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NEUTRON ACTIVATION DETERMINATION OF GOLD IN IRON METEORITES AND INCLUSIONS *

T. A. LINN Jr. ** and C. B. MOORE

Department of Chemistry and Center for Meteorite Studies, Arizona State University, Tempe, Arizona, USA

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The concentrations of gold in 19 iron meteorites have been determined via instrumental neutron activation analysis. The upper limits of gold concentrations in 10 sulfide nodules and in one phosphide inclusion were also established. Gold concentrations range from 0.2 ppm to just over 2 ppm in the metal. The sulfide nodules and phosphide inclusions show limiting concentrations of about 0.1 ppm gold.

1. INTRODUCTION

The first determinations of gold in meteorites by activation analysis were carried out by Goldberg and Brown [1]. Investigations by others [2-4] have resulted in the accumulation of considerable data for the abundance of gold in iron meteorites. A recent value of 0.10 ppm Au in troilite has been reported by Baedecker and Ehmann [5].

2. EXPERIMENTAL

Samples of meteoritic iron were taken by dry-milling metal chips ($\sim$ 8 mesh) from the freshly cut edge of meteorite specimens. Considerable care was exercised to avoid all visible macro inclusions. Drillings ($\sim$ 80–100 mesh) of the sulfide and phosphide inclusions were taken with a tungsten-carbide drill. Successive splits of each sample were made until duplicate samples of about 100 mg each resulted. These were sealed into polyethylene vials. Gold standards (0.50 and 0.05 μg Au, some as $Au(NO_3)_3$ in dilute HNO_3, and others in solution with 500 μg Fe as $Fe(NO_3)_3 \cdot 6H_2O$) were irradiated with the samples for three hours at a thermal-neutron flux of $\sim 1.2 \times 10^{12}$ n/cm^2-sec. After irradiation, the samples and standards were allowed 24 hours' cooling for the decay of short-lived radioactivities. They were then counted daily over a period of three to six days.

Gamma-ray spectra were taken from a 3 $\times$ 3-in. NaI(Tl) scintillation detector coupled to a 400-channel pulse-height analyzer system. Prominent photopeaks in the spectra were attributed to gamma-rays from ^{56}Mn, ^{64}Cu, ^{59}Fe, and ^{60}Co, in addition to the ^{198}Au. (A typical gamma-ray spectrum is shown in fig. 1.)

Gold activities were determined by measuring the area beneath the 0.412-MeV gamma-ray photopeak and correcting for the Compton contribution from other activities in the samples. Identification of gold was made by decay measurements on the 0.412-MeV gamma-ray photopeak. (Decay curves for typical samples and standard are illustrated in fig. 2.)

Specific activities of the gold standards indicated relatively insignificant (less than 1%) self-shielding effects in the standards. Assuming that the ratio of thermal to epithermal neutrons in the sample irradiation position is similar to that in a TRIGA reactor, it

* (Contribution No. 29 from the Center for Meteorite Studies.)

** Present address: Department of Chemistry, Oregon State University, Corvallis, Oregon.

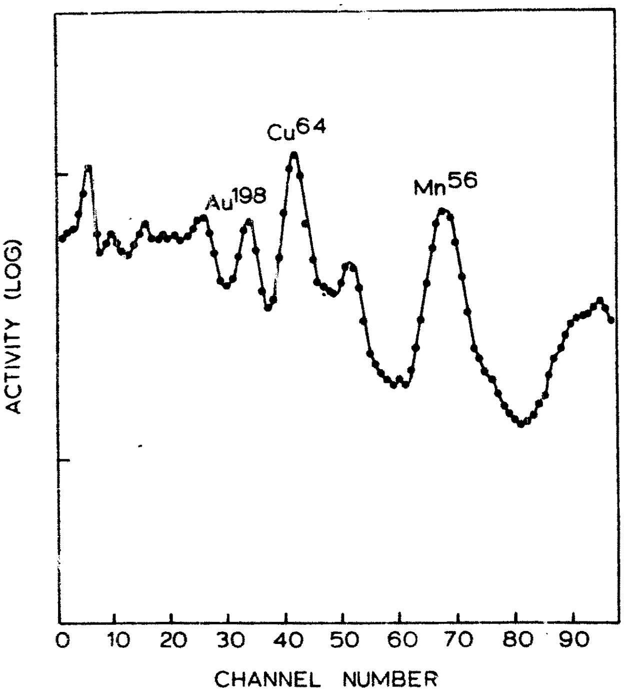

Fig. 1. Gamma-ray spectrum of typical metal sample.

was calculated that ^{198}Au production is about 60% by thermal flux and 40% by resonance flux [6]. It was also calculated that an error of less than 1% would result if all the gold (e.g., 1 μg Au) were concentrated in a single mass within the sample [7]. Therefore, errors arising from the large resonance capture cross section of ^{197}Au, the state of aggregation of the gold, and the nature of the matrix were estimated to be small compared with the combined operational errors related to instrumental fluctuations, statistics derived from counting, geometry, weighings, dilutions, etc.

The spacial flux variations during irradiation were monitored by six flux monitors for each irradiation. Corrections based on the specific activities of these monitors were applied to the related samples and varied from zero to about 9% (relative correction). The precision of replicate determinations reflects variations after the corrections were applied.

3. DISCUSSION

The gold concentrations measured are shown in tables 1 and 2 for the iron meteorites and their inclu-

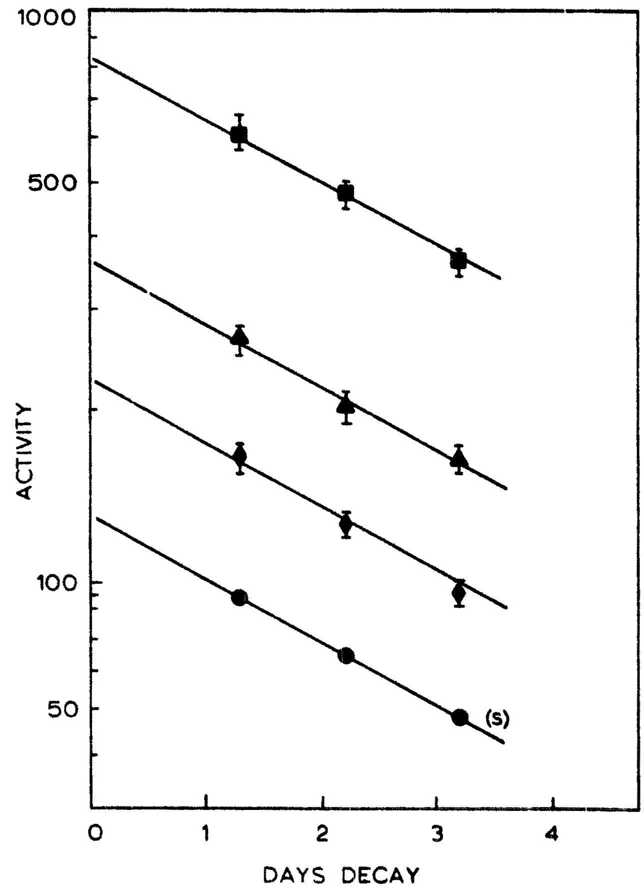

Fig. 2. Decay curves for typical metal samples and standard – (s). (Activity based on the 0.412-MeV gamma-ray photopeak.)

sions, respectively. The errors were estimated from the standard deviation of the individual counting rates. Additional errors from operational sources were estimated to be no more than a few percent (relative). Concentration limits for gold in the inclusions were based on the total counting rate in channels where the 0.412-MeV gamma-ray photopeak normally appeared. The overall precision of the method (including variations due to sample inhomogeneity) is reflected by the data for replicate analyses of Bella Roca (table 3).

A comparison of the gold concentrations measured with some data from the literature is shown in table 4. Except for the measurement by Cobb [2], some concentrations measured are somewhat lower than the data in the literature (for six of the meteorites studied). No gold abundance data were available in the literature for the other meteorites studied. The discrepancies may have arisen from differences between meteorite

Table 1
Gold concentrations in nickel-iron.
(Average values from duplicate determinations.)

No.	Meteorite	Structural class	Ga–Ge * group	% Ni **	% Co **	Au (ppm)
1	Hex River Mountains	H	II	5.69	0.35	0.32 ± 0.05
2	Scottsville	H	II	5.50	0.36	0.1 ± 0.1
3	Ainsworth	Ogg	II	5.57	0.40	0.83 ± 0.07
4	Osseo	Ogg	I	6.68	0.35	0.93 ± 0.06
5	Ponca Creek	Ogg	II	6.71	0.48	0.89 ± 0.06
6	Camp Verde	Og	I	7.25	0.49	1.17 ± 0.05
7	Mt. Stirling	Og	A	7.04	0.46	1.22 ± 0.05
8	Youndegin	Og	I	6.94	0.38	1.14 ± 0.07
9	Bendego	Og	II	6.64	0.39	0.53 ± 0.04
10	Goose Lake	Om-Og	II	8.27	0.39	1.14 ± 0.03
11	Carbo	Om	A	10.28	0.58	0.31 ± 0.06
12	Joe Wright Mountain	Om	(III) †	9.21	0.49	1.18 ± 0.06
13	Cleveland	Om	III	8.90	0.51	1.10 ± 0.05
14	Bella Roca	Of	III	9.95	0.54	2.02 ± 0.08
15	Cambria	Of	A	10.34	0.48	1.70 ± 0.05
16	Bear Creek	Of	III	9.64	0.52	1.63 ± 0.07
17	Duchesne	Of	IV	9.58	0.36	1.90 ± 0.07
18	Brenham	P	III	10.35	0.49	2.12 ± 0.06
19	Dayton	D	IV	17.75	0.45	1.45 ± 0.08

* After Wasson [9, 10]; A = anomalous.
** % Ni and % Co from unpublished data: C. F. Lewis and T. A. Linn Jr.
† Based on structural classification only [9].

Table 2
Gold concentrations in sulfide nodules and phosphide inclusions.

No.	Meteorite	Structural class	Ga–Ge * group	Au (ppm)
1	Hex River Mountains	H	II	< 0.11
2	Scottsville	H	II	< 0.09
3	Ainsworth	Ogg	II	< 0.02
4	Osseo	Ogg	I	< 0.07
5	Ponca Creek	Ogg	II	< 0.08
6	Camp Verde	Og	I	< 0.04
7	Mt. Stirling	Og	A	< 0.02
8	Youndegin	Og	I	< 0.04
14	Bella Roca	Of	III	0.08 ± 0.06
18	Brenham	P	III	< 0.07
18	Brenham (schreibersite)	P	III	< 0.07

* After Wasson [9. 10]; A = anomalous.

Table 3
Replicate analyses of splits of Bella Roca metal.

Sample weight	Au (ppm)
0.2010	1.96
0.2101	1.80
0.1917	2.31
0.1053	1.97
0.0544	1.90
0.0510	1.91
0.0308	2.03
0.0180	2.04
0.0104	2.00
0.0097	2.23
Mean:	2.02
Range:	0.51
± (95% C. L.)	2.02 ± 0.08
Precision (relative %)	∿4

Table 4
Comparison of Au measured in iron meteorites with literature data (data from individual samples).

No.	Meteorite	Structural class	Au (ppm) found	Au (ppm) from literature
8	Youndegin	Og	1.13 ± 0.05 1.16 ± 0.05	1.61 [3]
9	Bendego	Og	0.52 ± 0.02 0.54 ± 0.03	0.87 [3]
10	Goose Lake	Om-Og	1.13 ± 0.03 1.14 ± 0.03	1.83 [4]
15	Cambria	Of	1.64 ± 0.03 1.75 ± 0.03	1.92 [3]
16	Bear Creek	Of	1.63 ± 0.05 1.63 ± 0.05	2.54 [4]
18	Brenham	P	2.09 ± 0.03 2.15 ± 0.03	2.0 [2]

specimens, differences in sampling methods, differences in sample location within the meteorite, or inhomogeneous distribution of gold in the meteorite. Cobb [2] also noted his gold values were about 30% lower than those of Goldberg and Brown [1]. In addition to the above noted differences in sampling, he points out that "the discrepancy may be due to poor statistics in the peak-to-background ratio or to an overestimation of the background correction". Literature data were not available for comparison with the concentration limits for gold in the sulfide and phosphide inclusions.

The gold concentrations measured show gold to be siderophilic by concentration ratios of 60 : 1 or more. The positive correlation of gold concentrations in relation to nickel and to cobalt, noted previously by Goldberg, Uchiyama and Brown [4], was not pronounced in the data shown in table 1.

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