Elemental composition of Jagannath meteorite by neutron activation analysis

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A sample of Jagannath meteorite, which fell on 27 September 2003 at Kendrapara district, Orissa, India, has been analysed for elemental composition by the k_0-based internal mono standard instrumental neutron activation analysis method. Concentrations of 20 major, minor and trace elements were determined. The authenticity of the meteorite sample was established by comparing its composition with those of standard meteorites/chondrites. An attempt was made to classify the sample by comparing the abundances and concentration ratios of elements with those of two recent meteorites from Kobe and Czech and a standard chondrite.

METEORITES are generally dense and magnetic and contain oxides of metals. They show high enrichment of elements like Fe, Ni and Cr compared to crustal elemental abundances. They are classified on the basis of their mineralogy, structure and chemical compositions[1–4]. The main classes of meteorites are: (i) stony meteorites constituting 92.8% of all meteorites, (ii) stony iron meteorites constituting nearly 1.5% and (iii) iron meteorites with abundance of 5.7%. One of the important features of meteorite analysis is to distinguish the sample from that of a terrestrial one and to classify the meteorite regarding its origin. The standard method for identifying meteorites is to compare the chemical composition of the sample with that of the meteoritic rock previously studied. Intermetallic elemental concentration ratios like Fe + Mg : Al, Fe : Ni, Fe : Mn, As : K and Th : Sm are frequently used for classification[4–6]. The elemental abundances of platinum group elements (PGEs) such as Ir, Os and Pt along with gold play an important role in the study of meteorites[6,7]. In impact craters, these elements occur in concentrations that are 20–100 thousand times greater than those on the earth's crust. Such abnormal concentrations are also used as evidence for meteor impact.

Recently, on 27 September 2003, a large number of meteorites fell in Paschim Suniti, Purab Suniti and Jambu, Kendrepada district, Orissa, India (geographical coordinates: 17°46′E long. and 46°25′N lat.). The meteorites arrived from northwest southeast flight with high inclination path. The fireball produced by the meteoritic fall was exceptionally bright and was witnessed throughout the northeastern part of Orissa and coastal parts of Andhra Pradesh and Tamil Nadu. Samples from many craters were collected for investigation. The present study on chemical composition analysis corresponds to a meteorite sample collected from one of the craters called Balabhadra crater (lat. 20°26′32″N, long. 86°42′36″E, 6 m msl). The weight of this meteorite sample was of 535 g. The meteorite is named as Jagannath meteorite.

Non-destructive analyses methods like neutron activation analysis (NAA), neutron capture gamma-ray spectrometry and X-ray fluorescence are frequently used for elemental analysis of planetary bodies[1,2,7–10]. The Kobe meteorite[1] and the Czech meteorite[2] are some of the well-studied meteorites whose chemical compositions are reported using nuclear analytical techniques like instrumental neutron activation analysis (INAA), prompt gamma ray NAA and instrumental photon activation analysis. The former fell in September 1999 at Kobe, Japan and the latter fell in May 2000 at Moravka village, Czech Republic. It is well established that NAA using reactor neutrons is a powerful analytical tool suitable for simultaneous multi elemental analysis in diverse matrices[10]. The self-validation property of the NAA approach helps in confirming analytical results, where one element may have more than one isotope and one radioisotope/activation product has, in many cases, more than one gamma line. We have used the k_0-based internal mono standard INAA method, recently developed by us[11–13], for analysis of this meteorite. This method does not require a priori knowledge of elements present in the sample and uses one of the elements present in the sample as the internal mono standard. The method takes care of neutron flux perturbation inside the sample during irradiation in a high neutron flux from a reactor and gamma-ray self-attenuation using *in situ* relative detection efficiency[11,12]. It is promising in terms of analysing large size and irregular geometry samples. This method is advantageous over the relative method of conventional NAA and uses all advantages of prevalent k_0-based (single comparator) NAA[14–16].

Here we report some of the preliminary results of chemical analysis of the Jagannath meteorite sample. The results were analysed in terms of the authenticity of the sample as a meteorite in general and also by comparing its chemical composition with the elemental concentrations of two well-known meteorites, namely the Kobe meteorite[1] and the Czech meteorite 'Moravka'[2], and a standard chondrite.

Representative samples were collected from the site of impact, i.e. Kendrepada district. Magnetic prospecting method was used for recovering the debris of the meteorites scattered over a large area. The samples recovered were picked from the surrounding soil, which was clay in nature. The piece examined by us consists of two faces

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partly covered by fractured surfaces. The larger face representing the top of the ellipsoid was smooth, covered with indistinct radiating grooves and a few shallow regmaglypts. Chondrules appear to be well integrated with the matrix and are not easily distinguishable. The large face is brownish-grey in colour, 0.5 mm thick, having numerous polygonal shrinkage cracks. The matrix material in the cracks bears evidence of effervescence. The smaller face at the base is dark brown, both close-textured and scoriaceous, and variable in thickness (0.5 to 1 mm).

Sub-samples of mass about 100 mg each, prepared from a mass of about 10 g meteorite piece, were used for irradiation. One sample was prepared with small pieces of meteorite without grinding and another two were prepared after grinding them to powder form. Two samples (one unground and the other ground) were sealed in polythene pouches along with a sample of iron standard using ferric ammonium sulphate for long-duration irradiation. About 100 mg sample of certified reference material (CRM), Soil-7, obtained from International Atomic Energy Agency (IAEA) was also sealed along with the samples. Another grounded sample was packed in a polythene pouch along with Fe-standard and CRM Soil-7 for short-duration irradiation. Samples were irradiated in the E8 position at the swimming pool-type Apsara reactor, Trombay, Mumbai at a thermal neutron flux of $\sim 5 \times 10^{11}$ cm^{-2} s^{-1}. Both long (6 h duration) and short (10 min duration) irradiations were carried out. After appropriate cooling, samples were assayed for gamma activity by high-resolution gamma ray spectrometry using a 40% HPGe detector connected to a 8 k multichannel analyser. The resolution of the detector was 1.8 keV at 1332 keV of ^{60}Co. Peak areas under the full energy peaks were evaluated by a peak fit method using the PHAST software, developed at Bhabha Atomic Research Centre[17].

When a sample is irradiated in a neutron flux, the ratio of mass (m) of an element (x) to mass of the internal comparator element (y) in the sample using the k_0-based internal mono standard INAA method is given by the following expression[12],

$$\frac{m_x}{m_y} = \frac{((S.D.C.)(f + Q_o(\alpha)))_y}{((S.D.C.)(f + Q_o(\alpha)))_x} \cdot \frac{P_{Ax}}{P_{Ay}} \cdot \frac{(\varepsilon_\gamma)_y}{(\varepsilon_\gamma)_x} \cdot \frac{1}{k_{0,y}(x)}, \quad (1)$$

where P_{Ax} and P_{Ay} are the net peak areas under the gamma peaks of interest of the element and the comparator element respectively, S the saturation factor $(1 - e^{-\lambda t_i})$ and D the decay factor $(e^{-\lambda t_c})$. C is the term used for correcting the decay during the counting period and is given by $((1 - e^{-\lambda LT})/\lambda)$. t_i is the duration of irradiation, t_c the duration of cooling and LT the live time of counting. λ is the decay constant of the activation product, f the thermal to epithermal neutron flux ratio, $Q_0(\alpha)$ the α-corrected Q_0 value[14] and ε_γ the detection efficiency. The factor $k_{0,y}(x)$ is calculated from the literature $k_{0,Au}$-factors[15] using the expression

$$k_{0,y}(x) = \frac{k_{0,Au}(x)}{k_{0,Au}(y)}. \quad (2)$$

We have used *in situ* relative efficiency (ε_γ) using the gamma rays of the activation products present in the sample and this takes care of gamma-ray self-attenuation. Details of the method, including calculations are given elsewhere[11,12]. The relative elemental mass ratios are converted to absolute values using mono standard mass. In the present study, we have used Fe as the internal mono standard and the IAEA CRM Soil-7 has been used as control sample.

The relevant nuclear data were taken from De Corte and Simonitis[15]. Gamma-ray spectra of the neutron-activated meteorite sample at two different cooling times after irradiation are shown in Figure 1 *a* and *b*. Concentrations of 20 elements obtained from two independent measurements are given in Table 1. The relative elemental mass ratios arrived with respect to the Fe mono standard were converted to their absolute values using the Fe content of the standard. Elemental concentration values from Kobe and Czech meteorites are also given in Table 1. The uncertainties in the determined values (Table 1) are due to counting statistics. The IAEA CRM Soil-7, which served as control, was also analysed in a similar way. The per cent deviations of elements determined in CRM Soil-7 are within ± 5% of their certified values in many cases.

From Table 1 it may be noted that the major elements present in the sample in decreasing order of concentration are Fe, Mg, Ni, Ca, Al, Na, Cr and Mn. The correction factors for nuclear interference reactions arising out of (n, p) and (n, α) reactions were found to be negligible, as irradiations were carried out in a well-thermalized neutron irradiation position (thermal neutron component > 98%)[16]. The correction factors due to the above nuclear interference reactions are of the order of 10^{-3} mg per mg of the interfering elements, namely Al from Si[18] and Na from Al and Mg. Chondritic meteorites are inherently inhomogeneous because of the chondrule and the matrix components. The meteoritic fall results in variations in chemical composition due to vaporization and reaction with air. We evaluated the extent of heterogeneity by analysing a powdered sub-sample and the results are in good agreement with the analysis results of ungrounded sample, except for elements Cr, Ir and Au.

A comparison of some of the elemental concentrations obtained for the meteorite sample with those of the earth's crust and an ordinary chondrite[4] is given in Table 2. There is good agreement among these values except for lanthanum, confirming that the sample under investigation is of meteoritic origin. The Fe/Mn ratio is another indicative

parameter for samples of meteoritic origin. The ratio for the present meteorite sample is 107. This value is comparable with that of the Czech meteorite (Fe/Mn = 94)[2], but is lower than that of the Kobe meteorite (Fe/Mn = 175)[1]. We have compared the Ni to Cr ratio obtained in this work with some of the typical values of chondrites. The value obtained in the present case is 4.65 compared to the values for the chondrites, namely C1, C2 and H, which range[7] from 4.1 to 4.8.

Further inter-comparison of the analytical data with some known meteorites[1,2] was carried out with the aim to classify the Jagannath meteorite according to its elemental content. Table 1 gives the values reported for the Kobe and Czech meteorites. Classification solely based on chemical composition is difficult in view of the heterogeneity associated with the meteorite samples in general and loss of elements due to evaporation taking place during their (meteorites) passage through the earth's atmosphere. In spite of the inherent uncertainty that can arise due to the heterogeneous nature of the samples, the results show a striking similarity in the values, except for a few elements like Na and K. This might be due to terrestrial contamination where the alkaline and alkaline earth elements are relatively enriched. Oura *et al.*[1] classified the Kobe meteorites as of CK class mainly based on the Si-normalized Al, Mg, Ca and Ti values. Since we did not determine the Si and Ti concentrations in the present work, we have compared the Al/Ca, Al/Mg and Ca/Mg ratios in our case with those of the Kobe and Czech meteorites. Table 3 shows the ratios obtained for Jagannath meteorite along with those of Kobe and Czech. The values show good agreement; hence we believe that the Jagannath meteorite may be of the same class as that of the Kobe meteorite, namely CK, which is a carbonaceous

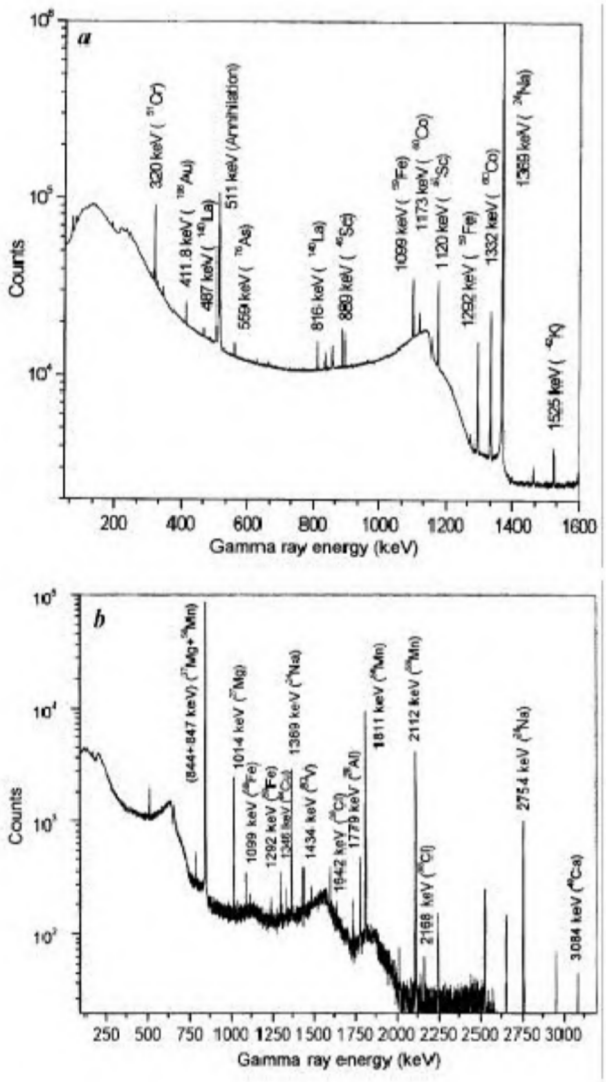

Figure 1. Gamma-ray spectra of a neutron activated sample of Jagannath meteorite with duration of irradiation = 6 h (***a***) and duration of irradiation = 5 min and decay = 5 min (***b***).

Table 1. Concentration of elements of Jagannath meteorite along with corresponding values from Kobe and Czech meteorites

Element	Jagannath meteorite	Kobe meteorite (ref. 1)	Czech meteorite (Mean value*: ref. 2)
Fe (%)	23.2 ± 0.5	23.1	24.02
Si (%)	NM	15.1	18.1
Mn (%)	0.217 ± 0.008	0.132	0.255
Cr (%)	0.33 ± 0.02	0.365	0.280
Co (%)	0.075 ± 0.003	0.0714	0.061
K (%)	0.080 ± 0.003	0.0260	NA
Na (%)	0.66 ± 0.03	0.22	0.58
Cu (%)	0.029 ± 0.002	NA	0.0179
Mg (%)	14.3 ± 0.8	14.2	15.98
Ca (%)	1.48 ± 0.15	1.63	1.39
Al (%)	1.17 ± 0.03	1.29	1.18
Ni (%)	1.53 ± 0.16	1.46	1.32
Sc (mg kg^{-1})	8.76 ± 0.56	NA	7.91
As (mg kg^{-1})	2.03 ± 0.22	NA	2.24
Au (mg kg^{-1})	0.18 ± 0.02	NA	0.23
La (mg kg^{-1})	0.44 ± 0.02	NA	0.44
Eu (mg kg^{-1})	0.060 ± 0.002	NA	0.077
Sm (mg kg^{-1})	0.13 ± 0.01	NA	0.261
Ir (mg kg^{-1})	0.30 ± 0.01	NA	0.603
Br (mg kg^{-1})	0.12 ± 0.01	NA	9.6
V (mg kg^{-1})	70.6 ± 3.5	NA	85.25

NM, Not measured; NA, Not available.
*Mean value arrived from individual results of bulk samples reported in ref. 2.

Table 2. Elemental abundance of some elements in Jagannath meteorite compared with those of an ordinary chondrite and with those of the earth's crust

Element	Jagannath meteorite	Ordinary chondrite (ref. 4)	Earth (ref. 4)
Na (%)	0.66	0.68	0.07 ± 0.06
K (mg kg^{-1})	800	850	130 ± 40
Ca (%)	1.48	1.21	0.95 ± 0.80
Sc (mg kg^{-1})	8.7	8.0	16.5 ± 14.5
La (mg kg^{-1})	0.44	0.24	0.52 ± 0.41

Table 3. Inter-elemental ratios for Jagannath meteorite along with those of Kobe and Czech meteorites

Element	Jagannath meteorite	Kobe meteorite	Czech meteorite
Al/Ca	0.79	0.79	0.85
Al/Mg	0.082	0.090	0.074
Ca/Mg	0.103	0.114	0.087

chondrite[1]. Among the rare earth elements only La, Eu and Sm could be determined in this work. There is good agreement in the concentration values of La and Eu in the present case with those of the Czech meteorite values, namely 0.44 mg kg^{-1} and 0.060 mg kg^{-1} against 0.44 mg kg^{-1} and 0.077 mg kg^{-1} respectively.

Iridium, a PGE, is present in small amounts in the earth's crust and upper mantle, but is more abundant in both the earth's core and meteorites. We observed Ir in the present case and its concentration (0.3 mg kg^{-1}) is ~ 300 times higher than that in the earth's crust. Similar is the case of gold, which is found to be 45 times more than the crustal value. The concentration values obtained for all the elements were compared with their respective crustal elemental abundance values. It is observed that the values corresponding to Fe, Mg, Cr and Ni are higher than the crustal values, whereas the values for elements like Al, Ca and Na are lower. Data obtained based on chemical composition substantiate the claim that the said sample collected is of meteoritic origin.

The k_0-based internal mono standard INAA method has been used for the determination of chemical composition of the Jagannath meteorite. The data on chemical composition and their comparison with those of other meteorites and of standard chondrite confirmed that the present sample analysed is an authentic meteorite. However, there is scope to investigate this sample in terms of isotopic abundance values, structure and age determination, which would be of help in further studies on the meteorite.

1. Oura, Y., Ebihara, M., Yoneda, S. and Nakamura, N., Chemical composition of the Kobe meteorite; neutron-induced prompt gamma ray analysis study. *Geochem. J.*, 2002, **36**, 298–307.
2. Randa, Z., Kucera, J. and Soukal, L., Elemental characterization of the new Czech meteorite 'Moravka' by neutron and photon activation analysis. *J. Radioanal. Nucl. Chem.*, 2003, **257**, 275–283.
3. Ebihara, M., Shinotsuka, K. and Kong, P., Chemical composition of Martian meteorites. 61st Annual Meteoritical Meeting, Germany, 1996.
4. Larimer, J. W., Composition of the earth: chondritic or achondritic? *Geochim. Cosmochim. Acta*, 1971, **35**, 769–786.
5. Korotev, R. L., Lunar meteorites. In http://epsc.wustl.edu/admin/resources/moon_meteorites.html, Department of Earth and Planetary Sciences, Washington University, St. Louis, 2004.
6. Ganzalez, M. A., *Of Meteors and Meteorites*, North Dakota Geological Survey, North Dakota, USA, 2003.
7. Palme, H., Janssens, M.-J., Takahashi, H., Anders, E. and Hertogen, J., Meteoritic material at five large impact craters. *Geochim. Cosmochim. Acta*, 1978, **42**, 313–323.
8. Ebihara, M., Determination of ten lanthanides in chondritic meteorites by radiochemical neutron activation analysis using coaxial and planar type Ge detectors. *J. Radioanal. Nucl. Chem.*, 1987, **111**, 385–397.
9. Nakahara, H. *et al.*, Some basic studies on non-destructive elemental analysis of bulky samples by PGAA. *J. Radioanal. Nucl. Chem.*, 2000, **244**, 405–411.
10. De Soete, D., Gijbels, R. and Hoste, J., *Neutron Activation Analysis*, John Wiley, London, 1972.
11. Sudarshan, K., Nair, A. G. C. and Goswami, A., A proposed k_0 based methodology for neutron activation of samples of non-standard geometry. *J. Radioanal. Nucl. Chem.*, 2003, **256**, 93–98.
12. Nair, A. G. C., Acharya, R., Sudarshan, K., Gangotra, S., Reddy, A. V. R., Manohar, S. B. and Goswami, A., Development of an internal mono standard INAA method based on *in situ* detection efficiency for analysis of large and non-standard geometry samples. *Anal. Chem.*, 2003, **75**, 4868–4874.
13. Acharya, R., Nair, A. G. C., Reddy, A. V. R. and Goswami A., Standard-less analysis of Zircaloy clad samples by an instrumental neutron activation method. *J. Nucl. Mater.* 2004, **326**, 80–85.
14. De Corte, F., Simonitis, A., De Wispelaere, A. and Hoste, J., Accuracy and applicability of the k_0-standardization method. *J. Radioanal. Nucl. Chem.*, 1987, **113**, 145–161.
15. De Corte, F. and Simonitis, A., k_0-measurements and related nuclear data compilation for (n, γ) reactor neutron activation analysis. IIIb tabulation. *J. Radioanal. Nucl. Chem.*, 1989, **33**, 43–130.
16. Acharya, R. N., Nair, A. G. C., Reddy, A. V. R. and Manohar, S. B., Validation of a neutron activation analysis method using k_0-standardization. *Appl. Radiat. Isot.*, 2002, **57**, 391–398.
17. Mukhopadhyay, P. K., The operating software of the PHAST PC-MCA card. Proceedings of the Symposium on Intelligent Nuclear Instrumentation (INIT-2001), Bhabha Atomic Research Centre, Mumbai, 2001, pp. 307–310.
18. Scindia, Y. M., Acharya, R. N., Nair, A. G. C., Reddy, A. V. R. and Manohar, S. B., Correction of interference due to phosphorous and silicon in the determination of aluminum by instrumental neutron activation analysis. Symposium on Nuclear and Radiochemistry (NUCAR-2001), University of Pune, 2001, pp. 501–502.

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