PRIMITIVE MATTER IN METEORITES

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ABSTRACT. A large number of elements in certain meteorites have isotopic composition different from that existing in rocks of the earth or the moon. Excess amounts of some isotopes, which are radiogenic daughters, are attributed to the *in situ* decay of their parent nuclide. Material containing radioactive parents is believed to have been injected into the condensing solar nebula, from astrophysical sites of their production *shortly* before formation of these grains. Other isotopic anomalies do not show mass dependent pattern which is characteristic of chemical fractionation. They must be *primary* isotopic abundances, if it is assumed that physico-chemical processes in the solar nebula cannot produce non-mass dependent fractionation. In such a case the observed isotopic ratios characterise elements differently synthesised and injected into the solar nebula which condensed before it had enough time to homogenise. Thus the isotopically anomalous matter has extra solar origin and may contain supernovae condensates, interstellar matter or dust from other stars. The evidence for different isotopic anomalies is briefly summarised and discussed in terms of the current ideas regarding chemical processes occurring in the early solar system.

1. ISOTOPIC ANOMALIES

Meteorites, particularly carbonaceous chondrites, contain the earliest grains which formed in our solar system, some of which have remained unaltered since. These grains are made of minerals which are first to condense in a cooling solar nebula such as refractory oxides and silicates like hibonite and melilite. Even though refractory condensates have many similarities with high temperature residues, the presence of 86 Myr ^{244}Pu fission tracks testify to their primitiveness and state of thermal preservation from subsequent alteration. A large number of isotopic anomalies relative to terrestrial (or lunar) abundances have been observed in such grains from carbonaceous chondrites eg Allende, Murchison and Murray. These are listed in Table 1. Some of the minerals of interest in which they are found to be present are listed in Table 2. Origin of these isotopic anomalies has been a matter of great interest

M. S. Vardya and S. P. Tarafdar (eds.), Astrochemistry, 485–491.

TABLE 1. Isotopic anomalies observed in meteorite grains

1.**Radiogenic anomalies**

2.6 yr	$^{22}\text{Na} \xrightarrow{\beta^+} {}^{22}\text{Ne}$: NeE anomaly (1,2,3)
0.73 Myr	$^{26}\text{Al} \xrightarrow{\beta^+} {}^{26}\text{Mg}$ (4,5)
6.5 Myr	$^{107}\text{Pd} \xrightarrow{\beta^-} {}^{107}\text{Ag}$ (6)
17 Myr	$^{129}\text{I} \xrightarrow{\beta^-} {}^{129}\text{Xe}$ (7)
86 Myr	^{244}Pu fission $\rightarrow {}^{134,136}\text{Xe}$, fission tracks (8,9,10)

2.**Primary anomalies**

$^{16}\text{O}:{}^{17}\text{O}:{}^{18}\text{O}$ (11)

$^{24}\text{Mg}:{}^{25}\text{Mg}:{}^{26}\text{Mg}$(5)

$^{28}\text{Si}:{}^{29}\text{Si}:{}^{30}\text{Si}$(12)

$^{40}\text{Ca}:{}^{42}\text{Ca}:{}^{43}\text{Ca}:{}^{44}\text{Ca}:{}^{46}\text{Ca}:{}^{48}\text{Ca}$(13)

$^{46}\text{Ti}:{}^{47}\text{Ti}:{}^{48}\text{Ti}:{}^{49}\text{Ti}:{}^{50}\text{Ti}$(14,15,16)

$^{84}\text{Sr}:{}^{86}\text{Sr}:{}^{88}\text{Sr}$(17)

$^{78}\text{Kr}(p):{}^{80}\text{Kr}(s,p):{}^{82}\text{Kr}(s):{}^{83}\text{Kr}(s,r):{}^{84}\text{Kr}(s,r):{}^{86}\text{Kr}(s,r)$(18)

$^{124}\text{Xe}(p):{}^{126}\text{Xe}(p):{}^{128}\text{Xe}(p):{}^{129}\text{Xe}(s,r):{}^{130}\text{Xe}(s):{}^{131}\text{Xe}(s,r):$
$^{132}\text{Xe}(s,r):{}^{134}\text{Xe}(r):{}^{136}\text{Xe}(r)$(19.20)

$^{130}\text{Ba}(p):{}^{132}\text{Ba}(p):{}^{134}\text{Ba}(s):{}^{135}\text{Ba}(s,r):{}^{136}\text{Ba}(p):{}^{137}\text{Ba}(s,r)$
$^{138}\text{Ba}(s,r)$(21)

$^{142}\text{Nd}(s):{}^{143}\text{Nd}(s,r):{}^{144}\text{Nd}(s,r):{}^{145}\text{Nd}(s,r):{}^{146}\text{Nd}(s,r):$
$^{148}\text{Nd}(r):{}^{150}\text{Nd}(r)$(21)

$^{144}\text{Sm}(p):{}^{147}\text{Sm}(s,r):{}^{148}\text{Sm}(s):{}^{149}\text{Sm}(s,r):{}^{150}\text{Sm}(s):$
$^{152}\text{Sm}(r):{}^{154}\text{Sm}(r)$(22)

TABLE 2. Refractory minerals in meteorites.

Corundum	Al_2O_3
Hibonite	$CaAl_{12}O_{19}$
Pervoskite	$CaTiO_3$
Fassaite	$Ca(Mg,Al,Ti)\ (Si,Al)_2O_6$
Melilite	$Ca_2Al_2SiO_7-Ca_2MgSi_2O_7$
Spinel	$MgAl_2O_4$
Diopside	$CaMgSi_2O_6$
Forsterite	Mg_2SiO_4
Anorthite	$CaAl_2SiO_8$

and debate. Chemical reactions, even at extreme temperature conditions, cannot give rise to observed abundances, starting from solar composition, since they follow a well defined mass dependent fractionation pattern. The assumption that non-mass dependent (NoMaD) fractionation is not responsible for these anomalies has been the corner stone of the models which attribute them to nucleosynthesis under different conditions. Other physical processes such as nuclear reactions induced by energetic solar particles within the solar system, magnetic fractionation in an ionised plasma or fractionation resulting from differences in ranges of energetic ions of different isotopes of an element cannot reproduce the observed isotopic pattern. The anomalies can, however, be explained within the framework of current nucleosynthetic concepts (23)or suitable modifications made to reproduce the observations. These isotopic abundances have been termed as FUN (Fractionated Unknown Nuclear) anomalies and it is widely accepted that the grains exhibiting anomalous isotopic composition represent extra solar system component, introduced in the solar nebula about 4.6 billion years ago at or before the initiation of grain and rock forming processes. These components could be supernovae condensates SUNOCONS, freshly synthesised material from other stars, STARDUST (23) and interstellar matter (ISM).

The typical anomalies measured in meteorite grains are small in magnitude. In case of radiogenic anomalies (Table 1) it is possible to obtain the relative abundances of the parent atom. Typical values (at the time of grain formation) are $^{26}Al/^{27}Al = 5x10^{-5}$, $^{107}Pd/^{108}Pd = 2x10^{-5}$, $^{129}I/^{127}I = 1x10^{-4}$. In some grains, tracks due to

^{244}Pu are atleast 20 times more than due to ^{238}U, leading to ^{244}Pu/^{238}U = 7x10^{-3}. These observations set strict time limits between nucleosynthesis and formation of the grain, Δ, which, in case of ^{26}Al-^{26}Mg anomaly, cannot be more than 3 Myr. In case ^{22}Na-^{22}Ne anomaly is due to *in situ* decay of ^{22}Na, Δ would be of the order of years and, it is quite likely that the grains are direct condensates from the expanding supernova envelope, containing freshly synthesised ^{22}Na. If this is true, then the meteorites may as well contain several other types of grains like graphites from interstellar space (24). Some of the carbonaceous matter has shown isotopic anomalies of various elements consistent with extra-solar system origin.

The magnitude of primary anomalies is also generally low. The slope of mixing line of oxygen isotopes (11) is close to 1, and does not follow mass-dependent fractionation pattern, indicating a rather constant ^{17}O/^{18}O, mixing with a nearly pure ^{16}O source. Study of various rocks from earth or moon do not show such a fractionation in chemical processes but some NoMaD fractionation has been demonstrated in the laboratory(25). In other elements the anomaly is determined by normalising to one of the isotopes, the choice of the normalising isotope being usually arbitrary. In many isotopes, positive as well as negative anomaly has been observed in different inclusions. Typical anomalies for Mg, Si, Ca and Ti isotopes in three Allende inclusions is listed in Table 3. In case of ^{50}Ti an enrichment of as much as 10% has been observed in hibonites from Murchison (16).

TABLE 3. Typical isotopic anomalies (per mil) in Allende inclusions(a)

Inclusion	$\delta^{18}O$	$\delta^{25/24}Mg$	$\delta^{26/24}Mg$	$\delta^{29}Si$	$\delta^{30}Si$	δCa	δTi
						per	amu
EK1-4-1	Yes	20	37	7.5	12.5	-1.8(b)	.83(e)
HAL	Yes	20	40			7.5(c)	-
C1	15	30	59	12.5	23.5	0.3(d)	-

(a) For source of data see (27,28)

(b) Except for +1.7‰ for ^{42}Ca and 14‰ for ^{48}Ca.

(c) Except for 1-2‰ for 42,43,48 Ca.

(d) Except for -2.7‰ for ^{48}Ca.

(e) Excess at ^{47}Ti, ^{49}Ti and ^{50}Ti normalised to ^{48}Ti.

It may be noted that some of these anomalies eg. ^{129}I, ^{244}Pu are frequently encountered in several ordinary chondrites whereas others are exclusively confined to carbonaceous chondrites type 2 and 3. Study of Allende (CV) meteorite has provided most of the anomalous isotopic composition since it has a large fraction, about 8% by volume, of refractory inclusions which are sometimes as big as a cm. CM meteorite like Murchison and Murray probably have minerals which are more refractory but they are generally small, making measurements difficult. NeE anomaly has been observed in Dimmit (H3 chondrite) and in Orgueil (C). ^{107}Pd-^{107}Ag anomaly has been detected in iron meteorites Santa Clara Gibeon and some others because they have very low silver abundance which is chemically favourable for such a measurement. We thus have a limited sampling of many anomalous elements, particularly those exhibiting primary anomalies. Most of them may therefore not be typical of extrasolar component and the models may change when more measurements become available.

2. NUCLEOSYNTHETIC PROCESSES

The isotopes leading to the anomalies can be produced in one or more processes within the framework of known nucleosynthetic concepts. Specific channels of production in stellar burning processes have been worked out (23,26-28). In massive stars, for example, Helium burning, carbon burning and neon burning can give rise to ^{16}O, carbon and neon burning to ^{26}Al and oxygen and silicon burning to elements upto iron group. Novae are believed to be the site for production of ^{26}Al and Red giants for several light isotopes. Heavy and anomalous isotopes produced in r and s processes are indicated in Table 1. Some isotopes like ^{50}Ti require special mechanism and attempts have been made to incorporate them in the general scheme of nucleosynthesis. The presence of different anomalies require more than one events of injection of freshly synthesised material (29), some in spikes and some probably continusouly over the history of the solar nebula before initiation of the formation of the solar system.

3. CONCLUSIONS

This is briefly the picture which emerges from the recent efforts in measurement and understanding of isotopic anomalies in meteorites. Exhaustive reviews on the subject discuss these aspects in detail (23,24, 26-30) and these have been incorporated in models of formation of solar system (31,33). All these models indicate the possibility of finding interstellar grains, supernovae condensates or presolar grains in meteorites which are the only such samples we can have for laboratory examination and which may still preserve the records of astrochemistry occurring in the early stages of the solar system.

4. REFERENCES

(1) Eberhardt P. (1974) Earth Planet.Sci. Lett. 24,182.
(2) Black D.C. (1972) Geochim.Cosmochim.Acta 36, 377.
(3) Black D.C. and Pepin R.O. (1969) Earth Planet.Sci. Lett. 6,395.
(4) Gray C.M. and Compston W. (1974) Nature 251, 495.
(5) Lee T. and Papanastassiou D.W. (1974) Geophys. Res. Lett. 1, 225.
(6) Kelly W.R. and Wasserburg G.J. (1978) Geophys. Res. Lett. 5, 1079.
(7) Reynolds J.H. (1960) Phys. Rev. Lett. 4, 8.
(8) Rowe M.W. and Kuroda P.K. (1965) J. Geophys. Res. 70, 709.
(9) Fleischer R.L., Price P.B. and Walker R.M. (1965) J. Geophys. Res. 70, 2703.
(10) Bhandari N., Bhat S.G., Lal D., Rajagopalan G., Tamhane A.S. and Venkatavaradan V.S. (1972) Nature, 234, 543.
(11) Clayton R.N., Grossman L. and Mayeda T.K. (1973) Science 182, 485.
(12) Clayton R.N., Mayeda T.K. and Epstein S. (1978) Geochim.Cosmochim. Acta Suppl. 9, 1267.
(13) Lee T., Papanastassiou D.A. and Wasserburg G.J. (1976) Geophys. Res. Lett 3, 41.
(14) Heydegger H.R., Foster J.J. and Compston W. (1979) Nature 278, 704.
(15) Niederer F.R., Papanastassiou D.A. and Wasserburg G.J. (1980) Lunar Planet Sci. XI, 809.
(16) Fahey A., Goswami J.N., McKeegan K.D. and Zinner E. Ap. J. (1985) 296, 417.
(17) Papanastassiou D.A., Huneke J.A., Esat T.M. and Wasserburg G.J. (1978) Lunar Planet Sci. IX, 839.
(18) Lewis R.S., Gros J. and Anders E. (1977) J. Geophys. Res. 82, 779.
(19) Lewis R.S., Srinivasan B. and Anders E. (1975) Science 190, 1251.
(20) Pepin R.O. (1968) in Origin and Distribution of elements. L. Ahrens (ed), Pergamon, 379.
(21) McCulloch M.T. and Wasserburg G.J. (1978). Ap. J. Lett. 220, L15.
(22) Lugmair G.W., Marti K. and Scheinin N.B. (1978) Lunar Planet Sci. XV, 672.
(23) Clayton D.D. (1979) Space Sci. Rev. 24, 147.
(24) Kerridge J.F. and Chang S. (1985) in Protostars and Planents II Univ. Arizona Press, 738.
(25) Heidenreich J.E. III and Thiemens M.H. (1985) Geochim.Cosmochim. Acta 49, 1303.
(26) Woosley S.E. (1981) in Nucleosynthesis (Biswas S, Ramadurai S. and Vahia M.N. (ed.) Tata Institute of Fundamental Res. Bombay, 17.
(27) Clayton R.N. (1978) Ann.Rev. Nucl. Part.Sc. 28, 501.
(28) Begemann F. (1980) Reports on Progress in Phys. 43, 1309.
(29) Wasserburg G.J. (1985) in Protostars and Planets II, Univ. Arizona Press, 703.
(30) Wasserburg G.J. and Papanastassiou D.A. (1982) in Essays in Nuclear Astrophys. Barnes C.A., Clayton D.D. and Schramm D.N. (eds.) Cambridge University Press,77.
(31) Reeves H. (1978) in Protostars and Planets, Univ. Arizona Press,399.
(32) Schramm D.N. (1978) in Protostars and Planets, Univ.Arizona Press, 384.
(33) Cameron A.G.W. and Truran J.W. (1977) Icarus 30, 337.

DISCUSSION

GOEL: (i) What is the age of Hibonite mineral? (ii) Was ^{26}Al alive in these minerals? (iii) Presence of solar flare gases has been reported in an iron meteorite. Does it not strongly speak against the magmatic origin?

BHANDARI: (i) Hibonites have track density due to ^{244}Pu fission of ~1×10^6 tracks/cm^2 leading to ^{244}Pu/^{238}U $> 10^{-3}$. This yields very small solidification age of hibonites. (ii) Yes, the indication is that ^{26}Al was alive in these grains. (iii) I agree with you that there is some puzzle about formation processes of iron meteorites, presence of solar flare gases and ^{107}Pd-^{107}Ag anomaly. There are a number of things which are not understood. May be there are non-magmatic processes by which iron meteorites can be formed.

LEGER: Do you think that the C in Cl meteorite gives us an idea of what could be an <u>interstellar</u> graphitic grain?

BHANDARI: There is a good possibility that some of the C-grains in Cl chondrites are of interstellar origin. Many anomalies like ^{22}Ne and Xe are inferred to reside on carbon carrier. Thus we may already have interstellar graphite grains available in meteorites.

NORMAN: If I understood your discussion, your conclusion is that the grains that show the ^{26}Mg/^{24}Mg anomalies are preserved interstellar grains. I wonder how the observed ^{107}Ag/^{109}Ag anomalies due to ^{107}Pd decay that have been seen in iron meteorites would be explained in this context?

BHANDARI: The correlation of ^{107}Ag with Pd clearly shows the presence of ^{107}Pd at some point of time. Now the iron meteorites are believed to be formed by planetary melting processes. The ^{107}Ag/^{109}Ag anomaly would therefore suggest that planetary formation and differentiation occurred quickly after nucleosynthesis and injection for ^{107}Pd to survive.