Absolute Activity Measurement of $^{125}$I Seed Brachytherapy by Two-Dimensional Photon-Photon Coincidence Spectroscopy

A. Biganeh$^1$, O. Kakuee$^{1,*}$, Z. Akbari$^1$, M. Azizi$^2$, M. Elahi$^1$, S. Sheibani$^3$, Y. Vosoughi$^1$

$^1$ Physics & Accelerators Research School, Nuclear Science and Technology Research Institute, P. O. Box 14395-836, Tehran, Iran.
$^2$ Nuclear engineering school, Shahid Beheshti University, Tehran, Iran.
$^3$ Radiation Application Research School, Nuclear Science and Technology Research Institute, Tehran, Iran.

(Received: 6 January 2024, Revised: 24 May 2024, Accepted: 9 June 2024)

A B S T R A C T

Photon-photon coincidence counting is a primary standardization technique used for the absolute activity measurement of short half-life radionuclides. In this study, a coincidence spectrometer based on digital signal processing was developed for the absolute standardization of $^{125}$I seed Brachytherapy. The spectrometer includes a waveform digitizer that samples at the preamplifier signals directly from two similar 2” × 2” NaI (Tl) detectors. The sampled signals were shaped into trapezoidal signals for pulse height analysis. These detected signals were then recorded in a list file and the software was used to recognize coincidence events. Detailed discussions were included on the formulas for determining absolute activity measurement. The activity of a $^{125}$I seed was measured and showed good agreement with the reference values. This presented technique is a quick method for measuring the activity of $^{125}$I at nuclear hospitals. The standardized source can also serve as a tracer for measuring the activity of the $^{109}$Cd source.

Keywords: Absolute activity, Coincidence counting, $^{125}$I radioisotope, Photon-photon coincidence.

1. Introductions

Cancer is one of the leading causes of death in Iran. As a result, the Nuclear Science and Technology Research Institute (NSTRI) has initiated numerous projects aimed at producing radioisotopes for cancer diagnosis and treatment [1-3]. One of the primary products is the $^{125}$I radioisotope, which is produced by neutron capture of enriched $^{124}$Xe in gaseous form. $^{125}$I seeds due to the low energy of their X-rays have numerous applications and advantages in nuclear medicine imaging [4], biological tests [5], and radiation therapy [6].
When compared to $^{131}$I, $^{125}$I requires 50% lower doses for thyroid studies, offers greater resolution for near-surface organ exploration, allows for simpler collimator design, and is more efficient for in-vitro analysis [7].

Different techniques for primary standardization of radioactivity can be described as follows:

1. The high geometric method involves $4\pi$ counting with sandwich detectors [8].
2. The defined solid angle technique is similar to the high geometry method, but with an aperture that restricts a fraction of the radiation. The solid angle of the detector with known efficiency is accurately determined [9].
3. Coincidence counting techniques include chance coincidence counting, sum peak [10], anti-coincidence counting, and liquid scintillation-based techniques.

Gamma-gamma coincidence spectroscopy has been utilized for radiation metrology since the 1960s [11]. In our previous paper, the absolute activity of $^{60}$Co was measured using the photon-photon technique [12]. In this paper, we conducted digital coincidence gamma-gamma spectroscopy to measure the absolute activity measurement of $^{125}$I from the spectroscopy of electron capture radiations. Standardizing of $^{125}$I is more complex due to the coincidence of gamma and k-shell characteristics of X-rays having similar energies that cannot be distinguished by high-efficiency detectors.

2. Theory of standardization

$^{125}$I is the radioisotope of iodine with a half-life of 59.38 days. It disintegrates by 100% electron capture to the excited level of 35.5 keV of $^{125}$Te. The energy of accompanying X-ray radiation also approximately ranges 27-31 keV with individual emission probabilities per disintegration. The decay scheme and emission characteristics of $^{125}$I are presented in Fig. 1, Table 1, and Table 2, respectively [13]. The theory of coincidence counting for absolute activity measurement has been described by many authors [14-16].

![Figure 1. The decay scheme and emission probability of $^{125}$I.](image)

**Table 1. The emission probability of $^{125}$I [17].**

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Intensity (%)</th>
<th>Type</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.47</td>
<td>73.2 (8)</td>
<td>X_{\beta1}</td>
<td>Te</td>
</tr>
<tr>
<td>27.20</td>
<td>39.3 (5)</td>
<td>X_{\alpha1}</td>
<td>Te</td>
</tr>
<tr>
<td>31.05</td>
<td>20.9 (3)</td>
<td>X_{\gamma1}</td>
<td>Te</td>
</tr>
<tr>
<td>4.07</td>
<td>14.70 (28)</td>
<td>X_{\gamma}</td>
<td>Te</td>
</tr>
<tr>
<td>35.49</td>
<td>6.63 (6)</td>
<td>$\gamma$</td>
<td>$^{125}$Te</td>
</tr>
<tr>
<td>31.76</td>
<td>4.54 (13)</td>
<td>X_{\alpha2}</td>
<td>Te</td>
</tr>
</tbody>
</table>

**Table 2. The electron capture data of $^{125}$I to $^{125}$Te [18].**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\beta}$</td>
<td>0.8007</td>
</tr>
<tr>
<td>$w_{K}$</td>
<td>0.875</td>
</tr>
<tr>
<td>$P_{\gamma}$</td>
<td>0.066</td>
</tr>
<tr>
<td>$\alpha_{K}$</td>
<td>11.9</td>
</tr>
</tbody>
</table>

When a $^{125}$I source is placed in front of the two NaI (Tl) detectors, the X and gamma rays are not distinguishable due to the poor energy resolution of the detectors. The count rate of the photopeak in the $i^{th}$ ($i=1,2$) detector can be calculated by the equation (1):

$$N_{i} = N_{0}(1 - \epsilon_{i}^{(1)} - \epsilon_{i}^{(2)} + \epsilon_{i}^{(1)} \epsilon_{i}^{(2)})$$  

(1)

Where $N_{0}$ is the decay rate of the source and $\epsilon_{i}^{(j)}$ is the detection probability of the $j^{th}$ photon in the $i^{th}$ detector. Therefore, $(1-\epsilon_{i}^{(j)})$ represents the probability of not-detection for the $j^{th}$ photon in the $i^{th}$ detector. The count rate of the coincidence event ($N_{C}$) can be described by equation (2):

$$N_{C} = N_{0}(\epsilon_{1}^{(1)} \epsilon_{2}^{(2)} + \epsilon_{1}^{(2)} \epsilon_{2}^{(1)})$$  

(2)
If \( K_{i} \) is the probability per disintegration of detecting the photon in the \( i \)th detector, we have:

\[
N_C = N_0 (K_1 + K_2) \varepsilon_1 \varepsilon_2
\]  

(3)

For two similar detectors, \( K_1 = K_2 = K \), and \( K \) is defined by equation (4):

\[
K = \frac{(\alpha_k \omega + 1)P_\gamma}{P_\omega \omega_k}
\]  

(4)

By utilizing the parameters from Table 2 as outlined in [18], and combining equations 1 and 4, the decay rate of the source can be calculated by equation (5). Where \( N_C \) is represents the coincidence rate for X-rays of electron capture and X-gamma ray. Because the photons have low energy (~35 keV) in our scenario, corrections for Compton continuum and angular correlation are not necessary for X-\( \gamma \) ray coincidence counting.

\[
N_0 = \frac{2K}{(1 + K)^2} \frac{(N_1N_2 - N_E^2)^2}{N_C(N_1 - N_C)(N_2 - N_C)}
\]  

(5)

In the above analysis, the effects of background, double coincidence counting [19], chance coincidence, and dead time are not considered.

3. Experimental details

In experimental applications, photon-photon counting can be performed using two identical solid detectors such as HPGe or NaI(Tl) detectors. In this paper, we used an HPGe detector (Canberra 20200) to characterize the photopeak of the \(^{125}\)I source. Fig. 2 shows the gamma spectrum of \(^{125}\)I. The photopeak of \( K_\alpha \) X-ray (average energy 27 keV), \( K_\beta \) X-ray (average energy 31 keV), and the gamma line of 35 keV are marked on the spectrum.

Fig. 3 displays the setup for measuring activity using photon-photon coincidence. Two identical 2" × 2" NaI(Tl) detectors (ORTEC 905-3) with an energy resolution of 6.5% at the 662 keV gamma line of \(^{137}\)Cs were positioned facing each other, with a \(^{125}\)I seed placed along the common axis of the detectors. The source was fixed to the detectors to minimize angle detection errors. A coincidence counting system was established using a CAEN DT5724B digitizer that samples directly from the preamplifier output of the detectors. The optimum selection of digital signal processing methods was discussed in our previous paper [20]. The trigger hold-off parameter of the Pulse Height Analysis (PHA) algorithm was set to twice the coincidence time window to prevent double coincidence counting [19].
window, the inherent delay of 100 ns between the coincidence gamma line of $^{60}\text{Co}$ was compensated. The coincidence time window was set at three times the Full Width at Half Maximum (FWHM) of the timing spectrum to reduce the likelihood of chance coincidence counting.

The issue that arises during data acquisition in the coincidence mode is the recording of double coincidence events on the energy spectrum. Double coincidence occurs due to the large coincidence time window and high-level activity of the source. In the case of double coincidence, two events from one channel coincide with a single event from the other channel [19]. To avoid recording double coincidence events, the trigger hold-off parameter of the PHA algorithm was set to twice the coincidence time window. Fig. 4 shows the 2D energy spectrum of the $^{125}\text{I}$. The 2D spectrum confirms the rejection of double coincidence events and the one-to-one recording of photons. The photopeak-photopeak events in the circle region shown on the diagonal cut are nearly free from the background, Compton scattering, incomplete charge collection, and summing coincidence events.

### 4. Discussion on results

The NaI(Tl) detector cannot resolve the decay structure of $^{125}\text{I}$. The method for activity measurement was discussed in the theoretical part of this paper. Fig. 5 shows the measured spectrum of $^{125}\text{I}$ by NaI(Tl) detectors in single and coincidence modes. Table 3 lists the results of the experiments. The source activity was calculated using Equation 1. The peak area calculation for substitution in Equation 1 was done by the gamma vision software using the total summation technique [21]. The total activity of the seed was determined to be 84.3 kBq at the reference time 2023-25-10, 13:43 IRST. The value agrees within a 10% margin with the measurement carried out on 2021-21-12, 10:12 IRST using a curimeter. The uncertainty in the results originates from the peak area calculation, acquisition dead time, the uncertainty of the reported reference activity, the use of $K_1=K_2=K$ in equation 5, and muon cosmic radiations [22].

The standardized source can be used as a tracer for the activity measurement of $^{109}\text{Cd}$. In this method, the energy spectrum of $^{109}\text{Cd}$ and $^{125}\text{I}$ are measured simultaneously in single and coincidence modes [23].

*Fig. 4. The 2D energy spectrum of $^{125}\text{I}$.*

*Fig. 5. Energy spectra of the $^{125}\text{I}$ source were measured by the two 2” × 2” NaI [Tl] detectors in coincidence and single modes.*
Table 3. The results of the calculated activity for $^{125}\text{I}$ source by photon-photon coincidence counting method. The standard errors in data are also presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$: Reference activity (kBq)</td>
<td>7.66 ± 5.36</td>
</tr>
<tr>
<td>$N_1$</td>
<td>11488 ± 1.78</td>
</tr>
<tr>
<td>$N_2$</td>
<td>10377 ± 1.69</td>
</tr>
<tr>
<td>$N_c$</td>
<td>817.76 ± 0.22</td>
</tr>
<tr>
<td>Measurement time (s)</td>
<td>3600</td>
</tr>
<tr>
<td>K factor</td>
<td>1.07</td>
</tr>
<tr>
<td>A: Measured activity (kBq)</td>
<td>84.3 ± 2.53</td>
</tr>
<tr>
<td>$A/ A_0$</td>
<td>1.10</td>
</tr>
</tbody>
</table>

5. Conclusion

Primary methods of standardization play a crucial role in many fields, especially in nuclear medicine, where radioactive sources have a very short half-life. Typically, measuring radionuclide sources with dominant emission of photons below 50 keV is challenging due to intense fluorescence escaping from scintillation detectors. Photon-photon coincidence counting is a cost-effective technique for the primary standardization of electron capture radioisotopes emitting low-energy photons. In this study, an experimental setup including a simple digital spectrometer was developed for the activity standardization of $^{125}\text{I}$. With well-optimized parameters, the measured activity for $^{125}\text{I}$ showed good agreement with the results from a measurement with a calibrated curiemeter. Following this study, we plan to design a compact system for the automatic primary standardization of $^{125}\text{I}$ for practical applications in hospitals.

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work.

References


