PHYSICAL REVIEW C VOLUME 56, NUMBER 4 OCTOBER 1997

Weak γ rays from the electron-capture decay of ^{194}Au

R. R. P. Teixeira, I. D. Goldman, and M. T. F. da Cruz
Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

E. Browne, I. Y. Lee, A. O. Macchiavelli, and E. B. Norman
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 26 December 1996)

We present γ-ray energies and intensities of 34 new weak transitions in the electron-capture decay of ^{194}Au. These γ rays were detected in singles experiments with high-purity Ge and anti-Compton detectors, and in γ-γ coincidence experiments, with the HERA array of Ge detectors. Their placements in the decay scheme confirm levels in ^{194}Pt at 1373.9 and 1737.3 keV observed in the electron-capture decay of ^{194}Au. [S0556-2813(97)02910-5]

PACS number(s): 23.20.Lv, 23.20.En, 27.80.+w

The electron-capture decay of ^{194}Au has been extensively studied, and the spectroscopic and nuclear data have been evaluated and published in the literature [1]. However, recently available large Ge detectors and high-efficiency Ge detector arrays have provided the opportunity for detecting weaker γ rays in singles and coincidence experiments, and thus, to verify and extend results from previous measurements. Although the experiments described in this paper produced a wealth of γ-ray data (167 transitions observed in singles, coincidence measurements, or angular correlation measurements), we present here the singles data for 34 γ rays that have not been previously reported in the electron-capture decay of ^{194}Au, and only the coincidence results that have significantly affected its decay scheme. These data have confirmed levels in ^{194}Pt at 1373.9 and 1737.3 keV, previously observed in other experiments [1], and established new placements in the decay scheme for the 59-, 224.0-, 304.9-, and 562.6-keV transitions. The complete list of γ rays measured in this work has been published elsewhere [2], and some of these results have been included in the most recent data evaluation of ^{194}Au [3].

We produced a source of ^{194}Au for measuring γ rays in a singles experiment by irradiating a foil of natural platinum with 10-MeV protons in the cyclotron of the Instituto de Pesquisas Energéticas e Nucleares (IPEN) at the University of São Paulo, Brazil. A beam energy of 10 MeV was chosen to optimize the production of ^{194}Au by the ^{194}Pt(p,n) reaction. The irradiation, with a beam current of 2 μA, lasted 1 h, and the γ-ray measurements started 25 h after the end of irradiation. We measured γ-ray singles with a 50-cm^3 Ortec high-purity Ge detector. The acquisition system consisted of conventional electronics (including a pileup rejection unit) coupled to a PDP-11/84 computer for storing the spectra on disk. Radioactive sources of ^{60}Co, ^{137}Cs, ^{133}Ba, ^{152}Eu, and ^{207}Bi were used for detector energy and efficiency calibrations. We also used an anti-Compton detection system to measure the γ-ray spectrum of ^{194}Au. This system consisted of a Ge detector surrounded by a NaI scintillator, and was calibrated in a similar fashion. To determine γ-ray energies with better precision, we simultaneously measured various ^{194}Au spectra with each calibrating standard.

We used a source of ^{194}Hg $(t_{1/2}=520\text{ yr.})$ with ^{194}Au in equilibrium for the γ-γ coincidence experiments. ^{194}Hg was produced through the ^{197}Au$(p,4n)$ reaction by bombarding a gold foil with 40-MeV protons from the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory (LBNL), Berkeley, California. The foil, which was irradiated for 24 h using a beam current of 1 μA, produced a ^{194}Hg source with an activity of 0.7 μCi. In order to reduce the background radiation caused by short-lived activities, the γ-ray measurements started 53 days after the end of irradiation, and lasted for about 4 days. The singles spectra contained γ rays from impurities, such as ^{195}Au, ^{195m}Pt, and ^{196}Au. The spectrum in coincidence with the 562.6-keV γ ray suggested the existence of some ^{194m}Ir impurity in the source, which may have been produced by the ^{197}Au$(p,3pn)$ reaction, or by neutron captures on a small impurity of ^{193}Ir contained in the target.

The (LBNL) High-Energy-Resolution-Array (HERA), used for γ-γ coincidences, consisted of an array of 20 high-purity Ge detectors, each surrounded by an anti-Compton shielding of bismuth germanate (BGO) and NaI, and was calibrated with sources of ^{207}Bi and ^{152}Eu. The event-by-event data accumulated on tape in this experiment was used to produce the coincidence matrices that were later analyzed in São Paulo, Brazil.

We measured γ rays from the electron-capture decay of ^{194}Au in singles over the energy range of 100–2500 keV, and accumulated several spectra for five days. A special procedure [4] was used to measure and analyze γ-ray spectra, which produced precise energies and intensities. Although the sum of these spectra contained 167 γ rays from ^{194}Au, we report in Table I only those that have not been seen before [1]. The intensities, given on an absolute scale (per 100 disintegrations of ^{194}Au), are based on a value of 60.4 (8)% for the 328.5-keV γ ray. We have deduced this intensity (as described in Ref. [1]) by using our measured intensity of the β^+ annihilation radiation and decay scheme considerations. A value of 60 (3)% given in Ref. [1] agrees well with our result. The γ rays reported in Table I decayed with a half-life consistent with that of ^{194}Au, and they were found to be in coincidence with well-known γ rays that were previously observed in the electron-capture decay of ^{194}Au.

Figure 1 shows the spectrum in coincidence with the

TABLE I. γ rays from the electron-capture decay of ^{194}Au, which have not been previously reported from the decay of this nuclide, are presented here. Numbers between parenthesis are the experimental uncertainties in the least significant digits.

E_γ (keV)	I_γ[a]	Placement E_i (keV)-E_f (keV)	Some prominent coincident γ rays[b] E_γ (keV)
212.11 (25)	0.005 (3)	2215.5-2003.7	1675.1
243.66 (17)[e,c]	0.009 (3)	2287.0-2043.7	1715.2, 2043.7
304.87 (7)	0.0182 (18)	1737.3-1432.5	224.0, 621.2, 810.6, 1104.1
338.88 (10)[d]	0.011 (3)	1961.3-1622.1	1000.2, 1293.9, 1622.1
363.10 (18)[d]	0.0059 (13)	1737.3-1373.9	224.0, 562.6
366.42 (3)	0.035 (4)	2163.7-1797.4	364.9, 1175.8, 1468.9, 1797.4
373.33 (14)	0.0067 (15)	2043.7-1670.6	1048.6, 1342.2
398.95 (11)	0.014 (4)	2215.5-1817.0	894.4, 1194.9, 1488.3
421.65 (5)	0.0304 (23)	2043.7-1622.1	1000.2, 1293.9, 1622.1
436.81 (8)	0.0134 (21)	2215.5-1778.6	1156.6, 1450.1
500.72 (19)	0.0070 (18)	2298.2-1797.4	1468.9
602.02 (9)	0.018 (8)	2114.0-1511.9	589.2, 1183.5
627.7 (6)[d]	0.0037 (10)	2298.2-1670.6	1048.6, 1342.2
699.20 (14)[c]	0.014 (3)	1622.1-922.7	300.8, 594.3, 675.2
807.06 (29)	0.020 (5)	2239.7-1432.5	202.8, 1104.1
814.89 (29)[d]	0.0073 (13)	1737.3-922.7	224.0, 300.8
857.59 (25)[c]	0.0075 (15)	1479.2-622.0	293.6, 318.1, 736.2
901.18 (7)	0.036 (3)	1229.5-328.5	202.8, 328.5
1080.63 (22)	0.012 (5)	2003.7-922.7	300.8
1121.3 (3)	0.04 (3)	2043.7-922.7	300.8, 594.3
1262.42 (9)	0.028 (3)	2185.2-922.7	300.8, 594.3
1346.7 (3)	0.009 (4)	2157.8-811.3	482.8
1388.74 (19)	0.016 (4)	2311.9-922.7	300.8, 594.3
1474.20 (13)	0.021 (3)	2397.5-922.7	300.8, 594.3
1488.3 (4)[d]	0.017 (4)	1817.0-328.5	328.5
1518.62 (5)	0.065 (4)	2140.8-622.0	293.6, 622.0
1535.51 (26)	0.0095 (17)	2157.8-622.0	293.6, 622.0
1541.64 (12)	0.0206 (22)	2163.7-622.0	293.6, 622.0
1565.28 (6)[c]	0.0519 (22)	1893.6-328.5	328.5
1665.42 (13)	0.027 (4)	2287.0-622.0	293.6, 622.0
1675.1 (5)[e,c]	0.06 (4)	2003.7-328.5	328.5
1775.82 (21)	0.020 (5)	2397.5-622.0	293.6, 622.0
1780.56 (18)[c]	0.033 (6)	2109.1-328.5	328.5
1812.21 (25)[c]	0.033 (7)	2140.8-328.5	328.5

[a] Intensities are absolute values per 100 disintegrations of ^{194}Au.

[b] Immediately preceding or following in the decay scheme the γ ray shown in column 1. γ-ray energies not shown in column 1 are from Ref. [2].

[c] Previously observed from ^{194m}Irβ^- decay [1].

[d] Observed in coincidence measurements only.

[e] Member of doublet.

224.0-keV γ ray. The γ rays observed at 304.9-, 363.1-, and 814.9-keV de-excite a 1737.3-keV level proposed in this paper, and the 562.6-keV γ ray has been placed between the 1373.9- and 811.3-keV levels. The spectrum in coincidence with the 562.6-keV γ ray, presented in Fig. 2, shows a possible doublet at about 365 keV. A peak-shape analysis of this doublet produced two components at 363.1 and 364.9 keV, implying the existence of a 59-keV transition between the 1432.5- and 1373.9-keV levels in coincidence with the 364.9-keV member of the doublet. L-conversion electrons from a 58.4-keV transition with intensities consistent with those from an $E2$ transition have been previously observed [5]. This result agrees with the present γ-γ coincidence measurements, and confirms our placement of a 59-keV transition in the decay scheme.

Column 4 of Table I shows information on coincident γ rays measured with HERA using a ^{194}Hg source with ^{194}Au in equilibrium. Those γ-ray energies that are shown in this column but not listed in column 1 may be found in Ref. [2]. These data provided invaluable information for correcting some previously misplaced γ-ray transitions and constructing a decay scheme.

Figure 3 shows a partial decay scheme, which includes only some of the new γ rays seen in this work. We have

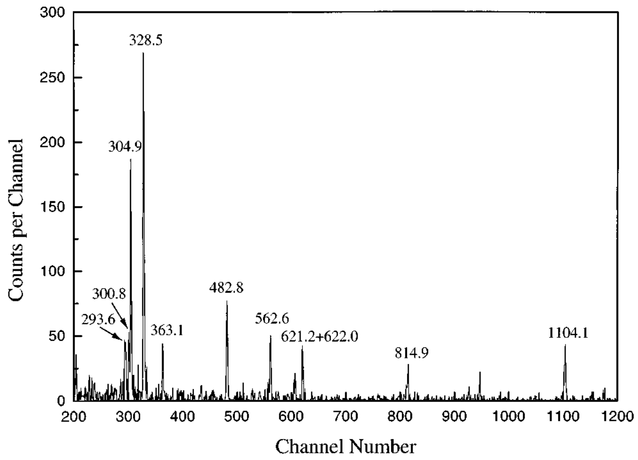

FIG. 1. γ-ray spectrum in coincidence with the 224.0-keV γ ray. Contributions to the spectrum from both higher-energy Compton tails contained in the gates and accidental coincidences have been removed.

deduced the level energies from a least-squares fit to γ-ray energies. Electron-capture feedings and log ft values are from a γ-ray transition intensity balance at each level, using multipolarities and mixing ratios from Ref. [3], and theoretical conversion coefficients from Ref. [6]. Most of the γ rays involved in the intensity balance have not been included in this paper; they are however given in Ref. [2].

Previous placements [1] of the 224.0-keV γ ray between the 2185.2- and 1961.3-keV levels, of the 562.6-keV γ ray between the 2185.2- and 1622.1-keV levels, and of the 304.9-keV γ ray between the 1817.0- and 1511.9-keV levels were not confirmed here.

The γ ray spectrum measured in coincidence with the 224.0-keV γ ray does not contain a 528.8-keV γ-ray line, which was thought before [1] to cascade through the 1961.3-keV level. Therefore, the 224.0-keV γ ray does not de-excite the previously suggested 2185.2-keV level.

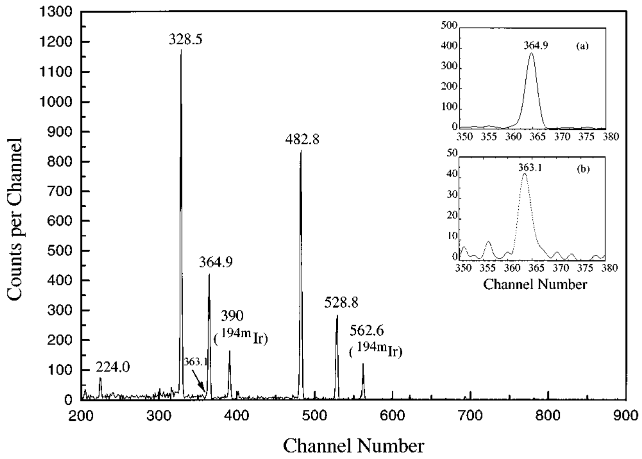

FIG. 2. γ-ray spectrum in coincidence with the 562.6-keV gamma ray. Contributions to the spectrum from both higher-energy Compton tails contained in the gates and accidental coincidences have been removed. The inset shows an expanded region around 365 keV: (a) Spectrum in coincidence with the 562.6-keV γ ray; (b) Spectrum in coincidence with the 224.0-keV γ ray (see Fig. 1). Notice the difference of about 2 keV between the 363.1- and 364.9-keV peaks.

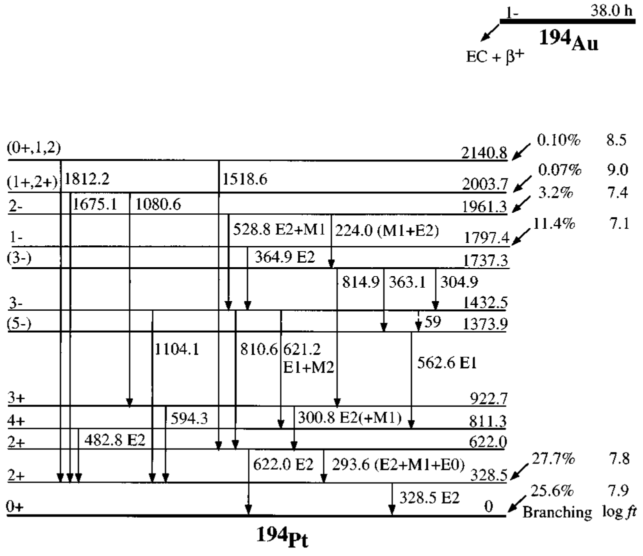

FIG. 3. ^{194}Au partial decay scheme. The decay scheme shows (except for the 810.6- and 594.3-keV γ rays) only γ ray transitions listed in Table I or presented in the coincidence spectra of Figs. 1 or 2. γ-ray multipolarities and level spin and parities (except those for the 1737.3-keV level) are from Ref. [1]. The 59-keV γ ray has been inferred in this work from coincidence measurements.

Our measurements show that the 562.6-keV γ ray is not in coincidence with either the 1000.2-, or the 1293.9- or the 1622.1-keV γ rays; consequently, it does not de-excite the 2185.2-keV level. We have confirmed, however, that the 1562.8- and 1856.8-keV γ rays observed before [1], as well as a weak 1262.4-keV γ ray seen here de-excite this level. Our placement of the 562.6-keV transition between the 1373.9- and 811.3-keV levels is based on its intensity in coincidence with the 482.8-keV γ ray. The 1373.9-keV level is populated by an $L=(5)$ transfer in the ^{194}Pt(p,p') reaction [7]. Therefore, it probably has a spin and parity of 5^-. This assignment is consistent with the $E1$ multipolarity of the 562.6-keV γ ray and with a spin and parity of 4^+ for the 811.3-keV level populated by this transition. The ground state of ^{194}Au has a spin and parity of 1^- [1]. It is therefore unlikely for the 1373.9-keV (5^-) level to be directly populated in the electron-capture decay of ^{194}Au. Thus, this level is populated through the 364.9–59 keV and 528.8–59 keV γ-ray cascades that originate at the 1797.4- (1^-) and 1961.3-keV (2^-) levels, respectively. The γ-ray spectrum in coincidence with the 562.6-keV γ ray showed a doublet near 365 keV. The 364.9-keV member of this doublet connects the 1797.4- (1^-) and 1432.5-keV (3^-) levels, and an unseen 59-keV $(E2)$ transition provides a path for populating the 1373.9-keV level. Additional population to the 1373.9-keV level comes from the 363.1-keV member of the doublet.

The intensity (photons+conversion electrons) of the 59-keV transition is about 63 times smaller [3,5] than that of the 1104.1-keV γ ray, that is, a de-excitation branching of about 1% from the 1432.5-keV level. The 304.9- is three times as intense as the 363.1-keV γ ray that also de-excites the 1737.3-keV level. However, because of the small branching just mentioned from the 1432.5- to the 1373.9-keV level, the

304.9-keV γ ray was not seen in coincidence with the 562.6-keV γ ray. In addition, the 304.9- and 363.1-keV γ rays were not seen in coincidence with each other. This result suggests that they are not in cascade, thus consistent with both de-exciting our proposed level at 1737.3-keV. The 304.9- and 363.1-keV γ rays were seen in coincidence with a 224.0-keV ($M1+E2$) [1] γ ray, which connects the 1961.3-(2^-) and 1737.3-keV levels. This result is consistent with a spin and parity of 3^- for the latter. The 814.9-, 300.8-, 293.6-, and 622.0-keV γ rays were also seen in the same spectrum, which suggests a placement of the 814.9-keV transition between the 1737.3- and 922.7-keV levels.

The 390- and 562.6-keV γ rays observed in coincidence with the 562.6-keV γ ray are from the β^- decay of an ^{194m}Ir ($t_{1/2}=171$ day) impurity. These γ rays belong to a cascade that originates at the 2438-keV ($8^+,9^+,10^+$) level and decays to the ground state through the 1373.9-keV level. Two γ rays with the same energy of 562.6 keV are members of the 2047-1485-1373.9-811.3 keV cascade from the β^- decay of ^{194m}Ir ($t_{1/2}=171$ day). This fact explains the presence of a 562.6-keV peak in the spectrum in coincidence with the 562.6-keV γ ray. Notice, however, that most of the intensity of the 482.8-keV γ ray, also seen in this coincidence spectrum, comes from the electron-capture decay of ^{194}Au. A strong 338-keV γ ray also de-excites the 2438-keV level through a cascade of 687-, 600-, 482.8-, and 328.5-keV γ rays. These γ rays (not shown in Table I because they are not from the electron-capture decay of ^{194}Au) were seen in coincidence with the 338-keV γ ray, which confirms the presence of the ^{194m}Ir ($t_{1/2}=171$ day) impurity in the source.

A level at 2003.7 keV, previously observed in the ^{193}Ir(^{3}He,d) [8] and ^{194}Pt($n,n'\gamma$) [9] reactions, is de-excited by a 1675.0-keV γ ray. This γ ray has been observed here in singles and coincidence experiments, which confirms its placement in the decay scheme. A 1080.6-keV γ ray de-excites the same level. This γ ray is the weaker member of a doublet, which has been previously seen [1], and was also detected here in singles and in coincidence with the 300.8-keV γ ray. Coincident γ rays of 1518.6- and 1812.2 keV defined a level at 2140.8 keV, which was previously known to be populated in ^{194m}Ir β^- decay [1].

The γ ray spectra measured in this work have provided data for 34 weak transitions that had not been seen before, and useful information for correcting previously misplaced transitions in the decay scheme. These data have confirmed levels at 1373.9- and 1737.3 keV, observed in the electron-capture decay of ^{194}Au.

This work was supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), São Paulo, Brazil, and by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

---

[1] B. Singh, Nucl. Data Sheets **56**, 75 (1989).
[2] R. R. Plaza Teixeira, Ph.D. thesis, University of São Paulo, Brazil, 1996.
[3] E. Browne and B. Singh, Nucl. Data Sheets **79**, 277 (1996).
[4] V. R. Vanin, G. Kenchian, M. Moralles, O. Helene, and P. R. Pascholati, Nucl. Instrum. Methods Phys. Res. A **391**, 338 (1997); G. Kenchian, Ph.D. thesis, University of São Paulo, Brazil, 1995.
[5] I. N. Vishnevskii, V. I. Gavrilyuk, V. T. Kupryashkin, G. D. Latyshev, I. N. Lyutyi, Y. V. Makovetskii, and A. I. Feoktistov, Izv. Akad. Nauk SSSR, Ser. Fiz. **35**, 2213 (1971); Bull. Acad. Sci. USSR, Phys. Ser. **35**, 2009 (1972).
[6] R. S. Hager and E. C. Seltzer, Nucl. Data, Sect. A **4**, 1 (1968).
[7] P. D. Cottle, V. Hnizdo, R. J. Philpott, K. A. Stuckey, K. W. Kemper, and J. A. Carr, Phys. Rev. C **38**, 1619 (1988).
[8] N. Blasi, R. Bijker, M. N. Harakeh, Y. Iwasaki, W. A. Sterrenburg, S. Y. Van Der Werf, and M. Vergnes, Nucl. Phys. **A388**, 77 (1982).
[9] A. J. Filo, S. W. Yates, D. F. Coope, J. L. Weil, and M. T. McEllistrem, Phys. Rev. C **23**, 1938 (1981).