Fig. 6. The typical experimental extrapolation curves for the bi-parametric fitting considering the 511 keV annihilation quanta and the 1077 keV total absorption peaks.

The extrapolated experimental solution activity applying covariance methodology for the 4 sources measured was (801.7 ± 5.1) kBq and the value calculated by means of Monte Carlo simulation was (804.6 ± 4.6) kBq, in good agreement.

Typical uncertainties components considered are shown in Table I in percentage of the activity concentration. The main uncertainties involved in the measurement were: counting statistics, dead time, half-life, background and efficiency curve extrapolation. The primary contribution to the overall uncertainty arises from the bi-parametric fitting and from the decay correction.

TABLE I

TYPICAL UNCERTAINTIES COMPONENTS , IN % OF THE ACTIVITY CONCENTRATION (k =1).

Components	%	Correlation
Statistics beta counting	0.05	0
Weighing	0.10	1
Efficiency parameter	0.13	0
Dead time	0.05	1
Resolution time	0.05	1
Background	0.10	0
Decay	0.40	1
Bi-parametric extrapolation - experimental	0.44	From the fitting
Bi-parametric extrapolation - Monte Carlo	0.35	From the fitting
Total experimental	0.63	
Total Monte Carlo	0.57	

1= correlated 0= non correlated

IV. CONCLUSION

The standardization of ^{68}Ga by means the SCS was successful and made possible accomplish all measurements in a single day. The results for the measured solution showed good agreement with Monte Carlo simulation, demonstrating the reliability of the simulation procedure providing a reliable extrapolation curve specially when there are not so many experimental data.

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