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# The Determination of Major and Trace Elements in Iron Meteorites by Neutron Activation Analysis

By

**Masako SHIMA**

Department of Physical Sciences, National Science Museum, Tokyo.

## I. Introduction

When we obtain a new meteorite, first of all it is necessary to analyze the mean elemental composition, not only major elements but also trace elements if it is possible. Of course, it is better that data are accurate enough to use further cosmochemical discussion.

Because number of meteorite falls are limited, and it is often observed that some classes contain only a small meteorite, it is also desireble to use as small a sample for analyses as possible.

In Fig. 1, the part of periodic table of the elements is shown. In iron meteorites, except for the upper 5 elements and Mn, Tc, Tl, Pb and Bi which are generally known to be present at less than the ppb level or none, all of the other elements in this table should be analyzed. These are so-called siderophile elements and part of calcophile elements.

Among these elements, major elements, Fe, Ni, and Co and trace element, Cu, showing in shaded cases, could be analyzing accurately by any methods such as titration, atomic absorption, inductively coupled plasma quantometry and so on. The concentration or the distribution of Cr in iron meteorites is very variable, $<1$ to $\sim 100$ ppm (Shima and Honda, 1966a and b). Higher content of Cr could be analyzed by atomic absorption spectroscopy or plasma quantometry (Shima *et al.*, 1978). The case of Cr was, therefore made a half shade. Phosphorus could be analyzed colorimetrically or plasmaquantometrically. In these methods, however, $\sim 1$ g each of sample is necessary for accurate quantitative analysis.

For the above purpose, thermal neutron activation analysis should be the best candidate, because all of these elements could be analyzed by using only less than 0.2 g sample without any complicated chemical procedure. The methods have been developed for a single or several elements in iron meteroites by several workers (Baedecker and Ehmann, 1965; Crocket, 1972; Hamaguchi *et al.*, 1961; Kiesl *et al.*, 1967; Kimberlin *et al.*, 1968; Wasson and Kimberlin 1966). No work, however, has been carried out for covering all of these elements.

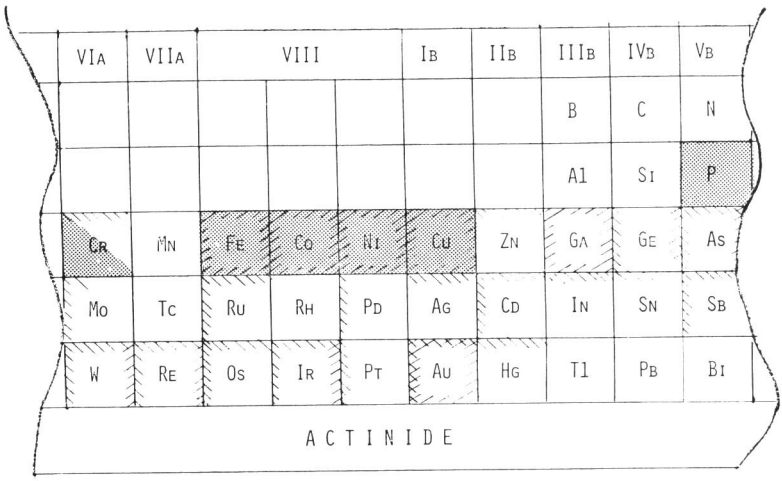


Fig. 1. A part of the periodic table of the elements.

[M] ; well known to be very low or none in iron meteorites.

[M] ; could be analyzed by other methods rather easily.

[M] ; depends on contents in iron meteorites, could be analysed by other methods.

[M] ; analyzed by instrumental (non-destructive) neutron activation analysis.

[M] ; depends on contents in iron meteorites, could be analyzed by instrumental neutron activation analysis.

[M] ; analyzed by radiochemical neutron activation analysis. Half-life of analyzed nuclides: less than 2 days.

[M] ; analyzed by radiochemical neutron activation analysis. Half-life of analyzed nuclides: longer than 2 days.

## II. Method and Procedure

Depending on analyses required, four methods were planned and applied for the analyses of iron meteorites. Main component elements, Fe, Co and Ni and some other special elements such as Ga and Au are not necessary to separate chemically from each other. Some elements produce only very short-lived nuclides by $(n, \gamma)$ reaction of thermal neutron and others contain nuclides only transformed to rather long-lived ones with very small efficiency by $(n, \gamma)$ reaction of thermal neutron. Each method and procedure are described successively.

A. *Monitors*:

Most of the standard solutions used as monitors for thermal neutrons in these experiments were prepared from accurately known weight of pure metals, normally better than 4 nines, except Ir, Ag, Hg and As.

*1. Ni, Cu, In;* These were dissolved separately in concentrated $HNO_3$ and after brown NO and $NO_2$ gas was expelled, these were diluted with $H_2O$ to the desired con-

centrations.

*2. Co, Re*; About 5N-$HNO_3$ was used for the dissolution of these metals.

*3. Pd, Pt, Au*; These were dissolved in agua-regia then diluted with $H_2O$.

*4. Mo*; Molybdenum was dissolved in aqua-regia, evaporated to dryness and the residue, $MoO_3$, was dissolved in $NH_4OH$.

*5. W*; Tungsten was dissolved in the mixture of $HNO_3$ and HF, evaporated to dryness and the residue, yellow $WO_3$ was dissolved in $NH_4OH$.

*6. Cr*; Chromium was dissolved in HCl and converted to nitrate by $HNO_3$.

*7. Ga*; Gallium was dissolved in the mixture of HCl and $H_2O_2$, excess $H_2O_2$ expelled and diluted in $H_2O$.

*8. Sn*; Tin was dissolved in concentrated HCl and diluted with water.

*9. Zn*; Zinc was dissolved in 2N-$H_2SO_4$.

*10. Cd*; Cadmium was dissolved in the mixture of $H_2SO_4$ and $HNO_3$, excess $HNO_3$ expelled and diluted with $H_2O$.

*11. Ge*; According to Wasson and Kimberlin (1967), Ge metal was dissolved in the mixture of oxalic acid solution, $NH_4OH$ and $H_2O_2$.

*12. Sb*; The 0.1 g of five nine metal was mixed with ~1 g of NaOH and ~0.5 g of $Na_2O_2$ and fused in Zr crucible. The melt was dissolved in HCl and the solution was made to 3N HCl.

*13. Ru*; The 0.1 g of three nine metal was mixed with the mixture of ~0.5 g of KOH and ~0.5 g of $KNO_3$, and fused in Zr crucible. The fused melt was extracted with $H_2O$ and acidified by concentrated HCl. The soultion was kept as 6N HCl. Ruthenium with valency state 8 is rather unstable, and reduced to valency state 3 by HCl. The reduction rate is rather slow. In the course of reduction from valency 8 to 3, Ru is passing through the valency state 4, which is insoluble in any kind of solvent. The present solution also precipitated $RuO_2$ some days later. The concentration of the solution was redetermined gravimetrically.

*14. Os*; The 0.1 g of 200 mesh four nine metal was mixed with the mixture of ~1 g of NaOH and ~0.5 g of $Na_2O_2$ and fused in Zr crucible. The fused melt was extracted with $H_2O$. The solution was kept as ~0.8 N NaOH. Osmium in the above solution is also meta-stable, just like Ru, gradually reduced to valency 4. A few months later, some precipitate was observed. In such case, the solution was standardized gravimetrically.

*15. As*; Arsenic solution was prepared by dissolving $As_2O_3$ in ~1N NaOH and acidified with $H_2SO_4$.

*16. Ag*; The $AgNO_3$ was dissolved in $H_2O$ for Ag standard solution.

*17. Hg*; Mercury standard solution was prepared by dissolving $HgCl_2$ in $H_2SO_4$.

*18. Ir*; Two kinds of Ir standard solutions were used in this study. One of them was the complex compound, $[(CH_3)_4N]$ $[IrCl_6]$, solution containing 401 ppm Ir supplied by professor T. Ishimori, St Paul's University. Another was the solution dissolving $IrCl_4 \cdot H_2O$, assay (Ir) 54.5% minimum, in $H_2O$ and HCl. The concentrations of both solutions were compared with each other.

For the monitors these solutions were diluted to appropriate concentration and weighed on teflon- or aluminum-foils or in quartz tube, and dried then sealed in polyethylene bag for Triga Mark II and in quartz tube for JRR-2 and JRR-4 reactors.

B. *Methods and Procedure*:

*1. Non-destructive thermal neutron activation analysis*; In Fig. 1, elements in boxes with oblique lines from upper right-hand could be analyzed by this method. As is well known besides major elements, depending on contents and thermal neutron activation efficiencies of each element in iron meteorites, some trace elements could

Table 1. Nuclear data on (n, $\gamma$) reaction used for instrumental neutron activation analyses in this work*.

| Stable nuclides | isotopic abundances (%) | $\sigma_{act.}$ (burns) | radio-nuclides | half life | main $\gamma$ ray energies (keV) (intensity)** |
|---|---|---|---|---|---|
| $^{58}$Fe | 0.3 | 1.16 | $^{59}$Fe | 44.6 d | 192.5 ( 2)<br>1098.6 ( 50)<br>1291.5 ( 40) |
| $^{64}$Ni | 0.9 | 1.48 | $^{65}$Ni | 2.520 h | 366.5 ( 10)<br>1115.4 ( 30)<br>1481.7 ( 50) |
| $^{59}$Co | 100 | 37 | $^{60}$Co | 5.27 y | 1173.1 (100)<br>1332.4 (100) |
| $^{63}$Cu | 69.2 | 4.4 | $^{64}$Cu | 12.71 h | 1345.5 (100) |
| $^{71}$Ga | 39.9 | 4.7 | $^{72}$Ga | 14.1 h | 630.1 ( 10)<br>834.1 ( 40)<br>2201.4 ( 14) |
| $^{74}$Ge | 36.5 | 0.52 | $^{75}$Ge | 82.8 m | 198.6 ( 10)<br>246.6 ( 80) |
| $^{76}$Ge | 7.8 | 0.15 | $^{77}$Ge | 11.30 h | 211.4 ( 50)<br>215.5 ( 50)<br>264.5 ( 50) |
| $^{75}$As | 100 | 4.4 | $^{76}$As | 26.3 h | 559.2 ( 75)<br>657.0 ( 10)<br>1215.8 ( 7) |
| $^{191}$Ir | 37.3 | 300 | $^{192}$Ir | 74.2 d | 295.8 ( 10)<br>316.5 ( 40)<br>467.9 ( 20) |
| $^{193}$Ir | 62.7 | 110 | $^{194}$Ir | 19.15 h | 328.0 ( 50)<br>644.6 ( 10)<br>938.4 ( 6) |
| $^{197}$Au | 100 | 98.8 | $^{198}$Au | 2.696 d | 411.8 (100) |

* Data from "Chart of Nuclides" (1977).

** Data are derived from Dams & Adams, Radiochim. Acta **10**, 5–8, (1968).

be analyzed. The nuclear data on $(n, \gamma)$ reaction by thermal neutrons used for this procedure are presented in Table 1. Due to the content of some elements in iron meteorites, some of nuclides in this table could not be detected.

For these purpose, cleaned and weighed about 50 mg iron meteorite specimen with monitors were irradiated by thermal neutron for 1, 6 and 12 hours in Triga Mark II reactor at a flux $1.5\times10^{12}$ neutron/cm$^2$·sec in St. Paul's University. After 3 to 20 hours cooling, irradiated meteorite samples and monitors were analyzed by Ge(Li) $\gamma$ ray spectrometer.

**2.** *Radiochemical neutron activation analysis-1*; This was designed for elements having only short-lived nuclides, half-life is less than a day, such as $^{75}$Ge; half-life: 82 min., $^{77}$Ge; 11.30 hrs., $^{109}$Pd; 13.43 hrs. and $^{197}$Pt; 18.3 hrs. These elements are rather insensitive for $(n, \gamma)$ reaction but important for the classification of iron meteorites.

About 50 mg of iron meteorite specimen was weighed accurately, sealed in quartz tube and irradiated together with monitors, Ge, Pd and Pt, sealed also in quartz tube for 3 hours in JRR 4 reactor at a flux $8\times10^{13}$ neutron/cm$^2$·sec in the Japan Atomic Energy Research Institute at Tokai. Irradiated samples were cooled for about 3 hours then dissolved in aqua regia. The post irradiation chemistry was composed of the precipitation of Ge with $H_2S$ in strong, ~6N, acidic media, and the anion exchange

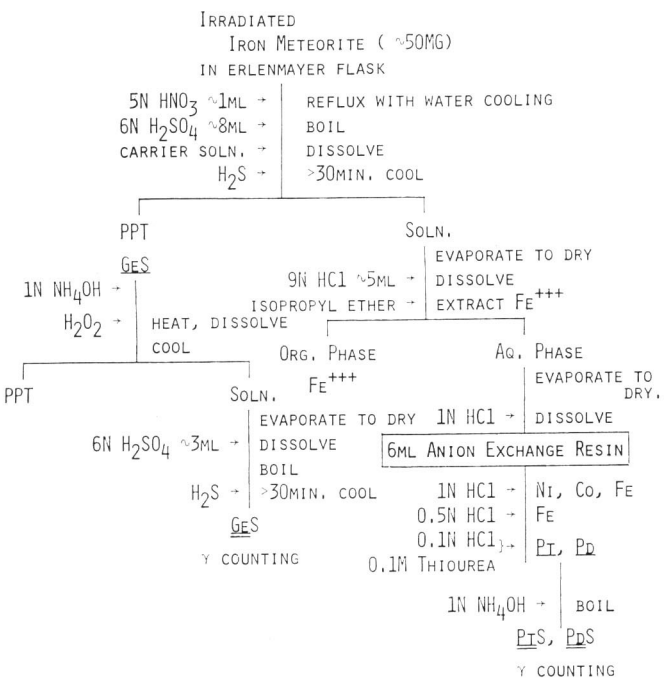


Fig. 2. Schematic diagram of the post-irradiation chemistry used for the radiochemical neutron activation analysis of Ge, Pd and Pt.

separation of Pt and Pd from Fe, Ni and Co followed by the precipitation of sulfide. The brief method is schematically given in Fig. 2.

A similar experiment was also made by irradiating about 50 mg of iron meteorites

Table 2. Nuclear data on $(n, \gamma)$ reaction used for radiochemical neutron activation analyses (Method 3).*

| Stable nuclides | isotopic abundances (%) | $\sigma_{act.}$ (burns) | radio-nuclides | half life | main $\gamma$ ray energies (keV) (intensity)** |
|---|---|---|---|---|---|
| $^{76}$Ge | 7.8 | 0.15 | $^{77}$Ge | 11.30 h | *** |
| $^{75}$As | 100 | 4.4 | $^{76}$As | 26.3 h | *** |
| $^{98}$Mo | 24.1 | 0.14 | $^{99}$Mo | 66.02 h | 140.6 ( 90)<br>180.9 ( 10)<br>739.9 ( 2) |
| $^{96}$Ru | 5.5 | 0.24 | $^{97}$Mo | 2.89 d | 215.8 ( 90)<br>325.1 ( 10) |
| $^{108}$Pd | 26.7 | 12.2 | $^{109}$Pd | 13.43 h | 311.5 ( 10)<br>88.0 (100) |
| $^{114}$Cd | 28.7 | 0.30 | $^{115}$Cd | 53.5 h | 492.5 ( 30)<br>527.7 ( 60) |
| $^{121}$Sb | 57.3 | $6.2_5$ | $^{122}$Sb | 2.72 d | 564.0 ( 90)<br>692.5 ( 5)<br>1140.5 ( 1) |
| $^{186}$W | 28.6 | 38 | $^{187}$W | 23.9 h | 134.3 ( 10)<br>479.3 ( 20)<br>685.7 ( 40) |
| $^{187}$Re | 62.60 | 75.3 | $^{188}$Re | 16.95 h | 155.1 ( 70)<br>478.0 ( 6)<br>633.0 ( 10) |
| $^{192}$Os | 41.0 | 2.0 | $^{193}$Os | 30.5 h | 139.0 ( 20)<br>460.4 ( 20)<br>557.7 ( 10) |
| $^{193}$Ir | 62.7 | 110 | $^{194}$Ir | 19.15 h | 328.0 ( 50)<br>644.6 ( 10)<br>938.4 ( 6) |
| $^{196}$Pt | 25.3 | $0.7_5$ | $^{197}$Pt | 18.3 h | 77.7 ( 90)<br>191.4 ( 10) |
| $^{198}$Pt | 7.2 | 3.7 | $^{199}$Pt<br>$\downarrow \beta^-$<br>$^{199}$Au | 30.8 m<br><br>3.14 d | <br>158.3 ( 80)<br>208.2 ( 20) |
| $^{197}$Au | 100 | 98.8 | $^{198}$Au | 2.696 d | *** |

* Data from "Chart of Nuclides" (1977).

** Data are derived from Dams & Adams, Radiochim. Acta **10**, 5–8 (1968).

*** See Table 1.

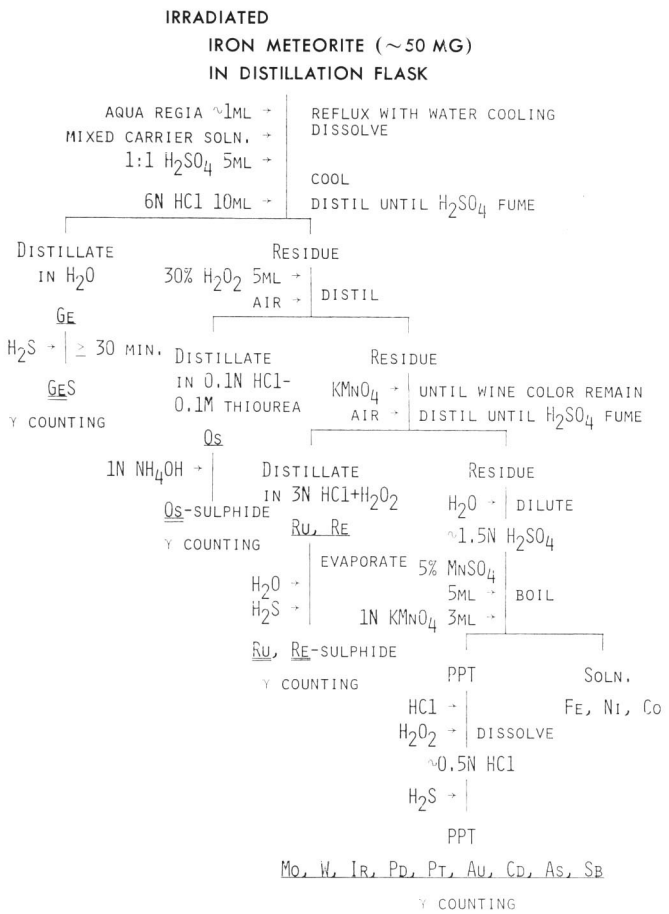


Fig. 3. Schematic diagram of the post-irradiation chemistry used for the radiochemical thermal neutron activation analysis of the elements with half-life of less than 2 days.

sealded in polyethylene bags with monitors for 12 hours in Triga Mark II reactor at a flux $1.5\times10^{12}$ neutron/cm$^2$·sec in St. Paul's University.

*3. Radiochemical neutron activation analysis-2*; The method was designed for the elements with short-lived nuclides, half-life; $\leq$ 2 days. The nuclear data of such elements on $(n, \gamma)$ reaction used for this method is shown in Table 2.

Cleaned and weighed about 50 mg iron meteorite samples with monitors including all elements to be analyzed were irradiated by thermal neutron for 10 hours in JRR 4 reactor at a flux $8\times10^{13}$ neutron/cm$^2$·sec in the Japan Atomic Energy Research Institute at Tokai. The post irradiation chemistry is shematically shown in Fig. 3.

After 17 hours cooling, iron meteorite with carrier was decomposed by aqua regia in distillation flask to which a water cooled reflux tube was attached. This method consists of successive distillation of Ge, Os, Ru and Re. Distilled elements were

precipitated as sulfides and counted by Ge(Li) $\gamma$ ray spectrometer. From the residue after distilling Ge, Os, Ru and Re, Pd and Pt were separated from Fe, Ni and Co by coprecipitating with $MnO_2$. The $MnO_2$ precipitate also contained Mo, W, Ir, Au, Cd, As and Sb. For purifying these elements, the precipitate was dissovled in HCl and $H_2O_2$, then Pd, Pt, Mo, W, Ir, Au, Cd, As and Sb were precipitated as sulfide with hydrogen sulfide in acidic solution. These were measured altogether with Ge(Li) $\gamma$ ray spectrometer, because $\gamma$ energies for each nuclide could easily be isolated.

*4. Radiochemical neutron activation analysis-3.* The method was planned for the nuclides having longer half lives. The nuclear data of each nuclides used for this experiments are tabulated in Table 3.

About 50 mg of acurately weighed iron meteorite specimen with monitors

Table 3. Nuclear data on $(n, \gamma)$ reaction used for radiochemical neutron activation analyses (Method 4)*.

| Stable nuclides | isotopic abundances (%) | $\sigma_{act.}$ (burns) | radio-nuclides | half life | main $\gamma$ ray energies (keV) (intensity)** |
|---|---|---|---|---|---|
| $^{64}Zn$ | 48.6 | 0.76 | $^{65}Zn$ | 243.8 d | 1115.4 (100) |
| $^{75}As$ | 100 | 4.4 | $^{76}As$ | 26.3 h | *** |
| $^{98}Mo$ | 24.1 | 0.14 | $^{99}Mo$ | 66.02 h | *** |
| $^{102}Ru$ | 31.6 | 1.4 | $^{103}Ru$ | 39.4 d | 497.0 ( 90)<br>610.2 ( 10) |
| $^{109}Ag$ | 48.17 | 4.4 | $^{110m}Ag$ | 252 d | 657.8 ( 30)<br>884.5 ( 20)<br>937.2 ( 10) |
| $^{113}In$ | 4.3 | 8 | $^{114m}In$ | 49.5 d | 190.2 (100) |
| $^{116}Sn$ | 14.7 | 0.006 | $^{117m}Sn$ | 14 d | 158.4 (100) |
| $^{124}Sn$ | 5.6 | $0.13_4$ | $^{125}Sn$ | 9.65 d | 332.0 (100) |
| $^{123}Sb$ | 42.7 | $4.2_6$ | $^{124}Sb$ | 60.20 d | 602.6 ( 50)<br>722.8 ( 6)<br>1690.7 ( 25) |
| $^{184}W$ | 30.67 | 1.8 | $^{185}W$ | 75.1 d | 125.5 (100) |
| $^{185}Re$ | 37.40 | 111 | $^{186}Re$ | 90.6 h | 122.6 ( 6)<br>137.0 ( 90) |
| $^{190}Os$ | 26.4 | 13 | $^{191}Os$ | 15.3 d | 129.4 (100) |
| $^{191}Ir$ | 37.3 | 300 | $^{192}Ir$ | 74.2 d | *** |
| $^{197}Au$ | 100 | 98.8 | $^{198}Au$ | 2.696 d | *** |
| $^{202}Hg$ | 29.8 | 4.9 | $^{203}Hg$ | 46.60 d | 279.1 (100) |

* Data from "Chart of Nuclides" (1977).

** Data are derived from Dams & Adams, Radiochim. Acta **10**, 5–8 (1968).

*** See Table 1 or Table 2.

in quartz tubes were irradiated for 260 hours in JRR 2 reactor at a flux $3\times10^{13}$ neutron/cm$^2$·sec in the Japan Atomic Energy Institute at Tokai. The post irradiation chemistry is schematically illustrated in Fig. 4.

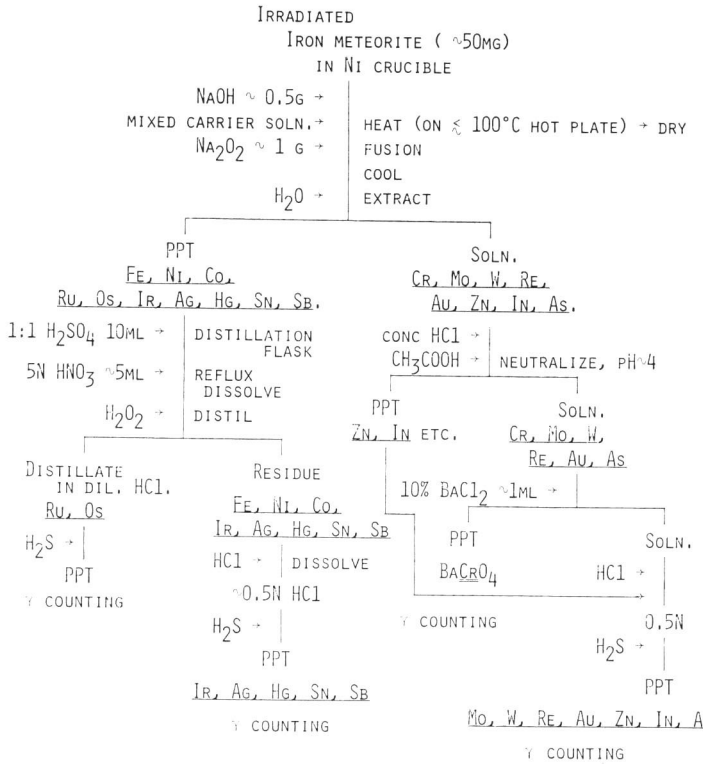


Fig. 4. Schematic diagram of the post-irradiation chemistry used for the radiochemical thermal neutron activation analysis of the elements with half-life of longer than 2 days.

The irradiated sample was fused by $Na_2O_2$ in Ni crucible. After extraction of the fused cake by $H_2O$, Ru and Os were distilled from the residue dissolved in $H_2SO_4$ and Ir, Ag, Hg, Sn and Sb were separated from Fe, Ni and Co by precipitation with hydrogen sulfide in acidic soultion. From the solution extracted from the fused cake, Cr was precipitated as $BaCrO_4$ and Mo, W, Re, Au, Zn, In and As were precipitated with hydrogen sulfide in slightly acidic solution. Nuclides collected and purified in each fraction were measured by their $\gamma$ energy with Ge(Li) $\gamma$ ray spectrometer.

C. *Chemical Yields*:

The chemical yields after radiochemical separations were determined by irradiating all separated samples again by thermal neutrons, for 1 or 5 hours depending on elements at flux $5\times10^{11}$ neutron/cm$^2$·sec in Triga Mark II reactor in St. Paul's

University. The chemical yields of germanium were measured gravimetrically by weighing $GeO_2$.

## III. Results and Discussion

An example of a $\gamma$ ray spectrum of the iron meteorite, Shirahagi, which was irradiated by thermal neutron for 6 hours in Triga Mark II reactor at a flux $1.5\times10^{12}$ neutron/cm$^2$·sec in St. Paul's Univesity, is shown in Fig. 5. This was taken for 1000 sec after $\sim$1 day cooling. One channel was adjusted for $\sim$ one keV.

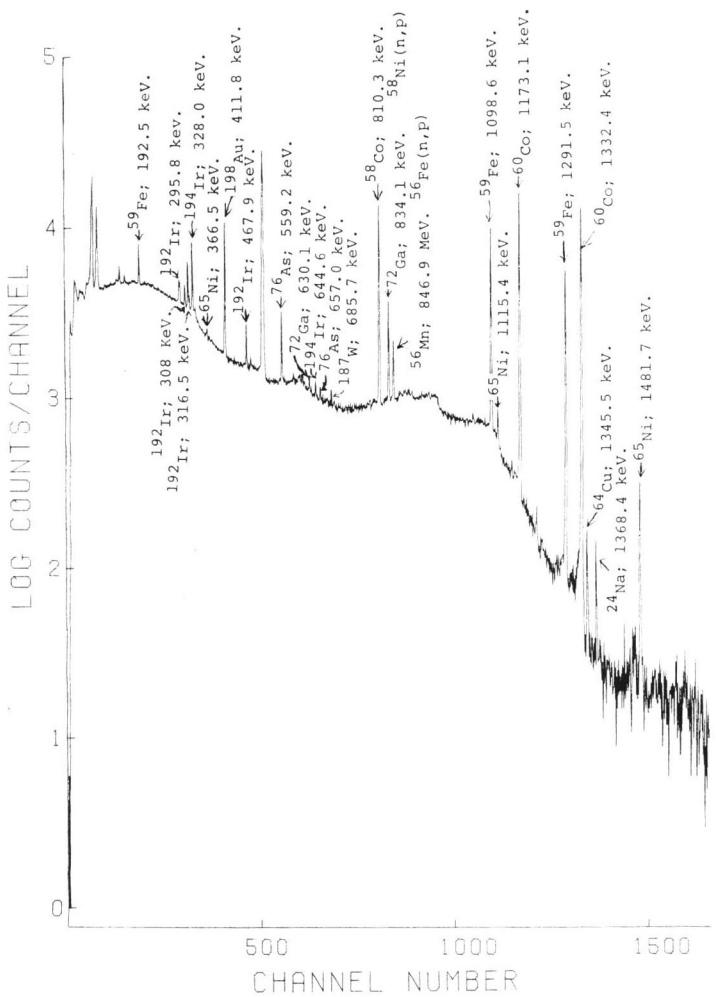


Fig. 5. An example of $\gamma$ ray spectrum obtained by Ge (Li) detector for the iron meteorite Shirahagi. (non-destructive).

It is clearly shown that besides $(n, \gamma)$ reactions of the main components, $^{58}Fe(n, \gamma)^{59}Fe$, $^{64}Ni(n, \gamma)^{65}Ni$ and $^{59}Co(n, \gamma)^{60}Co$, $(n, p)$ reactions $^{56}Fe(n, p)^{56}Mn$ and $^{58}Ni(n, p)^{58}Co$ also occurred. These were expected Triga Mark II reactor contains a significant proportion of high-energy neutrons.

The $\gamma$-ray energy peaks from some trace elements such as Cu, Ga, Ir, Au, As and W are also visible, that is, these elements in Shirahagi are determined only by comparison with monitors without any chemical treatment. However, depending on the meteorite, some element could not be detected. For example, in Fig. 5, Ge peaks are not observed while in Kuga and Tendo, they appeared to some extent. Contrary to the case of Ge, Ir peaks were not detected in Kuga whereas in Fig. 5, they are clearly observed. In this method, due to the effect of main components, background is so high that the accuracy of data for trace elements remains only $\sim \pm 10\%$.

All the nuclides in samples and in standards were measured at least three times each in one irradiation to check decay rate. This procedure is necessary to confirm each nuclide against impurities. Examples for decay curves of Os and Ru in standard and in separated samples from Shirahagi and Tendo are shown in Figs. 6 and 7.

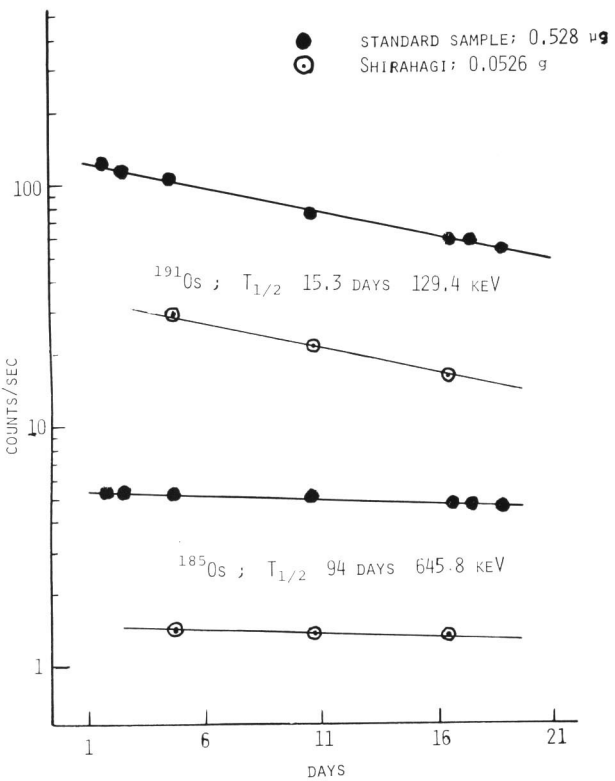


Fig. 6. Examples of decay curves of $^{191}$Os and $^{185}$Os.

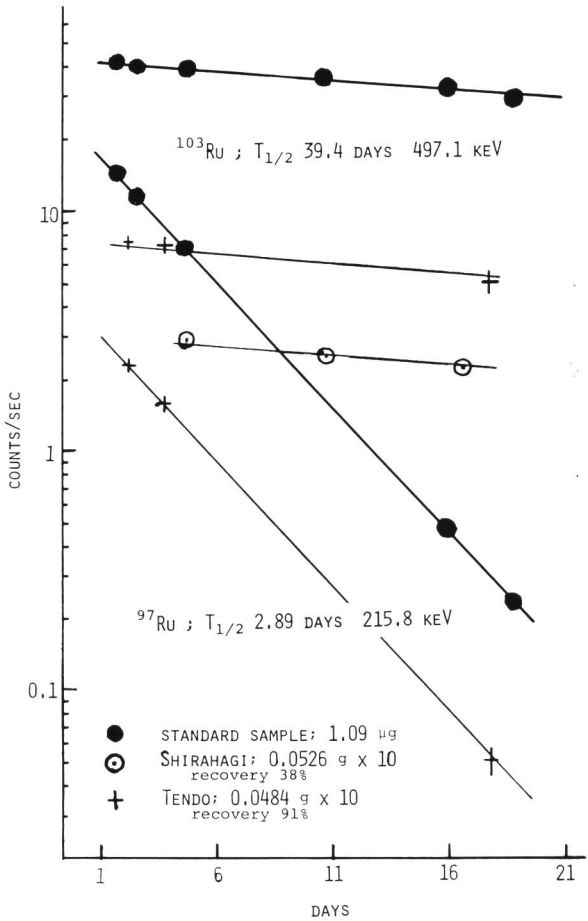


Fig. 7. Examples of decay curves of $^{97}$Ru and $^{103}$Ru.

The results are summarized in Table 4. Main component elements such as Ni and Co agreed very well with the values obtained by the method described in the former paper (Shima *et al.*, 1978). Wasson (1974) measured Ga, Ge and Ir in Shirahagi. Gallium and Ir in this work agreed well with his data.

Gallium, Ge and Ir have been used for the indicator elements for the classification of iron meteorites. The logarithmic concentrations of Ga, Ge and Ir in 439, 449 and 432 iron meteorites against the concentration of Ni were plotted in Tables 8, 9 and 10 respectively. The present values for Shirahagi, Tendo and Kuga in Table 4 are just in the clusters of Group IVA, IIIA and IIIB respectively. These fact confirm that these iron meteorites belong to respective groups, which have not surely been decided by the analyses of major elements and microanalytical observations (Shima *et al.*, 1978).

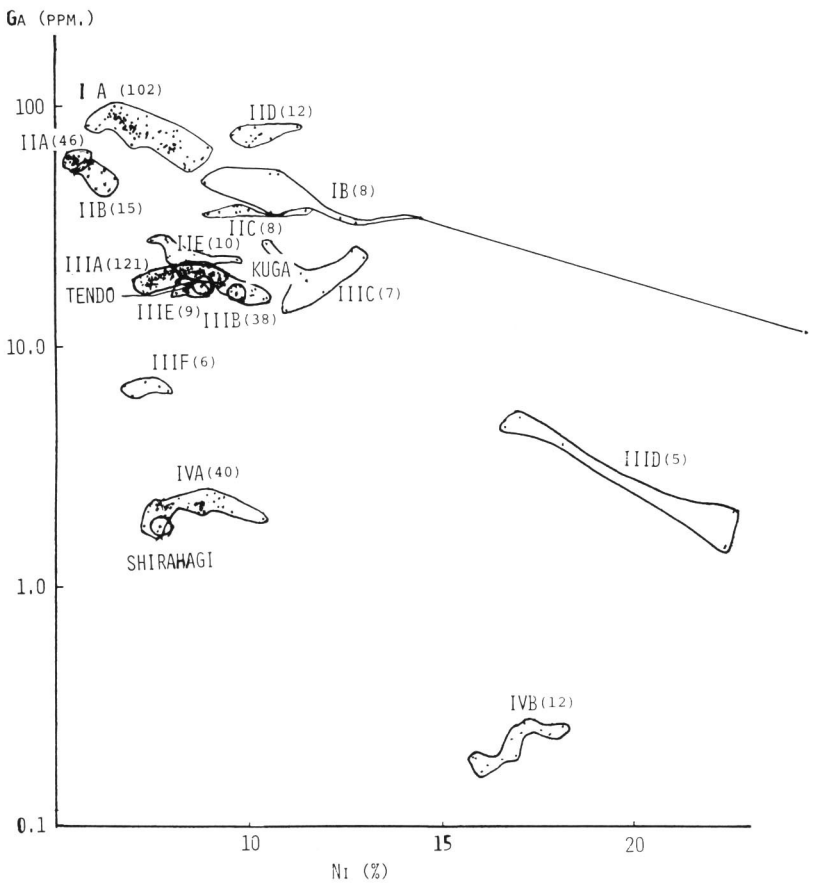


Fig. 8. The relationship between logarithmic concentration of Ga and the concentration of Ni. The data for Shirahagi, Tendo and Kuga are clearly situated in the clusters of IVA, IIIA and IIIB respectively.

The analytical results of other trace elements should have many implications for the formation of iron meteorites, the accretion of the elements from solar nebula, the recrystallization of constituent minerals during the long history of meteorite, behavior of elements in the different conditions other than the surface of earth etc. However, to discuss these facts further it is necessary to have more data for other iron meteorites.

## IV. Acknowledgements

The authour expresses her sincere thanks to Professors T. Ishimori and K. Tomura in St. Paul's University, Professor Y. Ito and Mr. T. Takano in Tokai Branch, Research

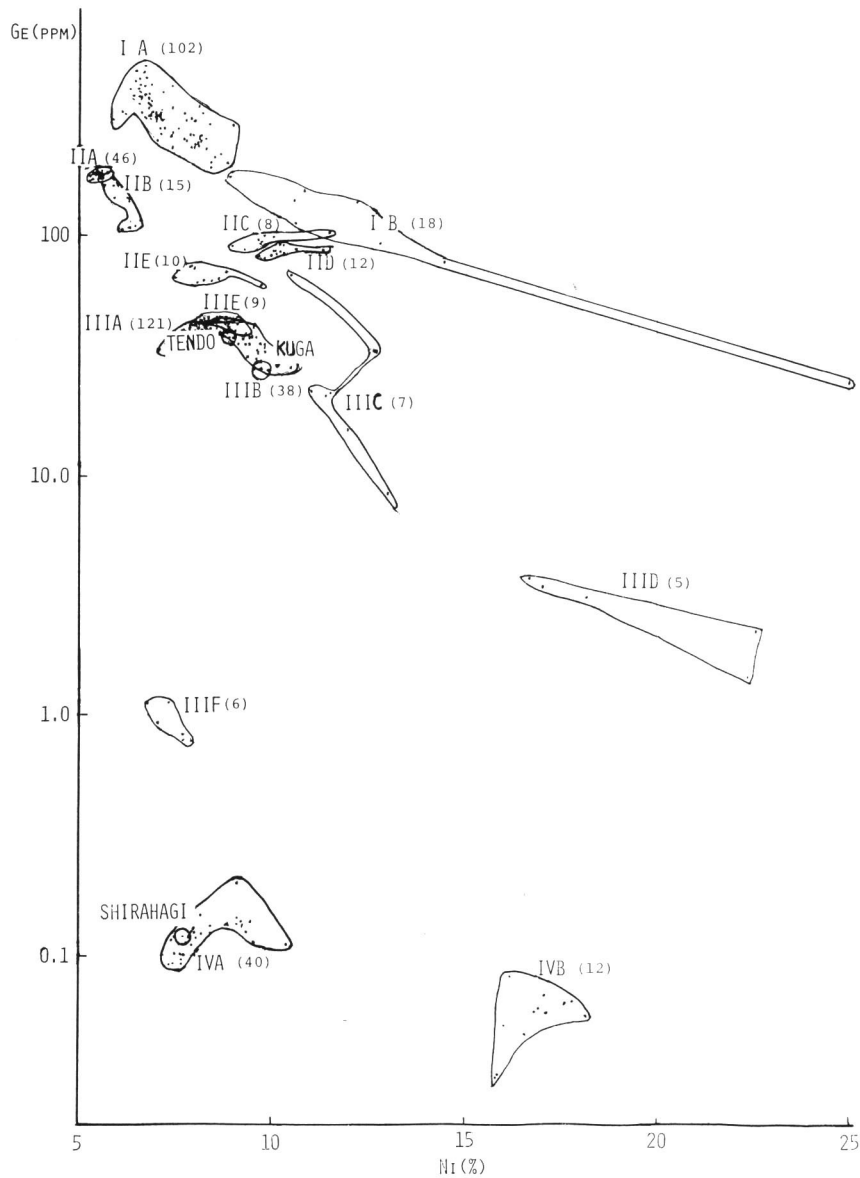


Fig. 9 The relationship between logarithmic concentration of Ge and the concentration of Ni. The data for Shirahagi, Tendo and Kuga are clearly situated in the clusters of IVA, IIIA and IIIB respectively.

Center for Nuclear Science and Technology, The University of Tokyo, and Professor M. Honda and Miss K. Horie in The Institute for Solid State Physics, The University of Tokyo, for allowing her to use facilities for chemical separation of

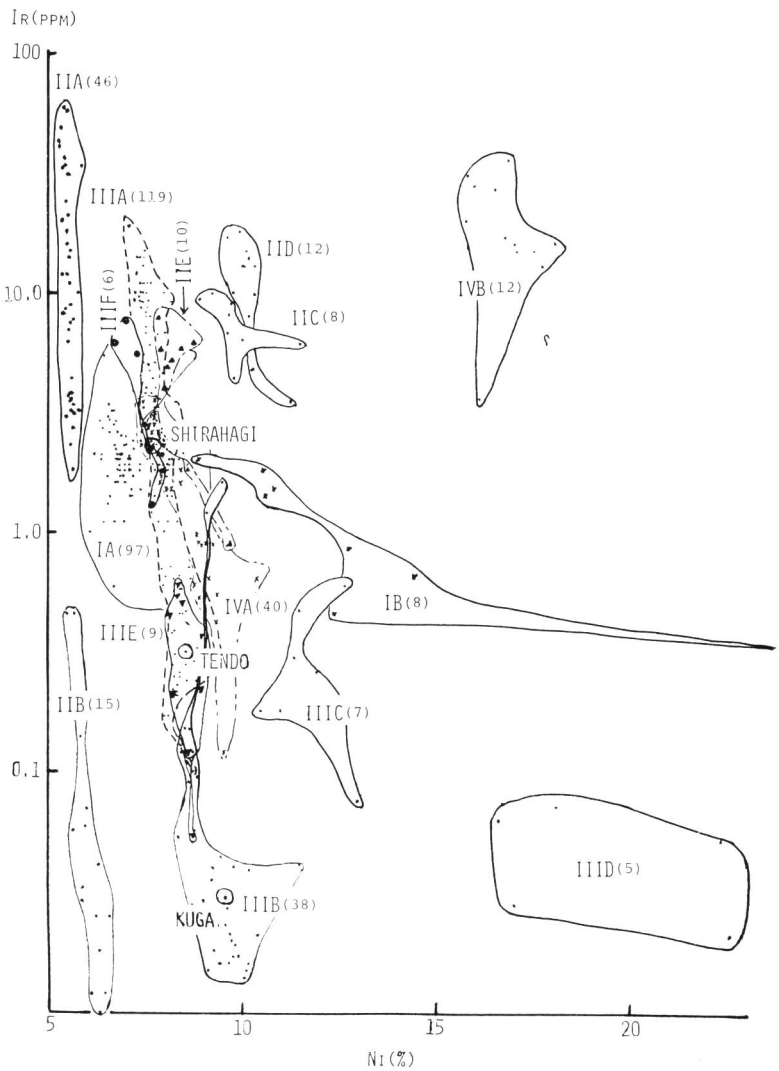


Fig. 10. The relationship between logarithmic concentration of Ir and the concentration of Ni. The data for Shirahagi, Tendo and Kuga are clearly situated in the clusters of IVA, IIIA and IIIB respectively.

radioactive samples and the Ge(Li) $\gamma$ ray spectrometer. This work has been performed by the collaboration of Dr. A. Okada and Mrs. S. Yabuki in The Institute of Physical and Chemical Research, and by miscellaneous assistance of individuals in St. Paul's University, in the Japan Atomic Energy Research Institute and in Tokai branch, Research Center for Nuclear Science and Technology, The University of Tokyo.

Table 4. The composition of major and trace elements in iron meteorites Shirahagi, Tendo and Kuga.*

| Element | Shirahagi | | Tendo | | Kuga | |
|---|---|---|---|---|---|---|
| | previous work | this work | previous work | this work | previous work | this work |
| Ni (%) | 7.68** | 7.65 | 8.89** | 8.56 | 9.68** | 9.63 |
| Co (%) | 0.39** | 0.42 | 0.54** | 0.43 | 0.58** | 0.594 |
| Cu (ppm) | 150** | 143 | 150** | — | 110** | 120 |
| Cr (ppm) | 310** | 61.3 | 3** | 3.33 | <20** | 5.09 |
| Ga (ppm) | 2.19*** | 1.89 | | 18.0 | | 16.5 |
| Ge (ppm) | 0.120*** | — | | 37 | | 26.5 |
| Ir (ppm) | 2.4*** | 2.37 | | 0.330 | | 0.034 |
| Mo (ppm) | | 6.5 | | 3.5 | | 11.6 |
| W (ppm) | | 0.44 | | 0.47 | | 0.41 |
| Ru (ppm) | | 0.430 | | 0.421 | | 0.408 |
| Os (ppm) | | 2.64 | | 0.101 | | 2.78 |
| Pd (ppm) | | 2.1 | | 7.8 | | 1.2 |
| Pt (ppm) | | 5.2 | | 8.0 | | 5.5 |
| Ag (ppm) | | 0.0081 | | 0.013 | | 0.0041 |
| Au (ppm) | | 0.79 | | 1.08 | | 2.2 |
| As (ppm) | | 5.5 | | 14 | | 36 |
| Sb (ppm) | | 0.018 | | 0.13 | | 0.34 |

* mean values of a couple of measurements.
** Shima *et al.*, (1978).
*** Wasson (1974).

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