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**Excitation functions of the $^{197}$Au($p$,pxn) and $^{197}$Au($p$,xn) reactions**

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Abstract: The cross-sections for the $^{197}$Au($p$,pxn)$^{196-193}$Au and $^{197}$Au($p$,xn)$^{197,195,193}$Hg reactions within the proton energy range of 49.8–66.5 MeV were measured at the high-intensity proton linac facility (KOMAC) in Korea using the stacked-foil activation and off-line γ-ray spectrometry technique. The proton beam intensity was determined based on the $^{65}$Cu($p$,x)$^{62}$Zn monitor reaction with the recommended data taken from the TENDL-2019 library, present work and existing literature were compared with the cross-section accessed from the IAEA database library. The data gathered in the present work are compared with the available data from the literature, which agreed well with each other. In this study, the $^{197}$Au($p$,p5n)$^{193}$Au reaction cross-section was measured for the first time. The data from the present work and existing literature were compared with the TALYS-1.9-based data taken from the TENDL-2019 library, which generally agreed well.

Keywords: $^{197}$Au($p$,pxn)$^{196-193}$Au and $^{197}$Au($p$,xn)$^{197,195,193}$Hg reactions; off-line γ-ray spectrometry; proton energy range from 49.8 to 66.8 MeV; stacked-foil activation; TENDL-2019 library.

1 Introduction

Gold is a mono-isotopic metal that has various medical applications in its inactive and active forms. Inactive gold in the form of salt is used as an effective medicine for treating and controlling some types of rheumatoid arthritis and related diseases [1]. It also helps relieve joint pain and stiffness, reduce swelling and bone damage, and reduce the risk of joint deformity and disability. The photon-, neutron-, and proton-induced reactions of $^{197}$Au were used as monitors for flux determination. The $^{197}$Au($n$,γ)$^{198}$Au reaction with low-energy neutrons and $^{197}$Au($γ$,xn)$^{195-193}$Au and $^{197}$Au($n$,2n)$^{196-193}$Au reactions with medium-to high-energy photons and neutrons are the monitoring reactions. Similarly, the $^{197}$Au($p$,xn)$^{196-193}$Au reactions were recommended as monitoring reactions within a wide range of proton energies, which are specified in the IAEA database library [2]. The radioactive isotopes produced from the $^{197}$Au($p$,pxn)$^{196-193}$Au and $^{197}$Au($p$,xn)$^{197,195,193}$Hg reactions have various medical uses. The radionuclide $^{195}$Au has a long half-life of 186.01 days [3, 4]; therefore, it is used for heart rate and blood pressure studies in rabbits, greyhounds, and pigs, as well as for diagnostic cardiac imaging (angiography of the heart) after intravenous injection [5, 6]. On the other hand, $^{197}$Hg has a shorter half-life of 23.8 h, which causes its higher specific activity and is thus used in therapeutic and diagnostic applications. The radionuclide $^{197m}$Hg in the form of chloromerodrin (C$_4$H$_9$ClHgO) is used for renal diagnosis in kidney imaging [7]. Therapeutic applications of $^{197m}$Hg are conceivable because of their suitable emission spectra comprising a multitude of X-rays, conversions, and auger electrons, as well as a few gamma emissions [2, 3].

The EXFOR [8, 9] compilation shows that the cross-sections for the $^{197}$Au($p$,pxn)$^{196-194}$Au reactions are available in the existing literature [10–15], but those for the $^{197}$Au($p$,4n)$^{193}$Au reaction are not available. For the $^{197}$Au($p$,xn)$^{197-193}$Hg reactions, the cross-sections are also available in the literature [12–24]. However, the formation cross-sections for reaction products from different references are mainly below 50 MeV, which differ significantly from one reference to the other. At higher proton energy, the formation cross-sections are primarily based on three references [11, 12, 16]. For a few reactions, the data are based on the work of Ditroi et al. [12], where some data have different trends than usual one. As an example, the $^{197}$Au($p$,pxn)$^{195}$Hg reaction cross sections do not follow the usual trend above the proton energy of 47 MeV. This means, above the proton energy of 47 MeV, no other literature data are available to cross-check each other. Thus, in this study, the $^{197}$Au($p$,pxn)$^{196-191}$Au and $^{197}$Au($p$,xn)$^{197,195,193}$Hg reaction
cross-sections within the proton energy range of 49.8–65.5 MeV were measured at the high-intensity proton linac facility (KOMAC) in Korea using off-line γ-ray spectrometric technique.

2 Experimental details

The present experiment was carried out using a 69-MeV proton beam from a 100-MeV proton linac in KOMAC, Gyeongju, Korea. The stacked-foil activation technique was used in the TR103 target room of the KOMAC facility [25, 26]. The stack contained 10 sets of Pb–Au foils with one Cu foil at the beginning and one in the middle of the stack. High-purity (>99.9%) 197Au, 208Pb, and 64Cu metal foils with a dimension of 1 × 1 cm and thickness of 100 μm were used as the targets in the stack. The 444Au and 444Pb foils were used as beam energy degraders, and the 238U, 238Pu, and 232Th source was used to determine the proton beam intensity. A total of 22 samples of 197Au, 208Pb, and 64Cu metal foils were prepared as stacks, which were placed in an aluminum sample holder for irradiation with a proton beam. The sample holder was fixed behind a collimator with a 0.9-cm diameter hole. The Al collimator was positioned at a distance of 1.7 m from the beam window (2.1 g/cm²) with a thickness of 0.5 mm, which consisted of Al and Be foils. A schematic diagram of the experimental setup is provided in Ref. [27].

The stacked foils were irradiated for 30 min with a proton energy of 69 MeV after beam alignment using a GaFChromic HD-V2 film. The proton linac was operated at a repetition rate of 2 Hz, pulse width of 100 μs, and average beam current of approximately 100 nA. The beam intensity remained stable and constant during the irradiation. The irradiated samples were placed behind the short-lived products to decay to avoid unnecessary dose problems. The irradiated Au and Cu foils were mounted on a Perspex sample holder for irradiation with a proton beam. The sample holder was fixed behind a collimator with a 0.9-cm diameter hole. The Al collimator was positioned at a distance of 1.7 m from the beam window (2.1 g/cm²) with a thickness of 0.5 mm, which consisted of Al and Be foils. A schematic diagram of the experimental setup is provided in Ref. [27].

The stacked foils were irradiated for 30 min with a proton energy of 69 MeV after beam alignment using a GaFChromic HD-V2 film. The proton linac was operated at a repetition rate of 2 Hz, pulse width of 100 μs, and average beam current of approximately 100 nA. The beam intensity remained stable and constant during the irradiation. The irradiated samples were placed behind the short-lived products to decay to avoid unnecessary dose problems. The irradiated Au and Cu foils were mounted on a Perspex sample holder for irradiation with a proton beam. The sample holder was fixed behind a collimator with a 0.9-cm diameter hole. The Al collimator was positioned at a distance of 1.7 m from the beam window (2.1 g/cm²) with a thickness of 0.5 mm, which consisted of Al and Be foils. A schematic diagram of the experimental setup is provided in Ref. [27].

The stacked foils were irradiated for 30 min with a proton energy of 69 MeV after beam alignment using a GaFChromic HD-V2 film. The proton linac was operated at a repetition rate of 2 Hz, pulse width of 100 μs, and average beam current of approximately 100 nA. The beam intensity remained stable and constant during the irradiation. The irradiated samples were placed behind the short-lived products to decay to avoid unnecessary dose problems. The irradiated Au and Cu foils were mounted on a Perspex sample holder for irradiation with a proton beam. The sample holder was fixed behind a collimator with a 0.9-cm diameter hole. The Al collimator was positioned at a distance of 1.7 m from the beam window (2.1 g/cm²) with a thickness of 0.5 mm, which consisted of Al and Be foils. A schematic diagram of the experimental setup is provided in Ref. [27].

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The stacked foils were irradiated for 30 min with a proton energy of 69 MeV after beam alignment using a GaFChromic HD-V2 film. The proton linac was operated at a repetition rate of 2 Hz, pulse width of 100 μs, and average beam current of approximately 100 nA. The beam intensity remained stable and constant during the irradiation. The irradiated samples were placed behind the short-lived products to decay to avoid unnecessary dose problems. The irradiated Au and Cu foils were mounted on a Perspex sample holder for irradiation with a proton beam. The sample holder was fixed behind a collimator with a 0.9-cm diameter hole. The Al collimator was positioned at a distance of 1.7 m from the beam window (2.1 g/cm²) with a thickness of 0.5 mm, which consisted of Al and Be foils. A schematic diagram of the experimental setup is provided in Ref. [27].

3 Data analysis

In this study, the cross-sections for the 197Au(p, xn)196,194,193Au and 197Au(p, xn)196,194,193Hg reactions have been measured. The proton beam energies for the individual foils were calculated from the SRIM code [29]. The nuclear spectroscopic data such as the half-lives, decay-modes, γ-ray energies and their intensities of the reaction products 196,195,194,193Au and 197,195,193Hg, as well as for the monitor reaction products 65,62Zn, were taken from Refs. [3, 4] and are listed in Table 1. The net detected photo-peak counts (Ni) for the γ-lines of the above-mentioned reaction products were obtained from their respective gross counts of the photo-peaks in the γ-ray spectra by subtracting the Compton background.

Natural copper foils undergo natCu(p, x)62,65Zn reactions. The natCu(p, x)62Zn reaction from natCu foils was used to determine the proton beam intensity. The photo-peak counts (Ni) for the 596.56-keV γ-line of 62Zn were integrated in Eq. (1) to estimate the proton flux (ϕ).

\[
ϕ = \frac{N_i (CL/LT) \lambda}{n \sigma_i I_p \epsilon_i (1 - e^{-LT}) e^{x_T} (1 - e^{-CL})},
\]

where \( n \) is the number of target atoms, and \( \sigma_i \) is the natCu(p, x)62Zn reaction cross-section, \( I_p \) is the intensity of the analyzed γ-ray, \( \epsilon_i \) is the detection efficiency of the γ-ray, and \( \lambda \) is the decay constant (=ln2/\( T_{1/2} \)).

The value of \( \sigma_i \) for the natCu(p, x)62Zn reaction was obtained from Ref. [2] and used in Eq. (1) to estimate the proton flux. The Cu foils in the beginning and middle of the stack had average proton energies of 66.78 ± 0.29 MeV and 58.31 ± 0.33 MeV, respectively. Moreover, the first and last Au-metal foils in the stack had average proton energies of 65.47 ± 0.47 MeV and 49.80 ± 0.60 MeV, respectively. During the calculations, the proton flux was assumed to be constant for all Au foils within the proton energy range of present work. For average proton energies of 66.8 MeV and 58.3 MeV of the Cu-foils, the respective recommended natCu(p,x)62Zn monitor reaction cross-sections are 7.4 ± 0.4 mb and 9.7 ± 0.5 mb [2], which are used in the flux calculation. The proton flux was assumed to be constant for all foils, which was confirmed by the proton flux in both the Cu foils. The flux of (4.889 ± 0.099) × 10¹³ protons cm⁻² s⁻¹ was estimated as an average value based on multiple measurements of the detected photo-peak counts of 596.56-keV γ-line of 62Zn in both the Cu foils.

The value of \( \phi \) estimated using Eq. (1) was used in Eq. (2), and the 197Au(p, xn)196,194,193Au and 197Au(p, xn)196,194,193Hg reaction cross-sections were obtained from the detected photo-peak counts (Ni) of the γ-lines of the reaction products of interest, as listed in Table 1.

\[
\sigma_i = \frac{N_i (CL/LT) \lambda}{n \phi I_p \epsilon_i (1 - e^{-LT}) e^{x_T} (1 - e^{-CL})},
\]

Eq. (2) is a rearrangement of Eq. (1); thus, all the terms have the same meaning.
4 Results and discussion

In this study, the cumulative formation cross-sections of $^{196m}$Au, $^{197}$Au, and $^{195}$Au and independent formation cross-sections of $^{196m}$Au, $^{195}$Au, and $^{194}$Au from the $^{197}$Au(p,pxn) reactions were measured and reported in Table 2. Similarly, the independent formation cross-sections of $^{197m}$Hg, $^{195m}$Hg, $^{195}$Hg, and $^{193}$Hg in the $^{197}$Au(p,pxn) reactions were measured and reported in Table 2. The uncertainties in the measured values were based on the statistical uncertainty of repeated measurements. The overall uncertainty is the quadratic sum of statistical and systematic errors. The random error in the observed activity is primarily due to counting statistics and is estimated to be 3–9%. This can be determined by accumulating data over an optimum period that depends on the half-life of the nuclide of interest. The systematic errors occur owing to uncertainties in the irradiation time (~0.1 %), proton flux (~5.2 %), detection efficiency (~3 %), half-life of the reaction products and γ-ray intensities (~2 %). Thus, the total systematic error is approximately 6.3 %. The overall uncertainty is between 7 and 11 % from the combination of a statistical error of 3–9% and systematic error of approximately 6.3 %.

The formation cross-sections of the aforementioned products in the $^{197}$Au(p,pxn)$^{196-195}$Au and $^{197}$Au(p,xn)$^{197,195,195}$Hg reactions measured in this study, along with those reported in...
Table 2: Cross-sections for the production of $^{193,195}$Au and $^{193,195}$Hg measured in the $^{197}$Au(p,xn) and $^{197}$Au(p,xn) reactions within the proton energies of 49.8–65.5 MeV.

<table>
<thead>
<tr>
<th>Proton energy (MeV)</th>
<th>$^{196m2}$Au Production cross-section (mb) of $^{193,195}$Au and $^{193,195}$Hg in the $^{197}$Au(p,x) reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{196m2}$Au Ind$^d$</td>
</tr>
<tr>
<td>49.80 ± 0.60</td>
<td>8.52 ± 0.69</td>
</tr>
<tr>
<td>51.62 ± 0.57</td>
<td>8.33 ± 0.60</td>
</tr>
<tr>
<td>53.42 ± 0.57</td>
<td>8.90 ± 0.49</td>
</tr>
<tr>
<td>55.18 ± 0.54</td>
<td>8.82 ± 0.52</td>
</tr>
<tr>
<td>56.85 ± 0.52</td>
<td>8.62 ± 0.49</td>
</tr>
<tr>
<td>59.16 ± 0.52</td>
<td>8.43 ± 0.74</td>
</tr>
<tr>
<td>60.77 ± 0.50</td>
<td>8.49 ± 0.42</td>
</tr>
<tr>
<td>62.34 ± 0.50</td>
<td>8.26 ± 0.49</td>
</tr>
<tr>
<td>63.92 ± 0.50</td>
<td>8.05 ± 0.35</td>
</tr>
<tr>
<td>65.47 ± 0.47</td>
<td>7.89 ± 0.43</td>
</tr>
</tbody>
</table>

$^d$Direct (Ind.) indicates subtraction of the $^{195m}$Hg decay contribution for the production cross-section of $^{195,197m}$Co in the $^{197}$Au(p,x) $^{195,197}$Au reaction.

$^f$Cumulative (Cum.) indicates inclusion of $^{195,197m}$Hg decay contribution besides the production of $^{195,197m}$Co in the $^{197}$Au(p,x) $^{195,197}$Au reaction.

the literature, are plotted as a function of proton energy in Figures 1–10. For comparison, the calculated cross-section values based on the TALYS 1.9 code [31, 32] available in the TENDL-2019 library [30] for the respective reactions are also plotted in Figures 1–10.

Figure 1: Independent production cross-sections of $^{196m2}$Au in the $^{197}$Au(p, pn) reaction and comparison with the literature data and the data from TENDL-2019 library [30].

Figure 2: Cumulative production cross-sections of $^{196m1-g}$Au in the $^{197}$Au(p, pn) reaction and comparison with the literature data and the data from TENDL-2019 library [30].

4.1 $^{197}$Au(p, pn)$^{196m2}$Au and $^{197}$Au(p, pn)$^{196m1-g}$Au reaction cross-sections

As reported in Table 1, radionuclide $^{196}$Au has two isomeric states and one ground state. The first isomeric state, $^{196m1}$Au, has a half-life of 8.1s and decays to the g-state with an
Figure 3: Cumulative production cross-sections of $^{195}$Au in the $^{197}$Au(p,p2n) reaction and comparison with the literature data and the data from TENDL-2019 library [30].

Figure 4: Independent production cross-sections of $^{195}$Au in the $^{197}$Au(p,p2n) reaction and comparison with the literature data and the data from TENDL-2019 library [30].

Figure 5: Independent production cross-sections of $^{194}$Au in the $^{197}$Au(p,p3n) reaction and comparison with the literature data and the data from TENDL-2019 library [30].

Figure 6: Cumulative production cross-sections of $^{197}$Au in the $^{197}$Au(p,p4n) reaction and comparison with the literature data and the data from TENDL-2019 library [30].

Figure 7: Independent production cross-sections of $^{197m}$Hg in the $^{197}$Au(p,n) reaction and comparison with the literature data and the data from TENDL-2019 library.

Figure 8: Independent production cross-sections of $^{195m}$Hg in the $^{197}$Au(p,3n) reaction and comparison with the literature data and the data from TENDL-2019 library [30].
internal transition branching fraction of 100%. The second isomeric state, 196m2Au, has a half-life of 9.6 h and also decays to the g-state with an internal transition branching fraction of 100%. Thus, in this study, it is possible to measure the independent formation of 196m2Au and cumulative formation cross-section of 196(m1+g)Au. The 197Au(p, pn)196m2Au and 197Au(p, pn)196(m1+g)Au reaction cross-sections measured in this study, those reported in the literature [12], and calculated values reported in the TENDL-2019 library [30] are plotted as a function of proton energy in Figure 3, all of which agree with each other. The independent cross-sections of the 197Au(p, pn)195Au reaction reported in this study and existing literature [12], [11] were found to closely agree with the data presented in this study. The independent cross-section of the 197Au(p, pn)195Au reaction reported in this study and existing literature [12], [11] were found to closely agree with the data presented in this study.

### 4.2 197Au(p, p2n)195Au reaction cross-section

As shown in Table 1, radionuclide 195Au has one isomeric state with a half-life of 3.5 s, which decays to the g-state with an internal transition branching fraction of 100%. The g-state has a half-life of 186.1 d; thus, it is possible to measure the cumulative production cross-section of the 197Au(p, p2n)195Au reaction. Note that the cumulative formation cross-section of 195Au is obtained with respect to 195mAu as well as 195mHg and 195mHg. The cumulative production cross-sections of 197Au(p, p2n)195Au reaction were obtained from the detected photo-peak counts of low intensity with higher detector efficiency for 98.86-keV γ-line of 195gAu. The cumulative 197Au(p, p2n)195Au reaction cross-sections measured in this study, those reported in the literature [12], and calculated values reported in the TENDL-2019 library [30] are plotted as a function of proton energy in Figure 3, all of which agree with each other. The independent cross-sections of the 197Au(p, pn)195mHg and 197Au(p, pn)195mHg reactions measured in this study were subtracted from the cumulative cross-section of the 197Au(p, p2n)195Au reaction, and thus, independent cross-sections were obtained. The independent cross-sections of the 197Au(p, p2n)195Au reaction at different proton energies were reported by Kavanagh et al. [11] and were found to closely agree with the data presented in this study. The independent cross-section of the 197Au(p, p2n)195Au reaction reported in this study and existing literature [12],
along with the values stated in the TENDL-2019 library [30], are plotted in Figure 4. From Figure 4, it can be observed that the values reported in this study and existing literature [12] above a proton energy of 40 MeV are slightly lower; whereas, those reported for a proton energy less than 35 MeV are slightly higher than the values reported in the TENDL-2019 library [30].

4.3 $^{197}$Au(p,p3n)$^{194}$Au and $^{197}$Au(p,p4n)$^{193}$Au reaction cross-sections

As listed in Table 1, the radionuclide $^{194}$Au has two isomeric states and one ground state. The isomeric states m1 and m2 have half-lives of 420 ms and 600 ms, respectively, whereas the g-state has a half-life of 38.02 h. Both the isomeric states decay to the g-state via internal transitions with a branching fraction of 100 % for each. Thus, the $^{197}$Au(p,p3n)$^{194}$Au reaction cross-section can be considered independent because $^{194}$Hg is a stable nucleus. The $^{197}$Au(p,p3n)$^{194}$Au reaction cross-sections within a proton energy range of 49.8–65.5 MeV were measured from the detected photo-peak counts of the low intensity 293.55 keV and high intensity 328.74-keV γ-lines; the average values are reported in Table 2. The data reported in this study and existing literature [12–14], along with the values calculated based on the data reported in the TENDL-2019 library [30], are plotted as a function of proton energy in Figure 5. From Figure 5, it can be observed that the data reported in this study and existing literature [12–14] within a proton energy range of 45–65.5 MeV agree well; however, below a proton energy level of 45 MeV the measured values are lower than those reported in the TENDL-2019 library [30]. Moreover, the values reported in the literature [12–14] below a proton energy level of 40 MeV are higher than those reported in the TENDL-2019 library.

$^{193}$Au has one isomeric state (Table 1) with a half-life of 3.9 s, whereas the half-life of the g-state is 17.65 h. The m-state decays via an internal transition, with a branching fraction of 99.97 %. Besides this, $^{193}$Au is fed by both the precursors $^{195}$Hg and $^{195}$Hg, which have the half-lives of 11.8 and 3.8 h, respectively. The precursors were produced from the $^{197}$Au(p,3n)$^{195}$Hg and $^{197}$Au(p,3n)$^{195}$Hg reactions, respectively. Thus, the $^{197}$Au(p,p3n)$^{193}$Au reaction cross-section is the cumulative one, which was obtained from the detected photo-peaks counts of low intensity 137.52-keV, 186.7-keV, and 268.22-keV γ-lines. In Table 2, the average values based on the three γ-lines were given. The cumulative cross-sections of $^{197}$Au(p,p3n)$^{193}$Au reaction were measured for the first time and are compared, in Figure 6, with the values reported in the TENDL-2019 library [30]. From Figure 6, it can be observed that the values reported in this study are higher, and, particularly above 59 MeV, they are significantly higher than the values reported in the TENDL-2019 library. However, the trend of the data reported in this work as a function of proton energy was somewhat similar to that of the values reported in the TENDL-2019 library.

4.4 $^{197}$Au(p,n)$^{197m}$Hg reaction cross-section

From Table 1, it is evident that the radionuclide $^{197}$Hg has one isomeric state with a half-life of 23.8 h, whereas the ground state has a half-life of 64.1 h. The m-state decays to the g-state with an internal transition branching fraction of 91.4 % and electron capture of 8.6 %. The radionuclide $^{197}$Hg has an intense γ-line of 133.98 keV, whereas $^{197}$Hg has no intense γ-line. Thus, only the $^{197}$Au(p,n)$^{197m}$Hg reaction cross-sections have been measured using the detected photo-peak counts of the 133.98-keV γ-line. The data measured in this study, those reported in the literature [12–18], and those calculated based on the TENDL-2019 library [30] are plotted in Figure 7 as a function of proton energy. From Figure 7, it can be observed that the data reported in this study within a proton energy range of 49.8–65.5 MeV agree well with those reported by Szelecsényi et al. [14]. The data reported in this study and existing literature [12–18] above a proton energy level of 14 MeV are valued lower than the values reported in the TENDL-2019 library [30]. However, the data below a proton energy level of 14 MeV reported in the literature [12–18] agree with the values reported in the TENDL-2019 library [30].

4.5 $^{197}$Au(p,3n)$^{195m}$Hg and $^{197}$Au(p,3n)$^{195g}$Hg reaction cross-sections

Table 1 reports that the radionuclide $^{195}$Hg has one isomeric state with a half-life of 41.6 h, whereas the ground state has a half-life of 10.53 h. The m-state decays to the g-state by an internal transition with a branching fraction of 54.2 % and electron capture of 45.8 %. The radionuclide $^{195m}$Hg has an intense γ-line of 261.75 keV as well as a low intense γ-line of 560.27 keV. Thus, the $^{197}$Au(p,3n)$^{195m}$Hg reaction cross-sections were obtained from the detected photo-peak counts of both the γ-lines, and the average values are reported in Table 2. The radionuclide $^{195g}$Hg has only one low intensity γ-line of 779.8 keV. Despite this, the $^{197}$Au(p,3n)$^{195g}$Hg reaction cross-sections were obtained from the detected photo-peak counts of the weak intensity γ-line and are reported in Table 2. The data reported in this study and existing literature [12–14, 21] as well as the values based on the data reported in the TENDL-2019 library [30]
for the $^{197}$Au(p,3n)$^{195m}$Hg and $^{197}$Au(p,3n)$^{195g}$Hg reactions are plotted in Figures 8 and 9. From Figure 8, it can be seen that the $^{197}$Au(p, 3n)$^{195m}$Hg reaction cross-sections from the present work and most of the literature data [12-14, 21] agree with the reported values of TENDL-2019 library [30]. However, the values reported by Nagame et al. [21] within a proton energy range of 35–51 MeV were slightly lower than the values reported in the TENDL-2019 library [30]. On the other hand, it can be seen from Figure 9 that for the $^{197}$Au(p, 3n)$^{195g}$Hg reaction, the values reported in this study and existing literature [12, 13, 21] above a proton energy level of 23 MeV are higher than the values reported in the TENDL-2019 library [30]. Below a proton energy level of 23 MeV, the data reported in the literature [12, 13] are in agreement with those from the TENDL-2019 library. However, the data reported by Ditroi et al. [12] within a proton energy range of 47–57 MeV are unusually higher than the present data and the values reported in the TENDL-2019 library [30].

### 4.6 $^{197}$Au(p,5n)$^{193m}$Hg reaction cross-section

Table 1 reports that the radionuclide $^{193}$Hg has one isomeric state with a half-life of 11.8 h, whereas the ground state has a half-life of 3.8 h. The m-state decays to the g-state via an internal transition with a branching fraction of 7.2 % and electron capture of 92.8 %. The radionuclide $^{193m}$Hg has intense γ-lines of 257.99 and 407.63 keV. Similarly, the radionuclide $^{193m}$Hg has intense γ-lines of 381.6 and 861.11 keV. Since the waiting time for the first counting is more than 30 h, it was not possible to obtain the $^{197}$Au(p,3n)$^{195m}$Hg reaction cross-sections. Therefore, only the $^{197}$Au(p, 3n)$^{195m}$Hg reaction cross-sections were obtained from the detected photo-peak counts of the above-mentioned γ-lines, and the average values are reported in Table 2. The data reported in this study and existing literature [12, 14], along with the calculated values reported in the TENDL-2019 library [30], are plotted in Figure 10. As shown in Figure 10, the $^{197}$Au(p, 3n)$^{195m}$Hg reaction cross-sections reported in this study and existing literature [12, 14] above a proton energy level of 50 MeV are higher than the corresponding values reported in the TENDL-2019 library. Below a proton energy level of 50 MeV, the data reported in the literature [12, 14] closely agree with the values reported in the TENDL-2019 library.

In addition, from Figures 1–10 it can be observed that the cross-section values increase sharply from their threshold values to a particular proton energy. Thereafter, they decrease or remain nearly constant owing to the opening of other reaction channels, underlining the role of excitation energy.

### 5 Conclusions

The cross-sections of the $^{197}$Au(p,xn)$^{196-193}$Au and $^{197}$Au(p,xn)$^{197,195,193}$Hg reactions within the proton energy range of 49.8–65.5 MeV have been measured using the stacked-foil activation and off-line γ-ray spectrometric techniques. To the best of our knowledge, the $^{197}$Au(p,p5-n)$^{195}$Au reaction cross-section was measured for the first time. The data collected during this study are compared with the data from existing literature; which agree for most of the reactions where data are available. The data collected in this study and existing literature were compared with the calculated values obtained from the TENDL-2019 library and found to be in agreement in some of the cases. In other cases, they were slightly higher or lower than the values reported in the TENDL-2019 library. However, the trends of data measured in this study and the existing literature are similar to those obtained from the TENDL-2019 library. All cross-sections first increased sharply from their threshold to a particular proton energy. Thereafter, they decrease or remain nearly constant owing to the opening of other reaction channels, underlining the role of excitation energy.

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### Author contributions

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### Conflict of interest statement

The authors declare no conflicts of interest regarding this article.

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