Prompt gamma-ray analysis of Antarctic meteorites (1) – C1-related chondrites

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Introduction

In the past, the meteorite catalogs published by the NIPR listed major element compositions for some meteorites (e.g., Yanai and Kojima, 1995). Those data were obtained by wet chemical analysis using g-scale powder samples. Since the wet chemical method is a destructive method, this method is not applicable to every sample because the specimens are consumed. Therefore, it is impractical to perform wet chemical analysis on such valuable, small recovered mass samples as those analyzed in this study. The prompt gamma-ray analysis (PGA) method employed in this study is an alternative to the wet chemical method in that it can be applied to such samples.

The reaction in which a stable nucleus captures a neutron is called the (n,γ) reaction, where γ stands for prompt gamma ray. Neutron-captured compound nuclei emit prompt gamma-ray within 10^{-14} seconds after neutron capture. The PGA method can be regarded as one of the instrumental neutron activation analysis (INAA) methods, but it is performed in a neutron irradiation field that is about 10^5 times smaller than the neutron flux used in conventional INAA. Therefore, the analyzed samples are not restricted as radioactive materials and can be reused as research samples except for the use of noble gas analysis (Ebihara and Oura, 2001). This is a major difference from the wet chemistry method and broadens the range of applicable samples. The disadvantage is that PGA requires gamma-ray measurement during neutron irradiation, which limits the number of facilities that can perform the analysis.

In 1990, a PGA system was installed in the neutron beam hall of the JRR-3 research reactor at JAEA (then JAERI). Since then, advanced technical improvements have been made to the sample exchange system, data acquisition system, etc. (e.g., Osawa, 2015), and today it is widely used as the best PGA instrument in the world. The purpose of this study is to systematically analyze Antarctic meteorites using this PGA instrument. The specific goal of the study is as follows;

(1) The total elemental composition of meteorites will be determined by PGA and made available as a database to a wide range of researchers. It is aimed to achieve a level of data quality equivalent to the values obtained by the wet chemistry method listed in the former NIPR catalogs.

(2) Based on the elemental compositions obtained by PGA, we will develop a cosmochemical argument for the formation environment of meteorites.

A series of analyses of Antarctic meteorites by PGA was started with carbonaceous chondrites. H, B, Si, S, Cl, and Gd, which cannot be quantified or are difficult to quantify by INAA, can be determined for their contents by PGA of carbonaceous chondrites. In addition to these elements, quantitative values of Mg, Al, Ca, Ti, Cr, Mn, Fe, Co, Ni, and Sm can be obtained. Thus, the composition of major elements can be determined. In this study, we report results for five meteorites classified as CI or CI-related group of carbonaceous chondrites, and add some cosmochemical considerations based on the results.

Experimental

The samples analyzed were Y-86029, Y-86737 (hereinafter referred to as Y86 CI1s), Y 980115, Y 980134 (hereinafter referred to as Y98 CI1s), and Y-82162. Information on the samples is shown in Table 1. Four meteorites, Y86 CI1s and Y98 CI1s, are classified in the CI1 group. There are currently nine meteorites classified as CI1. Only these four meteorites are classified as CI1 among Antarctic meteorites. Y-82162 is classified as "C1/2-ung" in the Meteorite Bulletin database, showing petrographic characteristics of C1 and C2. The samples analyzed were collected from inside the meteorite as much as possible. Samples (one or several chips) of 150 ~ 200 mg (for Y86 CI1s and Y98 CI1s) and about 240 mg (for Y-82162) were heat-sealed in FEP film bags and submitted for analysis. PGA was performed using the PGA equipment installed in the thermal neutron beamline at JAEA's research reactor JRR-3. Quantification was performed by a comparative method using reference standards. Chemical reagents (NH_4Cl, S, Cr, Ni, Co) and rock standards (basalt JB-1, carbonaceous chondrite Allende) were used as reference standards. The measurement time was 600 s for chemical reagents and 6000 s for rock standards and meteorite samples. Details of the quantitative method are described in Latif et al. (1999).

Results and Discussion

Some of the results of the PGA analysis of the five meteorites are shown in Table 2, in which the values for the Orgueil meteorite analyzed in this study together with the literature values (Anders and Grevesse, 1989) also are shown. Orgueil was analyzed as a control sample. Comparing the analytical values of Orgueil from this work with the literature values, they are generally consistent, although there seems a slight difference in Si. The compositions of the two Y86 CI1s meteorites are in excellent agreement with each other in the five elements H, Si, S, Fe, and Ni, within the statistical error due to prompt gamma-rays counting (shown in the bottom row of Table 2). This suggests that these two meteorites are very likely to be pairs in terms of chemical composition of the five elements. On the other hand, the two Y98 CI1s show no such compositional similarity for any elements, suggesting that these two meteorites are very likely to be individual meteorites, not paired. The Y86 CI1s 2 meteorite were analyzed with a sample mass of about 150 mg. It is noteworthy that the 150 mg scale is sufficient to ensure elemental compositional uniformity in these meteorite samples. Comparing the analytical values of the four CI1 chondrites analyzed in this study, Y 980134 is several times lower in H and S contents than those of the other three meteorites, and slightly higher in Si and Fe. These differences indicate that Y 980134 differs significantly from other Antarctic CI1s in terms of elemental composition. Since the Antarctic CI1s except Y 980134 are generally consistent with Orgueil in elemental compositions, it is reasonable to assign them to the same chemical group as CI chondrites, although the H content of Y86 CI1s is about half that of Orgueil, and differences are also observed in Si and Ni contents. It is also noteworthy that there is no correlation in content between H and S contents. It is thought that these differences could have originated from compositional inhomogeneities on the parent body.

Yamato-82162 was once classified as C1 or CI1, and, currently, it is classified as C1/2-ung in the Meteoritical Bulletin Database maintained by the Nomenclature Committee of the Meteorite Society. On the other hand, it was proposed to be classified as CY along with Y-86720 and Belgica 7904 (Ikeda, 1992), and it is still sometimes described as such (King et al., 2019; Greenwood et al., 2022). Although the H content of Y-82162 is lower than those of Orgueil and Antarctic CI1s excluding Y 980134, the S content is the highest among the meteorites analyzed this time. Judging from the elemental composition, it is inferred that Y-82162 was formed in an environment more similar to Y-86029 (and Y-86737) than Orgueil.

Table 1. CI-related meteorites analyzed in this study

Meteorite name	Classification*	Original mass/g	Sample mass for PGA/g
Y-86029	CI1	11.8	0.147
Y-86737	CI1	2.81	0.156
Y 980115	CI1	772	0.197
Y 980134	CI1	12.2	0.173
Y-82162	C1/2-ung	41.7	0.235

*Meteoritical Society database.

Table 2. Elemental contents (%) in C1-related chondrites determined by PGA

Meteorite name	H	Si	S	Fe	Ni
Y-86029	1.16	12.3	6.57	21.2	1.46
Y-86737	1.16	12.3	6.60	20.8	1.43
Y 980115	1.50	11.7	5.19	21.2	1.80
Y 980134	0.51	15.0	0.79	24.7	1.58
Y-82162	0.79	13.5	7.03	22.6	1.20
Orgueil	1.85	12.5	5.01	19.5	1.22
Orgueil*	2.02	10.7	5.25	18.5	1.10
Uncertainty**	2.9-3.1	3.7-4.3	4.5-29	2.6-2.9	8.4-9.2

*Literature values (Anders and Grevesse, 1989).

**Errors due to counting statistics in gamma-ray spectrometry (% RSD; 1s).

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