A Component of Primitive Nuclear Composition in Carbonaceous Meteorites

Abstract. *The oxygen of anhydrous, high-temperature minerals in carbonaceous meteorites is strongly depleted in the heavy stable isotopes ^{17}O and ^{18}O. The effect is the result of nuclear rather than chemical processes and probably results from the admixture of a component of almost pure ^{16}O. This component may predate the solar system and may represent interstellar dust with a separate history of nucleosynthesis.*

According to present models of nucleosynthesis (*1, 2*), a combination of several nuclear processes, operating in different environments and under different conditions of temperature and density, are required to produce the elemental and isotopic abundances observed for the matter in the solar system. If material from these various sources was not thoroughly homogenized prior to the formation of the solid bodies of the solar system, one would expect to find variations in the proportions of the isotopes of many elements in samples from different meteorites and planets. Variability of isotopic abundance has indeed been observed for many elements, but is, in most cases, clearly related to known processes occurring *within* the solar system, such as (i) radioactive decay and nuclear fission, (ii) chemical isotope effects and diffusional processes, (iii) cosmic-ray reactions such as spallation and neutron capture, and (iv) implantation of solar wind and solar flare particles. Only in one case has a component of unexplained isotopic abundance been attributed to an origin outside the solar system (*3*). Thus the galactic cosmic rays are the only certain example of matter within the solar system with a separate history of nucleosynthesis, but they have undergone considerable modification of nuclear abundances in traveling from their sources, thus making it difficult to deduce the source composition (*4*).

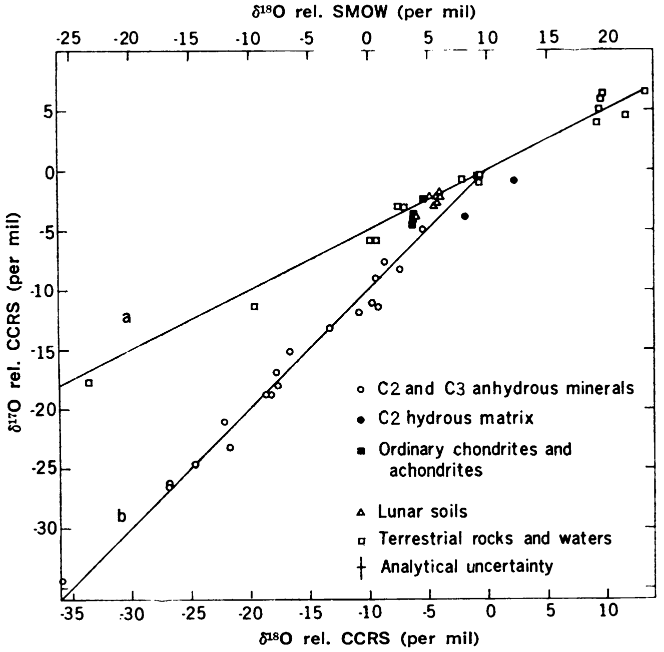
An important feature of chemical isotope effects makes possible the discrimination between chemical fractionations and nuclear processes for those elements which have three or more stable isotopes. Except for hydrogen, chemical isotope effects, whether kinetic or equilibrium, are on the order of a few percent at most and are almost linearly proportional to the relative mass difference of the isotopes, $\Delta m/m$ (*5*). Thus a chemical process that produces a 1 percent increase or decrease in the $^{17}O/^{16}O$ ratio produces a 2 percent increase or decrease in the $^{18}O/^{16}O$ ratio. In terms of the δ notation:

$$\delta^{18} = (R^{18}/R^{18}_{\text{std}} - 1)1000$$

and

$$\delta^{17} = (R^{17}/R^{17}_{\text{std}} - 1)1000$$

where $R^{18} = {}^{18}O/{}^{16}O$, $R^{17} = {}^{17}O/{}^{16}O$, and the subscript "std" refers to an arbitrary oxygen standard. A graph of δ^{17} versus δ^{18} for *all* samples with the same nucleosynthetic history should be very nearly a straight line with a slope of $+\frac{1}{2}$, independent of the choice of the reference standard. This principle was used by Hulston and Thode (*6*) to show that the variations in the isotopic composition of sulfur in meteorites are due entirely to chemical fractionation processes. Figure 1 shows that data for oxygen isotopes from a miscellaneous collection of terrestrial and lunar samples fall along the predicted



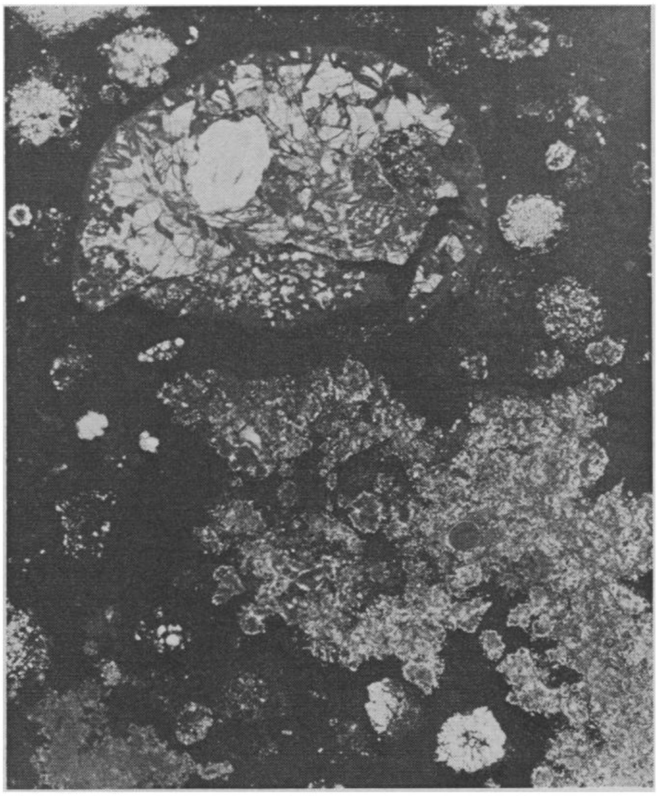


Fig. 1 (left). Relationship between $^{17}O/^{16}O$ variations and $^{18}O/^{16}O$ variations for terrestrial, lunar, and meteoritic samples. Points lying along line a, with a slope of $+\frac{1}{2}$, define the trend for chemical isotope effects; points lying along line b, with a slope of $+1$, define a mixing line between "normal" oxygen and an ^{16}O-rich component. The points on line b are all from phases in carbonaceous chondrites. The reference standards are SMOW [standard mean ocean water (*13*)] and CCRS [carbonaceous chondrite reference standard (see text)]. Fig. 2 (right). Photomicrograph of a section of the Allende meteorite, showing two large white inclusions (see text). Area of section, 8 by 10 mm. [Courtesy Richard J. Kjarval, Graphic Arts Facility, Physical Sciences Division, University of Chicago] mass-dependent fractionation line (line a) with a slope of + ½.

The samples selected for oxygen isotopic analysis in this study were the anhydrous high-temperature phases which occur in the type-2 and type-3 carbonaceous chondrites (C2 and C3) (*7*) as inclusions, fragments, chondrules, or isolated crystals. The mineralogy, trace-element content, and textural features of the inclusions are strikingly similar to those predicted for high-temperature condensates from the solar nebula (*8*). About half of the samples were from the Allende (C3) meteorite; the remainder were from other C2 and C3 meteorites. Samples, 3 to 10 mg each, were taken from individual inclusions by excavation from sawed surfaces. The major minerals were identified by means of a petrographic microscope and x-ray powder patterns. Oxygen was extracted by the BrF_5 procedure (*9*), and isotopic analyses for both δ^{17} and δ^{18} were carried out mass spectrometrically with the use of CO_2 gas (*10*). Results of the isotopic analyses are presented in Table 1.

Taylor *et al.* have noted that the δ^{18} values of olivine and pyroxene of C2 and C3 meteorites are variable (*11*) and are lower than those for the same minerals in ordinary chondrites. Some of the δ^{18} values observed by Onuma *et al.* (*12*) were so low that they could not be accounted for by the chemical fractionation model of Onuma *et al.* for condensation in the solar nebula. The reason is clear from the results of combined δ^{18} and δ^{17} determinations as shown in Fig. 1. The low-^{18}O samples do not fall along the chemical fractionation trend but instead define another line with a slope of + 1. This line intersects the chemical trend line at a value of $\delta^{18} = +10$ parts per thousand (per mil), relative to standard mean ocean water (SMOW) (*13*). For purposes of simplification and without loss of generality, we have plotted the δ values in Fig. 1 relative to a new reference standard (CCRS = carbonaceous chondrite reference standard), defined so that $\delta^{18} = \delta^{17} = 0$ at the point of intersection of line a and line b. Thus the two lines in Fig. 1 have the equations:

$$\text{line a: } \delta^{18} = 2\delta^{17}$$
$$\text{line b: } \delta^{18} = \delta^{17}$$

Table 1. Oxygen isotopic compositions of meteorites and some separated fractions.

Sample No.	Mineralogy*	Textural class†	δ^{18} SMOW‡	δ^{18} CCRS§	δ^{17} CCRS§
		Murchison, class C2			
Mn 1	Hyd. sil.	Mx	+ 8.2	− 1.9	− 3.9
Mn 2	Ol, Opx		− 17.1	− 26.9	− 26.5
Mn 3	Ol, Opx		− 7.8	− 17.8	− 16.9
		Murray, class C2			
My 1	Ol, Opx		− 7.7	− 17.7	− 18.0
		Cold Bokkeveld, class C2			
CB 1	Hyd. sil.	Mx	+ 12.3	+ 2.1	− 0.8
		Allende, class C3			
Al 1	Ol	Mx	+ 1.4	− 8.7	− 7.6
Al 2	Ol	D	+ 5.0		
Al 3	Ol	D	+ 4.8	− 5.4	− 4.9
Al 4	Ol	D	+ 4.0		
Al 5	Ol	D	+ 2.7	− 7.4	− 8.3
Al 6f	Gr, Me, Sp	C	+ 0.8	− 9.2	− 11.4
Al 6c	Gr, Sp, Me	C	+ 0.4	− 9.7	− 11.1
Al 7	Me, Sp, Gr	A	+ 0.7	− 9.4	− 9.0
Al 8	Me, Sp, Gr	B	− 0.8	− 10.8	− 11.9
Al 9	Sp, Cpx	B	− 3.4		
Al 10	Cpx, Sp	B	− 7.6		
Al 11	Ol, Opx	C	− 8.4	− 18.2	− 18.8
Al 12	Sp, Cpx	B	− 11.9	− 21.8	− 23.2
Al 13	Sp, Cpx, Gr, Me	A	− 12.4	− 22.2	− 21.0
Al 14	Sp, Cpx, Gr	A	− 14.8	− 24.7	− 24.6
Al 15	Sp, Me, Cpx	A	− 17.0	− 26.9	− 26.2
Al 16	Ol	C	− 26.2	− 36.0	− 34.5
		Grosnaja, class C3			
Gr 1	Ol		+ 5.6	− 4.5	− 3.9
Gr 2	Ol		− 6.5	− 16.7	− 15.2
		Vigarano, class C3			
Vi 1	Ol		− 8.7	− 18.7	− 18.8
		Karoonda, class C4			
Ka 1	Mt		− 3.1	− 13.3	− 13.2
		Bruderheim, class L6			
Br 1	Ol, Px, Pc		+ 4.7	− 5.4	− 2.4
		Richardton, class H5			
Ri 1	Ol, Px, Pc		+ 3.8	− 6.3	− 4.6
		Yurtuk, class howardite			
Yu 1	Pc		+ 4.0	− 6.2	− 3.6
Yu 2	Pc		+ 4.0	− 6.2	− 4.1

* Major minerals as identified by x-ray powder patterns and optical microscopy. Abbreviations: Hyd. sil., hydrous ferromagnesian silicates; Ol, olivine; Px, pyroxene; Opx, orthopyroxene; Cpx, clinopyroxene; Gr, grossularite; Me, melilite; Sp, spinel; Pc, plagioclase; and Mt, magnetite. † Mx, matrix. Fragments and inclusions from Allende have been classified texturally as follows: A, "chondrules"; white, coarse-grained; fine-grained opaque rim; B, very fine-grained; purple or pink, sometimes with white rim; ragged shape; C, fine-grained; amoeboid; usually tan-colored; botryoidal outlines in interiors (in thin section); and D, dark fragments. ‡ δ^{18} in parts per thousand relative to the SMOW standard (*13*). Error, ± 0.1 per mil. § δ^{18} in parts per thousand relative to the CCRS standard (see text); error, ± 0.1 per mil. δ^{17} in parts per thousand relative to the CCRS standard; error, ± 1 per mil.

The Allende white inclusions exhibit several different morphologies, textures, and mineralogies. No correlation has been seen between any of these properties and the isotopic compositions. Figure 2 shows two inclusions of very different texture and morphology, both of which are strongly depleted in the heavy oxygen isotopes. The coarse-grained, rounded inclusion occupying the top one-third of the area was the source for sample Al 14; the large fine-grained, amoeboid inclusion in the lower right was the source for sample Al 16. The δ^{18} values of the dark fragments of Allende are consistently higher than those of the white inclusions and are similar to the δ^{18} values of ordinary chondrites. In the two samples for which a δ^{17} value is available, the data points fall on the trend of other samples from the carbonaceous meteorites. The full range of data on line b of Fig. 1 can be generated from samples from a single meteorite, as shown by Allende. Unrelated samples from other C2 and C3 meteorites fall on the same line. Although most of the scatter of the data about the line is attributable to analytical error in the ^{17}O determinations, part of it must come from small superimposed chemical isotope effects, since the samples have variable mineralogy. Larger chemical effects are evident for the low-temperature hydrous silicate matrix material from the C2 chondrites Murchison and Cold Bokkeveld.

The strong departure of the meteorite data from the chemical trend line clearly implies the intervention of nuclear processes. The C2 and C3 samples have lower $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios than all other meteorites studied, and the ratios extend well below the range observed for terrestrial rocks. Hence a process of depletion of the heavy isotopes, or of the addition of ^{16}O, is implied. Specific types of irradiation of a mixture of oxygen isotopes by protons, neutrons, or alpha particles might remove a larger proportion of ^{17}O and ^{18}O nuclei, relative to the more stable ^{16}O, but the observation that the two heavy isotopes suffer equal fractional depletions requires reactions which have the same cross sections for both nuclei, a highly unlikely coincidence. Furthermore, depletions of these relatively abundant species by as much as 3 percent in situ would be expected to have major nuclear consequences for the elemental and isotopic abundances of other elements. No such anomalies have been reported.

Line b may be interpreted as a mixing line between a component lying on or near line a and a component with lower $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios. Barring the fortuitous possibility that the ^{16}O-rich component has the same $^{18}O/^{17}O$ ratio as CCRS, the most likely end-member is a component so depleted in ^{17}O and ^{18}O as to act as a pure ^{16}O diluent.

Oxygen containing a much lower abundance of ^{17}O and ^{18}O may exist or may be formed in stars as a product of helium burning *(14)* (producing pure ^{16}O), or as a product of carbon burning in explosive nucleosynthesis *(2, 15)*. If the ^{16}O component in the carbonaceous chondrites is of such an origin, it must be determined whether the star involved was our sun or some other star or stars. The sun, as a population I star, was formed with a complement of heavy elements in the abundances observed in the meteorites and planets, presumably including ^{17}O and ^{18}O. To derive the ^{16}O component from the sun would require the burnup of these elements prior to ejection and incorporation into the meteorites. No evidence is yet available on the abundances of ^{17}O and ^{18}O in the present solar wind, which might permit evaluation of this hypothesis.

There remains the interesting and exciting possibility that the meteoritic inclusions contain a small component (up to 3.5 percent in the samples analyzed) of ^{16}O-rich matter derived from outside the solar system. Cameron *(16)* has suggested that interstellar grains may have been incorporated into meteorites. If the inclusions of C2 and C3 meteorites do indeed contain matter with a history of nucleosynthesis different from that in the earth, moon, and ordinary chondrites, we may expect to find isotopic anomalies in other light elements. In an extreme case, matter which had undergone only α-process reactions would contain only integral α nuclei, such as ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si, so that large effects should be identifiable in the isotopic abundances of magnesium and silicon. If the ^{16}O component is the result of carbon burning in a supernova explosion as envisioned by Arnett and his co-workers *(2, 15)*, isotope anomalies in magnesium and silicon should also exist, with their directions and magnitudes dependent on the composition and size of the star prior to explosion. Both magnesium and silicon have three stable isotopes, so that the approach used here for oxygen can be applied to detect the presence of excesses of ^{24}Mg and ^{28}Si in those samples in which the ^{16}O excess has been found. By interrelating all of the isotopic measurements, a clear picture of the exotic component should be attainable. The quantities of the ^{16}O-rich component are sufficiently great that the grains might be visible microscopically and analyzable by microprobe techniques if they are large enough.

It is interesting to consider the distribution of the ^{16}O component within the solar system. Since the earth, moon, and ordinary chondrites lie on a single chemical fractionation trend, it can be concluded that they were derived from a reservoir homogenized with respect to oxygen isotopes, and that the small differences among them are due to chemical fractionations during condensation and accretion. The C2 and C3 meteorites have acquired, in addition to this homogenized material, a small excess of material either from the sun or from a source outside the solar system. This difference of behavior may have resulted from differences in the available surface areas during the addition of the foreign component or may reflect spatial inhomogeneities in the solar system. Further studies on physically separated and fractionated samples of meteorites may help resolve this problem.

On a whole-rock basis, the C3 meteorites have $\delta^{18} \approx 0$ per mil relative to SMOW *(11, 12)* or − 10 per mil relative to CCRS, implying about a 1 percent addition of the ^{16}O-rich component over that present in the homogenized reservoir. It is not necessary to postulate that the region in which the carbonaceous chondrites formed contained an excess of the ^{16}O-rich component, but only that it was not volatilized (and thus mixed with the large gaseous reservoir) before incorporation into the meteorite. In the region in which the materials of the earth, moon, and ordinary chondrites condensed and accreted, the ^{16}O-rich component could have been volatilized and diluted beyond detection by the larger reservoir of oxygen (ten times as large), present predominantly as CO, in the gas phase.

Whether or not solid interstellar grains would escape evaporation during a high-temperature stage in the early solar system depends on their chemical and mineralogical composition, which in turn depends on their nucleosynthetic history. If the grains were composed only of products of the α-process, evaporation is more likely, since all of the most refractory condensates contain either aluminum or titanium *(7)*, which are not produced in the α-process. Explosive carbon burning, on the other hand, can produce magnesium and aluminum in solar system abundances *(2, 15)*, so that refractory phases such as corundum (Al_2O_3) and spinel ($MgAl_2O_4$) may be made. These could survive and perhaps act as condensation nuclei for the calcium-aluminum silicates and magnesium silicates which make up the major phases of the inclusions in C2 and C3 meteorites.

It is hoped that further isotopic and chemical studies of the constituents of the C2 and C3 meteorites will lead to a more complete characterization of the ^{16}O-rich component in terms of its chemical and mineralogical composition. The existence of more than one type of matter in the solar system with different histories of nucleosynthesis would be of great value in testing the models of nucleosynthesis, and would also be of benefit in the construction of models of the origin and evolution of the solar system.

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Hypothalamic Obesity: The Myth of the Ventromedial Nucleus

Abstract. *Lesions restricted to the ventromedial nucleus of the hypothalamus were neither necessary nor sufficient for, and did not contribute to, the production of hypothalamic obesity. Hypothalamic lesions and knife cuts that do produce obesity damage the nearby ventral noradrenergic bundle or its terminals.*

For over 30 years the ventromedial nucleus of the hypothalamus (VMN) has been linked in theory to the suppression of eating. There have been many reports of hyperphagia and obesity after destruction of the VMN (*1*). Both neurophysiological and anatomical evidence for connections between a presumed VMN satiety center and a lateral hypothalamic feeding center have been reported (*2*).

However, there is evidence that the overeating and obesity that once seemed associated with destruction of the VMN is not due to VMN damage per se, but rather to destruction of the nearby ventral noradrenergic bundle (*3*). The ventral noradrenergic bundle ascends from brainstem nuclei to innervate limbic areas, including several hypothalamic loci, but sends relatively few terminals to the VMN (*4*).

That VMN damage itself contributes to hypothalamic obesity is open to question. Lesions of the VMN that are produced by radio-frequency currents fail to produce obesity (*5*). Closer examination of the studies that do link VMN lesions to obesity reveals that the effective lesions overflow the bounds of the VMN, the largest lesions typically producing the fattest rats (*1*). Finally, lesions caudal or lateral to the VMN, parasagittal knife cuts rostrolateral to the VMN, and midbrain lesions can all produce obesity even though the VMN is left intact (*1*, *6*).

I now report that even under optimal testing conditions lesions restricted to the VMN, even iron depositing lesions (*5*), produce neither overeating nor obesity. The VMN lesions cause obesity only when they overflow the VMN, and the magnitude of the obesity is proportional to the amount of overflow.

Female albino rats ($N = 119$) were allowed free access to a highly palatable high fat diet (*7*) and tap water. Lesions were produced by passing an anodal direct current through platinum-iridium, stainless steel, or iron wire electrodes. The lesions were all aimed at the rostral tip of the VMN, with the use of stereotaxic coordinates that had previously been associated with rapid weight gains (*8*).

For the initial series of rats the bilateral lesions were produced by a current of 2 ma for 20 seconds (40 millicoulombs) as described in (*7*, *9*). The lesions that resulted from 40 mcoulomb were enormous (Fig. 1L), with iron electrode lesions by far the largest, and platinum-iridium the smallest (*10*). The lesioning dosages for subsequent groups of rats were therefore halved to 20 mcoulomb and for the iron and steel electrodes, halved again to 10 mcoulomb. Finally, to approximately match the size of the very large lesions produced by 40 mcoulomb delivered by iron or steel electrodes, platinum electrode lesions were made with 160 mcoulomb (*11*).

Lesions that fell entirely within the borders of the VMN and the intervening midline area (Fig. 1F) did not produce obesity. Weight gains for the five animals with these lesions fell within the range (0 to 1.6 g/day) of 17 sham-operated controls. Lesions that damaged both the VMN and the dorsomedial nucleus also did not cause obesity (Fig. 1C). In contrast, lesions that extended ventrally from the VMN did produce slight obesity (3.0 g/day) (Fig. 1G). This slight effect appears to be due to the damage ventral to the VMN. The failure to produce obesity with lesions completely restricted to the VMN occurred despite the use of all of the parameters that maximize postlesion weight gains, that is, female rats (*7*), heavy iron deposits from anodal current delivered through iron or steel electrodes (*5*), and a palatable high fat diet (*7*).

The brain areas destroyed by the 55 smallest lesions were compared. There was a common area for the lesions of the five rats with the greatest weight gains (9.0 to 12.6 g/day). These most effective of the smallest lesions all destroyed an area immediately rostral to the rostral tip of the VMN (Fig. 1A). It is precisely across this area that a group of noradrenergic fibers crosses the midline within the suprachiasmatic decussation. These noradrenergic fibers are thought to derive from the ventral ascending noradrenergic bundle (*4*). Small lesions located more dorsally or more caudally were less effective (Fig. 1, B and D) (*12*).

Larger lesions produced far greater weight gains. If the thalamus and the nigro-striatal dopamine pathway at the extreme lateral edge of the hypothalamus (*4*) were spared, then the bigger the lesion, the greater the initial rate of weight gain. For example, a large platinum electrode lesion spared the VMN but produced rapid weight gains of 10.6 g/day (Fig. 1E). The correlation between lesion size and weight gain is illustrated by the representative series of lesion reconstructions in Fig. 1, F to L.