Activation cross sections of proton-induced reactions on natural platinum up to 30 MeV

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Abstract

Activation cross sections of proton-induced reactions on natural platinum were measured. The stacked-foil activation technique and high-resolution gamma-ray spectrometry were used. The production cross sections of $^{198, 196, 196m2, 195, 194, 193, 192, 191}$Au, ^{191}Pt, and $^{192, 190}$Ir were determined up to 30 MeV. The experimental results were compared with previous experimental data and theoretical calculations in the TENDL-2019 library.

Keyword

Gold-198; Proton irradiation; Platinum target; Cross section; Excitation function

1. Introduction

Gold-198 has two long-lived states, the ground state ^{198g}Au ($T_{1/2}$ = 2.6941 d) and the metastable state ^{198m}Au ($T_{1/2}$ = 2.272 d) that decays to the ground state by the isomeric transition (IT: 100%). The radionuclide ^{198g}Au is a beta emitter (β^-: 100%, $<E_{\beta^-}>$ = 312.5 keV) and is widely used for therapy in nuclear medicine, such as brachytherapy (Fernandes et al., 2003; Horiuchi et al., 1991; Karvat et al., 2001; Konishi et al., 2021) and nanoparticles (Black et al., 2014; Chakravarty et al., 2019; Chanda et al., 2010).

The large-scale production route of ^{198g}Au is the neutron capture reaction on monoisotopic element ^{197}Au in nuclear reactors. The route, however, can produce only the low specific activity of

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^{198g}Au because of difficult chemical separation from the ^{197}Au target. The high specific activity ^{198g}Au can be produced using cyclotrons with proton- and deuteron-induced reactions on natural and enriched platinum targets.

In this paper, we focused on the proton-induced reactions on ^{nat}Pt targets (^{190}Pt: 0.012%, ^{192}Pt: 0.782%, ^{194}Pt: 32.864%, ^{195}Pt: 33.775%, ^{196}Pt: 25.211%, and ^{198}Pt: 7.356%) (Meija et al., 2016). Four previous experimental studies (Showaimy et al., 2019; Smith et al., 2017; Tárkányi et al., 2004a, 2004b) for isotope production by proton-induced reactions on platinum were found in our literature survey. The previous experimental cross section data have large uncertainties and show discrepancies among them. More reliable and accurate data are required. Therefore, we measured the excitation functions of the proton-induced reaction on ^{nat}Pt up to 30 MeV, with a particular focus on the ^{198g}Au production. Activation cross sections of several co-produced radioisotopes were also determined. The results were compared with the experimental data published earlier (Showaimy et al., 2019; Tárkányi et al., 2004a, 2004b) and the TENDL-2019 data based on a calculation using the theoretical model code TALYS (Koning et al., 2019).

2. Experimental method

The experiment was performed at the AVF cyclotron of the RIKEN RI Beam Factory. The stacked foil activation technique and high-resolution gamma-ray spectrometry were used.

The target for the experiment consisted of pure metallic foils of ^{nat}Pt (20-μm thick, 99.95% purity, 100×100 mm size), and ^{nat}Ti (5-μm thick, 99.6% purity, 50×100 mm size), which were purchased from Nilaco Corp., Japan. The ^{nat}Ti foils were used for the ^{nat}Ti(p,x)^{48}V monitor reaction to assess the beam parameters and the target thicknesses. The target thicknesses were derived using measured sizes and weights of the foils. The derived thicknesses of the ^{nat}Pt and ^{nat}Ti foils were 39.2, and 2.24 mg/cm^2, respectively. The foils were then cut into a size of 10×10 mm to fit a target holder served as a Faraday cup. Twenty-five sets of Pt-Pt-Ti-Ti foils were stacked in the target holder.

The stacked target was irradiated for 30 min with a 30.1±0.1 MeV proton beam. The primary beam energy was measured by the time-of-flight method (Watanabe et al., 2014). The energy degradation in the stacked target was calculated using the SRIM code (Ziegler et al., 2010). The average beam intensity measured by the Faraday cup was 101 nA.

The gamma-ray spectra of each irradiated foil were measured without chemical separation by a high-resolution HPGe detector (ORTEC GEM-25185-P). The gamma-ray spectra were analyzed by the dedicated software (SEIKO EG&G Gamma Studio). The detector was calibrated by a multiple gamma-ray emitting point source consisting of ^{57,60}Co, ^{85}Sr, ^{88}Y, ^{109}Cd, ^{113}Sn ^{137}Cs, ^{139}Ce, ^{203}Hg, and ^{241}Am (Eckert & Ziegler Isotope Products). Every second foil of the same element pairs was measured to compensate for the recoil losses of the products. Each foil was measured four times in 2 h - 70 days

to follow the decay of the produced radioisotopes with different half-lives. The distance between the detector and the foils was arranged to keep the dead time less than 4.7%.

The nuclear reaction and decay data for the gamma-ray spectrometry were taken from NuDat 3.0 (National Nuclear Data Center, 2021), LiveChart (International Atomic Energy Agency, 2009), Lund/LBNL Nuclear Data Search (Chu et al., 1999), and QCalc (Sonzogni & Pritychenko, 2003). Reaction and decay data for the radionuclides of interest are listed in Table 1.

The self-absorption of low-energy gamma lines in the Pt foils was considered using the following equation (Alfassi et al., 2009)

$$A(E) = A_0(E)\frac{\rho[\mu(E)/\rho]d}{1-\exp\left[-\rho(\mu(E)/\rho)d\right]} \quad (1)$$

where $A_0(E)$ is the measured activity for the gamma line at the energy E, $A(E)$ is the corrected activity, d is the thickness of the Pt foil, ρ is the density of the foil, $\mu(E)/\rho$ is the mass attenuation coefficient for the gamma line at the energy. The mass attenuation coefficient was taken from the online database (Hubbel & Seltzer, 2004).

Cross sections of the ^{nat}Ti(p,x)^{48}V monitor reaction were derived to assess the beam parameters and target thicknesses. The gamma line at 983.5 keV (I_γ = 99.98%) from the decay of ^{48}V ($T_{1/2}$ = 15.9735 d) in each second Ti foil was measured. The dead time during the measurements was kept at less than 0.3% after a cooling time of 2 days. The possible contribution from ^{48}Sc ($T_{1/2}$ = 43.67 h) in the spectra was negligible because production cross sections of ^{48}Sc are tiny in this energy region and the 1037.52-keV gamma line from ^{48}Sc was not found in the spectra. The derived cross sections were compared with the IAEA recommended values (Hermanne et al., 2018; Tárkányi et al., 2007) as shown in Fig. 1. Our result is consistent with the recommended values published in 2007. The measured thicknesses and beam parameters were used without any correction to derive production cross sections.

3. Result and discussion

The activation cross sections of $^{198, 196, 196m2, 195, 194, 193, 192, 191}$Au, ^{191}Pt, and $^{192, 190}$Ir were determined for the proton-induced reactions on ^{nat}Pt up to 30 MeV. The numerical data of the measured cross sections are listed in Tables 2 and 3. The results are displayed in Figs. 2-12 together with the previous experimental studies (Showaimy et al., 2019; Tárkányi et al., 2004a, 2004b) and the TENDL-2019 data (Koning et al., 2019). The TENDL-2019 data shown in each figure were normalized to the natural isotopic ratio and appropriately summed up for independent or cumulative elemental cross sections for comparison.

The median projectile energy at each foil is listed in Tables 2 and 3 with the total uncertainty and energy loss in parathesis. The total energy uncertainties of 0.1-0.7 MeV were propagated from the uncertainties of the primary beam energy (±0.1 MeV) and target thickness (1%). The estimated energy loss in the ^{nat}Pt foils was 0.2-0.6 MeV. The total uncertainty of the cross sections was estimated to be

7.2-29.9%. It was derived from the square root of the quadratic summation of each component; beam intensity (5%), gamma-line intensity (<17%), detector efficiency (5%), target thickness (1%), target purity (1%), and counting statistics (0.3-28.7%).

3.1 The ^{198g}Au production

The cross sections of the ^{nat}Pt(p,x)^{198g}Au reaction were derived by measuring the gamma line at 411.80205 keV (I_γ = 95.62%) from the decay of ^{198g}Au after a cooling time of 13 days. In addition to the direct production, ^{198g}Au ($T_{1/2}$ = 2.6941 d) could be formed through the decay of a co-produced metastable state ^{198m}Au ($T_{1/2}$ = 2.272 d, IT: 100%). The possible contribution through ^{198m}Au was negligibly small because intense gamma lines of ^{198m}Au could not be found in the spectra. The cross sections were obtained from the net counts of the photopeak area.

The derived cross sections are shown in Fig. 2 and compared with the previous studies (Showaimy et al., 2019; Tárkányi, et al., 2004a) and the TENDL-2019 data (Koning et al., 2019). The literature data normalized to enriched ^{198}Pt targets (Tárkányi et al., 2004a) were re-normalized to natural targets. The present cross-section data show a smooth curve and are consistent with previous experimental data within the uncertainty except for the scattered data of Tárkányi et al. (2004a) at 17-23 MeV. The TENDL-2019 data show the same trend as the experimental excitation function while they slightly underestimate the peak position.

3.2 The ^{196g}Au production

The cross sections for ^{196g}Au production were derived by measuring the 355.73-keV gamma line (I_γ = 87%) from the decay of ^{196g}Au ($T_{1/2}$ = 6.1669 d). The measurements of the gamma line were performed after an average cooling time of 13 days. Two metastable states with shorter half-lives ($T_{1/2}$ = 8.1 s and 9.6 h, IT: 100%) decayed to ^{196g}Au during the cooling time. The contributions of the same gamma line from ^{196g}Ir ($T_{1/2}$ = 52 s, β^-: 100%), and ^{196m}Ir ($T_{1/2}$ = 1.4 h, β^-: 100%) could be neglected because of their shorter half-lives.

The cumulative cross sections of $^{196(g+m1+m2)}$Au are shown in Fig. 3 together with the previous experimental data (Showaimy et al., 2019; Tárkányi, et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). The data by Tárkányi et al. (2004b) are slightly lower than ours between 17 and 24 MeV while larger above 26 MeV. The experimental data of Showaimy et al. (2019) are in partial agreement with our data. The peak positions of the TENDL-2019 values slightly shifted to the lower energy region although the amplitudes are consistent with the experimental data.

3.3 The ^{196m2}Au production

The excitation function of the ^{nat}Pt(p,x)^{196m2}Au reaction was derived from measurements of the gamma line at 147.81 keV (I_γ = 43.5%) from the ^{196m2}Au decay ($T_{1/2}$ = 9.6 h). The measurements were

performed after a cooling time of 21 h. The interference of the 147.49-keV gamma line (I_γ = 0.77%) from ^{191}Au ($T_{1/2}$ = 3.18 h) was negligibly small because the more intense gamma line at 586.44 keV (I_γ = 15.0%) of ^{191}Au disappeared in the used spectra.

The cross sections are shown in Fig. 4 together with the previous experimental data (Showaimy et al., 2019; Tárkányi, et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). Our result measured in the energy range between 19 and 30 MeV is consistent with the data of Tárkányi et al. (2004b) within the uncertainty. The data of Showaimy et al. (2019) are not overlapped with ours but are consistent with the other experimental result. The TENDL-2019 data overestimate the experimental cross sections.

3.4 The ^{195g}Au production

The cross sections for the ^{195g}Au production were derived using spectra measured after an average cooling time of 69 days. The metastable state ^{195m}Au with a short half-life ($T_{1/2}$ = 30.5 s, IT: 100%) decayed to the ground state ^{195g}Au ($T_{1/2}$ = 186.01 d) soon after the end of the bombardment. The 98.857-keV gamma line (I_γ = 11.21%) from the decay of ^{195g}Au was used to derive the cross sections. The possible contribution to the same gamma line from ^{195m}Pt ($T_{1/2}$ = 4.01 d, IT: 100%) was negligible after the long cooling time. The self-absorption of the low-energy gamma line was calculated using equation (1) and the correction factor was estimated as 1.11. The measured activities were corrected by multiplying the factor.

The cumulative cross sections of $^{195(g+m)}$Au using the corrected activities are shown in Fig. 5 together with the previous experimental data (Showaimy et al., 2019; Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). Both previous experimental data of Showaimy et al. (2019) and Tárkányi et al. (2004b) are in partial agreement with our data. The TENDL-2019 values show a trend and amplitude similar to the experimental excitation functions while its peak energy seems slightly higher.

3.5 The ^{194g}Au production

The cross sections of the ^{nat}Pt(p,x)^{194g}Au reaction were derived using spectra measured after a cooling time of 21 h. Two co-produced short-lived metastable states ($T_{1/2}$ = 600 and 420 ms, IT: 100%) decayed to the ground state ^{194g}Au ($T_{1/2}$ = 38.02 h) soon after the irradiation. Intense gamma lines at 328.47 keV (I_γ = 62.8%) and 293.549 keV (I_γ = 10.9%) from the decay of ^{194g}Au were interfered with those from decays of the ground state ($T_{1/2}$ = 19.28 h) and an excited state of ^{194}Ir ($T_{1/2}$ = 171 d). The interference-free gamma line at 1468.904 keV (I_γ = 6.8%) was instead selected. The gamma line also included the contribution from ^{194g}Ir (I_γ = 0.186%), which was confirmed to be negligible based on decay curve analysis. The cumulative cross sections were obtained from the net counts of the photopeak area.

The cumulative cross sections of $^{194(g+m1+m2)}$Au are shown in Fig. 6 and compared with the previous studies (Showaimy et al., 2019; Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). Our result is in good agreement with both previous experimental data below 16 MeV. The data of Tárkányi et al. (2004b) is slightly larger than ours above 27 MeV. The TENDL-2019 values agree well with the experimental data.

3.6 The ^{193g}Au production

Measurements of the 255.57-keV gamma line (I_γ = 6.5%) after a cooling time longer than 21 h were used to derive the production cross sections of ^{193g}Au ($T_{1/2}$ = 17.65 h). The metastable state ^{193m}Au ($T_{1/2}$ = 3.9 s, IT: 99.97%) decayed during the irradiation. The more intense gamma line at 186.17 keV (I_γ = 9.7%) was unselected to avoid the interference of the 186.68-keV gamma line from the ground state ($T_{1/2}$ = 11.78 d, I_γ = 50%) and an excited state of ^{190}Ir ($T_{1/2}$ = 3.087 h, I_γ = 64.37%).

The cumulative cross sections of $^{193(g+m)}$Au are shown in Fig. 7 in comparison with the previous experimental data (Showaimy et al., 2019; Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). The present data are in good agreement with the previous data of Showaimy et al. (2019) and Tárkányi et al. (2004b). The TENDL-2019 data overestimate the experimental cross sections.

3.7 The ^{192g}Au production

The cross sections of the ^{nat}Pt(p,x)^{192g}Au reaction were derived from the measurements of the 316.50618-keV gamma line (I_γ = 59%) emitted with the ^{192g}Au decay ($T_{1/2}$ = 4.94 h) after cooling time of 2 h. Two metastable states ($T_{1/2}$ = 29 and 160 ms, IT: 100%) decayed during the irradiation. The contribution to the same gamma line (I_γ = 82.86%) from ^{192g}Ir ($T_{1/2}$ = 73.829 d) was neglected because of the long half-life and small cross sections (see section 3.10). The contribution of the gamma line at 316.19 keV (I_γ = 3.0%) from ^{196m2}Au ($T_{1/2}$ = 9.6 h) was estimated using another intense gamma line at 147.81 keV (I_γ = 43.5%) and found to be negligibly small.

The cumulative cross sections of $^{192(g+m1+m2)}$Au are shown in Fig. 8 in comparison with the previous experimental data (Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). The data reported by Tárkányi et al. (2004b) are consistent with ours except for a few data at 22-24 MeV. The TENDL-2019 data are roughly consistent with experimental results.

3.8 The ^{191g}Au production

Measurements of the 586.44-keV gamma line (I_γ = 15%) after a cooling time of 2 hours were used to derive the production cross sections of ^{191g}Au ($T_{1/2}$ = 3.18 h). The metastable state ^{191m}Au ($T_{1/2}$ = 0.92 s, IT: 100%) decayed during the irradiation.

The cumulative cross sections of $^{191(g+m)}$Au are shown in Fig. 9 in comparison with the previous experimental data (Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). Our result

is consistent with the data of Tárkányi et al. (2004b) within the uncertainty. The TENDL-2019 data are larger than experimental data above 29 MeV.

3.9 The ^{191}Pt production

The production cross sections of ^{191}Pt ($T_{1/2}$ = 2.83 d) were derived from the gamma line at 538.87 keV (I_γ = 14.3%). We used the gamma spectra recorded after a cooling time of 13 days. Its parent radionuclide ^{191}Au ($T_{1/2}$ = 3.18 h) decayed to ^{191}Pt completely during the cooling time. The derived cumulative cross sections of ^{191}Pt and ^{191}Au were, however, smaller than the independent cross sections of ^{191}Au. This inconsistency was caused by large uncertainties of gamma-ray intensities (12% for ^{191}Au and 17% for ^{191}Pt) and net-count statistics (4-30%).

The cumulative cross sections are shown in Fig. 10 together with the previous experimental data (Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). The present data are consistent with the data of Tárkányi et al. (2004b) within the uncertainty. The TENDL-2019 data are roughly consistent with experimental results and overestimate above 26 MeV.

3.10 The ^{192g}Ir production

The cross sections of the ^{nat}Pt(p,x)^{192g}Ir reaction were derived from the measurements of the 316.50618-keV gamma line (I_γ = 82.86%) emitted with the ^{192g}Ir decay ($T_{1/2}$ = 73.829 d) after an average cooling time of 69 days. The short-lived metastable state ^{192m}Ir ($T_{1/2}$ = 1.45 m, IT: 99.98%) decayed to ^{192g}Ir soon after the end of the bombardment. The second metastable state has a very long half-life ($T_{1/2}$ = 241 y, IT: 100%) and its decay less contributed to spectra. The contribution of ^{192g}Au ($T_{1/2}$ = 4.94 h) to the same gamma line was negligible because it completely decayed during the cooling time.

The cumulative cross sections of $^{192(g+m1)}$Ir are shown in Fig. 11 in comparison with the previous experimental data (Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). The present cross-section data show a smooth curve and are consistent with the data reported by Tárkányi et al. (2004b). The TENDL-2019 values have a different shape from the experimental ones in the 21-29 MeV energy region.

3.11 The ^{190g}Ir production

The cross sections for ^{190g}Ir production were derived by measuring the 186.68-keV gamma line (I_γ = 50%) from the decay ($T_{1/2}$ = 11.78 d). The measurements were performed after an average cooling time of 13 days. Two metastable states with shorter half-lives ($T_{1/2}$ = 1.12 h, IT: 100% and $T_{1/2}$ =3.087 h, IT: 8.6%) decayed to ^{190g}Ir or ^{190}Os during the cooling time. The interference of the gamma lines at 186.17 keV (I_γ = 9.7%) from ^{193g}Au ($T_{1/2}$ = 17.65 h) and 188.27 keV (I_γ = 30.0%) from ^{196m2}Au ($T_{1/2}$ = 9.6 h) was negligible after the long cooling time.

The cumulative cross sections of $^{190(g+m1+0.086m2)}$Ir are shown in Fig. 12 together with the previous experimental data (Tárkányi et al., 2004b) and the TENDL-2019 data (Koning et al., 2019). The previous data are in good agreement with ours. The TENDL-2019 values overestimate the experimental data and show a different shape.

4. Conclusion

Activation cross sections of the proton-induced reactions on ^{nat}Pt were measured up to 30 MeV at the RIKEN AVF cyclotron. The stacked-foil activation technique and the high-resolution gamma-ray spectrometry were used for the cross-section measurements. The excitation functions for 11 radioisotopes $^{198, 196, 196m2, 195, 194, 193, 192, 191}$Au, ^{191}Pt, and $^{192, 190}$Ir were determined and compared with data published earlier and the TENDL-2019 library. Our measured excitation functions show smooth curves and are in acceptable agreement with the previous studies of Showaimy et al. (2019) and Tárkányi et al. (2004a, 2004b) within uncertainty. Our results can contribute to nuclear reaction databases required for optimization of the ^{198}Au production.

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Declarations of interest

None

References

Alfassi, Z. B., Persico, E., Groppi, F., & Bonardi, M. L. (2009). On the photon self-absorption correction for thin-target-yields vs. thick-target-yields in radionuclide production. Applied Radiation and Isotopes, 67, 240-242. https://doi.org/10.1016/j.apradiso.2008.10.004

Baglin, C. M. (2012). Nuclear Data Sheets for A = 192. Nuclear Data Sheets, 113, 1871–2111. https://doi.org/10.1016/J.NDS.2012.08.001

Black, K. C. L., Wang, Y., Luehmann, H. P., Cai, X., Xing, W., Pang, B., Zhao, Y., Cutler, C. S., Wang, L. V., Liu, Y., & Xia, Y. (2014). Radioactive ^{198}Au-doped nanostructures with different shapes for in vivo analyses of their biodistribution, tumor uptake, and intratumoral distribution. ACS Nano, 8, 4385–4394. https://doi.org/10.1021/nn406258m

Chakravarty, R., Chakraborty, S., Guleria, A., Kumar, C., Kunwar, A., Nair, K. V. V., Sarma, H. D., & Dash, A. (2019). Clinical scale synthesis of intrinsically radiolabeled and cyclic RGD peptide

functionalized ^{198}Au nanoparticles for targeted cancer therapy. Nuclear Medicine and Biology, 72, 1-10. https://doi.org/10.1016/j.nucmedbio.2019.05.005

Chanda, N., Kan, P., Watkinson, L. D., Shukla, R., Zambre, A., Carmack, T. L., Engelbrecht, H., Lever, J. R., Katti, K., Fent, G. M., Casteel, S. W., Smith, C. J., Miller, W. H., Jurisson, S., Boote, E., Robertson, J. D., Cutler, C., Dobrovolskaia, M., Kannan, R., & Katti, K. v. (2010). Radioactive gold nanoparticles in cancer therapy: therapeutic efficacy studies of GA-^{198}AuNP nanoconstruct in prostate tumor-bearing mice. Nanomedicine: Nanotechnology, Biology, and Medicine, 6, 201-209. https://doi.org/10.1016/j.nano.2009.11.001

Chen, J. (2022). Nuclear Data Sheets for A=48. Nuclear Data Sheets, 179, 1–382. https://doi.org/10.1016/J.NDS.2021.12.001

Chen, J., & Singh, B. (2021). Nuclear Data Sheets for A=194. Nuclear Data Sheets, 177, 1–508. https://doi.org/10.1016/J.NDS.2021.09.001

Chu, S. Y. F., Ekström, L. P., & Firestone, R. B. (1999). The LUND/LBNL nuclear data search (version 2.0) [WWW Document]. URL http://nucleardata.nuclear.lu.se/toi/

Fernandes, M. A. R., Andrade, A. L. de, Biazzono, L., Luvizotto, M. C. R., Santos, A. dos, & Correa, C. (2003). Gold (^{198}Au) foils brachytherapy use on canine skin tumor. Brazilian Journal of Veterinary Research and Animal Science, 40, 321-327. https://doi.org/10.1590/s1413-95962003000500002

Hermanne, A., Ignatyuk, A. v., Capote, R., Carlson, B. v., Engle, J. W., Kellett, M. A., Kibédi, T., Kim, G., Kondev, F. G., Hussain, M., Lebeda, O., Luca, A., Nagai, Y., Naik, H., Nichols, A. L., Nortier, F. M., Suryanarayana, S. v., Takács, S., Tárkányi, F. T., & Verpelli, M. (2018). Reference Cross Sections for Charged-particle Monitor Reactions. Nuclear Data Sheets, 148, 338-382. https://doi.org/10.1016/j.nds.2018.02.009

Horiuchi, J., Takeda, M., Shibuya, H., Matsumoto, S., Hoshina, M., & Suzuki, S. (1991). Usefulness of ^{198}Au grain implants in the treatment of oral and oropharyngeal cancer. Radiotherapy and Oncology, 21, 29-38. https://doi.org/10.1016/0167-8140(91)90338-H

Huang, X. (2007). Nuclear Data Sheets for A = 196. Nuclear Data Sheets, 108, 1093–1286. https://doi.org/10.1016/J.NDS.2007.05.001

Huang, X., & Kang, M. (2014). Nuclear Data Sheets for A = 195. Nuclear Data Sheets, 121, 395–560. https://doi.org/10.1016/J.NDS.2014.09.003

Huang, X., & Kang, M. (2016). Nuclear Data Sheets for A = 198. Nuclear Data Sheets, 133, 221-416. https://doi.org/10.1016/j.nds.2016.02.002

Hubbel, J. H., & Seltzer, S. M. (2004). Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients (version 1.4). [Online] National Institute of Standards and Technology, Gaithersburg, MD. https://dx.doi.org/10.18434/T4D01F

International Atomic Energy Agency. (2009). LiveChart of Nuclides [WWW Document]. URL https://www-nds.iaea.org/livechart/

Karvat, A., Duzenli, C., Ma, R., Paton, K., & Pickles, T. (2001). The treatment of choroidal melanoma with ^{198}Au plaque brachytherapy. Radiotherapy and Oncology, 59, 153-156. https://doi.org/10.1016/S0167-8140(00)00334-0

Koning, A. J., Rochman, D., Sublet, J. C., Dzysiuk, N., Fleming, M., & van der Marck, S. (2019). TENDL: Complete Nuclear Data Library for Innovative Nuclear Science and Technology. Nuclear Data Sheets, 155, 1-55. https://doi.org/10.1016/j.nds.2019.01.002

Konishi, M., Fujita, M., Takeuchi, Y., Kubo, K., Imano, N., Nishibuchi, I., Murakami, Y., Shimabukuro, K., Wongratwanich, P., Verdonschot, R. G., Kakimoto, N., & Nagata, Y. (2021). Treatment outcomes of real-time intraoral sonography-guided implantation technique of ^{198}Au grain brachytherapy for T1 and T2 tongue cancer. Journal of Radiation Research, 62, 871–876. https://doi.org/10.1093/jrr/rrab059

Meija, J., Coplen, T. B., Berglund, M., Brand, W. A., de Bièvre, P., Gröning, M., Holden, N. E., Irrgeher, J., Loss, R. D., Walczyk, T., & Prohaska, T. (2016). Atomic weights of the elements 2013 (IUPAC Technical Report). Pure and Applied Chemistry, 88, 265-291. https://doi.org/10.1515/pac-2015-0305

National Nuclear Data Center. (2021). Nuclear structure and decay data on-line library, Nudat 3.0 [WWW Document]. URL https://www.nndc.bnl.gov/nudat3/

Shamsuzzoha Basunia, M. (2017). Nuclear Data Sheets for A=193. Nuclear Data Sheets, 143, 1–381. https://doi.org/10.1016/J.NDS.2017.08.001

Showaimy, H., Solieman, A. H. M., Hamid, A. S. A., Khalaf, A. M., & Saleh, Z. A. (2019). Measurements of activation cross sections for proton induced reactions on natural platinum targets leading to the formation of gold radioisotopes. Radiation Physics and Chemistry, 157, 97-101. https://doi.org/10.1016/j.radphyschem.2018.12.024

Singh, B., & Chen, J. (2020). Nuclear Data Sheets for A=190. Nuclear Data Sheets, 169, 1–390. https://doi.org/10.1016/J.NDS.2020.10.001

Smith, S. V., McCutchan, E., Gürdal, G., Lister, C., Muench, L., Nino, M., Sonzogni, A., Herman, M., Nobre, G., Cullen, C., Chillery, T., Chowdury, P., & Harding, R. (2017). Production of platinum radioisotopes at Brookhaven Linac Isotope Producer (BLIP). EPJ Web of Conferences, 146, 09029. https://doi.org/10.1051/epjconf/201714609029

Sonzogni, A., & Pritychenko, B. (2003). Q-value Calculator (QCalc). NNDC, Brookhaven National Laboratory [WWW Document]. URL https://www.nndc.bnl.gov/qcalc /

Tárkányi, F., Ditrói, F., Takács, S., Csikai, J., Hermanne, A., Uddin, M. S., Hagiwara, M., Baba, M., Shubin, Y. N., & Dityuk, A. I. (2004b). Activation cross-sections of light ion induced nuclear reactions on platinum: Proton induced reactions. Nuclear Instruments and Methods in Physics

Research, Section B: Beam Interactions with Materials and Atoms, 226, 473-489. https://doi.org/10.1016/j.nimb.2004.06.042

Tárkányi, F., Hermanne, A., Takács, S., Shubin, Y. N., & Dityuk, A. I. (2004a). Cross sections for production of the therapeutic radioisotopes ^{198}Au and ^{199}Au in proton and deuteron induced reactions on ^{198}Pt. Radiochimica Acta, 92, 223-228. https://doi.org/10.1524/ract.92.4.223.35588

Tárkányi, F, Takács S, Gul K, Hermanne A, Mustafa M.G, Nortier M, Obložinský P, Qaim S.M, Scholten B, Shubin Y.N, and Youxiang Z. (2007). Charged particle cross-section database for medical radioisotope production (updated version). IAEA-TECDOC-1211 [WWW Document]. URL https://www-nds.iaea.org/medical/medical-old/monitor_reactions.html

Vanin, V. R., Maidana, N. L., Castro, R. M., Achterberg, E., Capurro, O. A., & Martí, G. v. (2007). Nuclear Data Sheets for A = 191. Nuclear Data Sheets, 108, 2393–2588. https://doi.org/10.1016/J.NDS.2007.10.002

Watanabe, T., Fujimaki, M., Fukunishi, N., Imao, H., Kamigaito, O., Kase, M., Komiyama, M., Sakamoto, N., Suda, K., Wakasugi, M., & Yamada, K. (2014). Beam energy and longitudinal beam profile measurement system at the RIBF. IPAC 2014: Proceedings of the 5th International Particle Accelerator Conference, 3566-3568. https://doi.org/10.18429/JACoW-IPAC2014-THPME136

Ziegler, J. F., Ziegler, M. D., & Biersack, J. P. (2010). SRIM - The stopping and range of ions in matter (2010). Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 268, 1818-1823. https://doi.org/10.1016/j.nimb.2010.02.091

Tables

Table 1. Reactions and decay data of reaction products.

Nuclide	Half-life	Decay mode (%)	E_γ (keV)	I_γ (%)	Reaction Products	Q-value (MeV)	References
^{198g}Au	2.6941 d	β^- (100)	**411.80205**	95.62(6)	^{198}Pt(p,n)^{198g}Au	-1.1	Huang & Kang (2016)
^{196g}Au	6.1669 d	β^- (7)	333.03	22.9(9)	^{198}Pt(p,3n)^{196g}Au	-15.7	Huang (2007)
		$\varepsilon+\beta^+$ (93)	**355.73**	87(3)	^{196}Pt(p,n)^{196g}Au	-2.3	Huang (2007)
					^{195}Pt(p,γ)^{196g}Au	5.6	
^{196m2}Au	9.6 h	IT (100)	**147.81**	43.5(15)	^{198}Pt(p,3n)^{196m2}Au	-16.3	
			188.27	30.0(15)	^{196}Pt(p,n)^{196m2}Au	-2.9	
					^{195}Pt(p,γ)^{196m2}Au	5.0	
^{195g}Au	186.01 d	ε (100)	**98.857**	11.21(15)	^{198}Pt(p,4n)^{195g}Au	-22.3	Huang & Kang (2014)
					^{196}Pt(p,2n)^{195g}Au	-8.9	
					^{195}Pt(p,n)^{195g}Au	-1.0	
					^{194}Pt(p,γ)^{195g}Au	5.1	
^{194g}Au	38.02 h	$\varepsilon+\beta^+$ (100)	293.549	10.9(3)	^{196}Pt(p,3n)^{194g}Au	-17.4	Chen & Singh (2021)
			328.470	62.8(16)	^{195}Pt(p,2n)^{194g}Au	-9.4	
			1468.904	6.8(20)	^{194}Pt(p,n)^{194g}Au	-3.3	
^{193g}Au	17.65 h	$\varepsilon+\beta^+$ (100)	112.515	2.2(3)	^{196}Pt(p,4n)^{193g}Au	-24.2	Shamsuzzoha Basunia (2017)
			173.52	2.8	^{195}Pt(p,3n)^{193g}Au	-16.3	
			186.17	9.7(11)	^{194}Pt(p,2n)^{193g}Au	-10.2	
			255.57	6.5(9)	^{192}Pt(p,γ)^{193g}Au	4.4	
			268.22	3.8(5)			
			439.04	1.85(23)			
^{192g}Au	4.94 h	$\varepsilon+\beta^+$ (100)	295.95650	23(3)	^{195}Pt(p,4n)^{192g}Au	-25.0	Baglin (2012)
			316.50618	59(7)	^{194}Pt(p,3n)^{192g}Au	-18.9	
					^{192}Pt(p,n)^{192g}Au	-4.3	
^{191g}Au	3.18 h	$\varepsilon+\beta^+$ (100)	**586.44**	15.0	^{194}Pt(p,4n)^{191g}Au	-26.0	Vanin et al. (2007)
					^{192}Pt(p,2n)^{191g}Au	-11.3	
					^{190}Pt(p,γ)^{191g}Au	3.8	
^{191}Pt	2.83 d	ε (100)	**538.87**	14.3(24)	^{196}Pt(p,t3n)^{191}Pt	-28.8	Vanin et al. (2007)
					^{195}Pt(p,t2n)^{191}Pt	-20.9	
					^{194}Pt(p,tn)^{191}Pt	-14.8	

					^{192}Pt(p,d)^{191}Pt	-6.4	
					^{191}Au decay		
^{192g}Ir	73.829 d	ε (4.76)	295.95650	28.71(7)	^{198}Pt(p,α3n)^{192g}Ir	-14.4	Baglin (2012)
		β^- (95.24)	308.45507	29.70(7)	^{196}Pt(p,αn)^{192g}Ir	-1.0	
			316.50618	82.86(3)	^{195}Pt(p,α)^{192g}Ir	6.9	
			468.06885	47.84(3)	^{194}Pt(p,^{3}He)^{192g}Ir	-7.6	
^{190g}Ir	11.78 d	ε+β^+ (100)	**186.68**	50(3)	^{196}Pt(p,α3n)^{190g}Ir	-15.2	Singh & Chen (2020)
			361.09	12.3(5)	^{195}Pt(p,α2n)^{190g}Ir	-7.3	
			371.24	21.6(7)	^{194}Pt(p,αn)^{190g}Ir	-1.2	
			407.22	22.7(13)	^{192}Pt(p,^{3}He)^{190g}Ir	-7.2	
			518.55	32.2(15)			
			557.95	28.5(13)			
			569.30	27.0(12)			
			605.14	37.8(18)			
^{48}V	15.9735 d	ε (100)	**983.525**	99.98	^{nat}Ti(p,x)^{48}V		Chen (2022)
			1312.105	98.2			

Table 2. Measured cross sections of $^{198, 196, 196m2, 195, 194}$Au in the ^{nat}Pt(p,x) reaction. The projectile energy is listed with total uncertainty and energy loss in parathesis.

E (MeV)	^{198g}Au	$^{196(g+m1+m2)}$Au	^{196m2}Au	$^{195(g+m)}$Au	$^{194(g+m1+m2)}$Au
29.6 ±0.1 (0.2)	1.69 ±0.17	52.1 ±4.2	7.31 ±0.94	84.9 ±6.3	292 ±26
28.8 ±0.1 (0.2)	1.62 ±0.16	63.6 ±5.1	7.36 ±0.92	81.2 ±6.0	330 ±29
28.1 ±0.1 (0.2)	1.74 ±0.17	70.3 ±5.6	7.92 ±0.97	68.7 ±5.1	349 ±30
27.3 ±0.1 (0.2)	1.84 ±0.18	84.4 ±6.8	9.55 ±1.12	66.0 ±4.9	365 ±32
26.5 ±0.1 (0.2)	1.84 ±0.19	90.6 ±7.3	9.00 ±1.05	60.7 ±4.5	379 ±33
25.8 ±0.1 (0.2)	2.05 ±0.20	101 ±8	8.58 ±1.02	61.4 ±4.6	379 ±33
24.9 ±0.1 (0.2)	1.77 ±0.18	94.1 ±7.5	7.83 ±1.06	61.5 ±4.6	348 ±30
24.1 ±0.1 (0.2)	1.71 ±0.18	92.1 ±7.4	6.20 ±0.89	70.8 ±5.3	348 ±30
23.3 ±0.1 (0.2)	1.74 ±0.18	90.6 ±7.2	6.38 ±0.98	92.1 ±6.8	344 ±30
22.4 ±0.1 (0.2)	2.07 ±0.20	88.0 ±7.0	5.85 ±1.08	125 ±9	349 ±30
21.5 ±0.2 (0.2)	2.08 ±0.20	79.8 ±6.4	3.39 ±0.71	163 ±12	361 ±31
20.6 ±0.2 (0.2)	2.10 ±0.20	64.3 ±5.1	2.55 ±0.38	202 ±15	328 ±29
19.6 ±0.2 (0.2)	2.04 ±0.19	49.0 ±3.9	2.08 ±0.34	245 ±18	336 ±29
18.7 ±0.2 (0.2)	2.17 ±0.20	32.1 ±2.6	1.19 ±0.28	273 ±20	355 ±31
17.6 ±0.2 (0.2)	2.19 ±0.20	16.5 ±1.3		254 ±19	347 ±30

16.6 ±0.2 (0.2)	2.16 ±0.20	10.9 ±0.9	245 ±18	366 ±32
15.5 ±0.2 (0.3)	2.21 ±0.20	11.2 ±0.9	209 ±15	307 ±27
14.3 ±0.3 (0.3)	2.45 ±0.22	14.9 ±1.2	181 ±13	269 ±24
13.0 ±0.3 (0.3)	2.96 ±0.25	21.3 ±1.7	147 ±11	221 ±20
11.7 ±0.3 (0.3)	4.05 ±0.33	31.3 ±2.5	108 ±8	156 ±15
10.3 ±0.4 (0.3)	4.30 ±0.35	28.9 ±2.3	56.2 ±4.2	64.3 ±7.6
8.7 ±0.4 (0.4)	2.71 ±0.23	11.7 ±0.9	16.0 ±1.2	15.7 ±3.1
6.9 ±0.5 (0.4)	0.490 ±0.043	1.51 ±0.12	1.87 ±0.18	2.05 ±0.53
4.8 ±0.7 (0.6)	0.0121 ±0.0020	0.0346 ±0.0045		

Table 3. Measured cross sections of $^{193, 192, 191}$Au, ^{191}Pt, and $^{192, 190}$Ir in the ^{nat}Pt(p,x) reaction. The projectile energy is listed with total uncertainty and energy loss in parathesis.

E (MeV)	**$^{193(g+m)}$Au**	**$^{192(g+m1+m2)}$Au**	**$^{191(g+m)}$Au**	**^{191}Pt(cum)**	**$^{192(g+m1)}$Ir**	**$^{190(g+m1+0.086m2)}$Ir**
29.6 ±0.1 (0.2)	347 ±55	517 ±72	20.1 ±2.2	19.9 ±3.7	1.40 ±0.12	1.51 ±0.16
28.8 ±0.1 (0.2)	380 ±60	515 ±72	10.3 ±1.6	9.93 ±1.92	1.44 ±0.12	1.43 ±0.15
28.1 ±0.1 (0.2)	367 ±58	466 ±65		4.87 ±1.02	1.34 ±0.11	1.14 ±0.13
27.3 ±0.1 (0.2)	393 ±62	463 ±64		3.72 ±0.82	1.47 ±0.12	1.13 ±0.13
26.5 ±0.1 (0.2)	391 ±62	432 ±60		4.53 ±0.97	1.35 ±0.11	0.897 ±0.116
25.8 ±0.1 (0.2)	391 ±62	420 ±58		4.79 ±1.01	1.29 ±0.11	0.795 ±0.109
24.9 ±0.1 (0.2)	382 ±60	347 ±48	5.70 ±1.43	5.04 ±1.07	1.12 ±0.10	0.497 ±0.091
24.1 ±0.1 (0.2)	383 ±60	298 ±41	6.94 ±1.75	6.48 ±1.32	1.05 ±0.09	0.400 ±0.084
23.3 ±0.1 (0.2)	403 ±63	237 ±33	8.79 ±1.67	8.28 ±1.64	1.05 ±0.09	0.368 ±0.087
22.4 ±0.1 (0.2)	433 ±68	165 ±23	6.86 ±1.64	9.47 ±1.86	1.00 ±0.09	0.227 ±0.068
21.5 ±0.2 (0.2)	446 ±70	81.8 ±11.4	9.25 ±1.65	9.18 ±1.80	0.971 ±0.085	
20.6 ±0.2 (0.2)	415 ±65	21.9 ±3.1	8.18 ±0.92	7.69 ±1.53	0.809 ±0.074	
19.6 ±0.2 (0.2)	351 ±55	2.26 ±0.37	8.15 ±0.90	7.94 ±1.58	0.702 ±0.066	
18.7 ±0.2 (0.2)	291 ±46	0.872 ±0.224	7.20 ±0.85	7.27 ±1.45	0.640 ±0.060	
17.6 ±0.2 (0.2)	256 ±41		7.43 ±0.93	6.40 ±1.30	0.442 ±0.047	
16.6 ±0.2 (0.2)	222 ±35		5.96 ±0.90	5.52 ±1.14	0.326 ±0.038	
15.5 ±0.2 (0.3)	183 ±29		4.88 ±0.89	3.63 ±0.80	0.176 ±0.023	
14.3 ±0.3 (0.3)	141 ±23		3.50 ±0.79	2.79 ±0.65	0.101 ±0.015	
13.0 ±0.3 (0.3)	73.7 ±12.3				0.0409 ±0.0116	
11.7 ±0.3 (0.3)	27.1 ±5.3					

Figure captions

Fig. 1. Excitation function of the $^{nat}Ti(p,x)^{48}V$ monitor reaction with the recommended values (Hermanne et al., 2018; Tárkányi et al., 2007).

Fig. 2. Excitation function of the $^{nat}Pt(p,x)^{198g}Au$ reaction.

Fig. 3. Excitation function of the $^{nat}Pt(p,x)^{196(g+m1+m2)}Au$ reaction.

Fig. 4. Excitation function of the $^{nat}Pt(p,x)^{196m2}Au$ reaction.

Fig. 5. Excitation function of the$^{nat}Pt(p,x)^{195(g+m)}Au$ reaction.

Fig. 6. Excitation function of the $^{nat}Pt(p,x)^{194(g+m1+m2)}Au$ reaction.

Fig. 7. Excitation function of the $^{nat}Pt(p,x)^{193(g+m)}Au$ reaction.

Fig. 8. Excitation function of the $^{nat}Pt(p,x)^{192(g+m1+m2)}Au$ reaction.

Fig. 9. Excitation function of the $^{nat}Pt(p,x)^{191(g+m)}Au$ reaction.

Fig. 10. Excitation function of the $^{nat}Pt(p,x)^{191}Pt(cum)$ reaction.

Fig. 11. Excitation function of the $^{nat}Pt(p,x)^{192(g+m1)}Ir$ reaction.

Fig. 12. Excitation function of the $^{nat}Pt(p,x)^{190(g+m1+0.086m2)}Ir$ reaction.