ISOTOPE COSMOCHEMISTRY II
ORIGIN OF SHORT-LIVED NUCLIDES

There is some debate over exactly how the short-lived radionuclides were synthesized. As we saw earlier in this chapter, heavy element nucleosynthesis occurs mainly in red giant stars and in supernovae. Anomalous isotopic compositions of stable elements, which we discuss below, provides clear evidence that meteorites contain some material synthesized in both these environments. However, they provide no constraints on when this happened. Only with the unstable nuclides can we address the question of when. On galactic scales of time and space, red giants and supernovae continually inject newly synthesized elements into the interstellar medium. Those nuclides that are unstable will steadily decay away. These two competing processes will result in steady-state abundance of these nuclides in the interstellar medium. The abundances of $^{10}$Be, $^{125}$I, and $^{182}$Hf listed in Table 16.1 roughly match the expected steady-state galactic abundances and hence do not require a specific synthesis event. However, the abundances of shorter-lived $^{10}$Be, $^{26}$Al, $^{41}$Ca, $^{53}$Mn or $^{60}$Fe in the early Solar System requires synthesis of these nuclides at the time of, or just before, Solar System formation.

The conventional view is that these nuclides were synthesized in a red giant and/or a supernova in the region where the solar system formed just shortly before its formation. Some of these elements, such as $^{26}$Al are most efficiently synthesized in red giants; others, such as $^{60}$Fe are most efficiently synthesized in supernovae. Thus most models invoke both environments, which may or may not have been the same star at different times. From an astronomical perspective, nucleosynthesis shortly before the solar system formed is not surprising: stars usually form not in isolation, but in clusters in large clouds of gas and dust known as nebulae. The Great Nebula in Orion is a good example. Some of the stars formed in these stellar nurseries will be quite large and have short lifetimes, ending their existence in supernova explosions. Thus stellar death, including the red giant and supernova phases, goes on simultaneously with star birth in these nebulae. Indeed, one popular hypothesis is that the formation of the solar system was actually triggered by a supernova shock wave. Boss and Vanhala (2001) provide a good discussion of this view.

Evidence of the existence of $^{10}$Be in some CAI’s has led to an alternative hypothesis, namely that many of the short-lived extinct radionuclides were produced by spallation within the solar system as it was forming. As we have seen, $^{10}$Be is not synthesized in stars, hence it presence in CAI’s and other primitive chondritic components is problematic for the red giant-supernova injection hypothesis. Another key observation is that young protostars emit X-rays. X-rays are produced by accelerating charged particles. Hence some have suggested that near the surface of the accreting protosun, magnetic reconnection events could produce flares that accelerate ions up to very high energies – essentially creating cosmic rays. Spallation would occur when the accelerated particles encounter dust grains – the CAI’s – that happen to be close to the forming Sun (within 0.1 AU). According to this theory, some of these irradiated CAI’s would have been carried back out to the vicinity of the asteroid belt by the energetic “X-winds” that are associated with these protostars. This theory can readily account for the abundances of $^{10}$Be, $^{26}$Al, $^{41}$Ca, and $^{53}$Mn observed. If it is correct, it solves the problem of the age gap between CAI’s and chondrules. Based on their apparent $^{26}$Al/$^{27}$Al ratios, CAI’s appear to be several million years older than chondrules. Yet the time required for these particles to drift through the solar nebula is only about 10,000 years. The spallation hypothesis means that initial isotope ratios are not simple functions of time, but might also vary in space, particularly radial distance from the protosun, because of variations in radiation flux. Russell et al. (2001) provide a concise summary of this hypothesis.

Proponents of the red giant/supernova injection hypothesis point out that the spallation hypothesis cannot explain the presence of $^{60}$Fe, which cannot be produced by spallation. They concede that spalla-
tion is the only way to produce $^{10}\text{Be}$, but argue that it can be produced by collisions with particles accelerated in the enhanced solar winds of red giants and/or in the expanding envelopes of supernovae. Thus debate continues on this subject. We point out only that the two sets of ideas are not mutually exclusive, and it is very possible that both spallation and stellar/explosive nucleosynthesis were involved.

**STARDUST AND ISOPTIC ANOMALIES IN METEORITES**

In the previous lecture, we looked at the geochronology of meteorites, both from the perspective of conventional decay systems and from the perspective of extinct radionuclides. The decay of these extinct radionuclides results in anomalous isotopic compositions of the daughter elements. However, there are other isotopic anomalies in meteorites that are not due to the *in situ* decay of radionuclides. Many of these anomalies, like those created by decay of extinct radionuclides, may reflect the injection of newly synthesized material into the cloud of dust and gas from which the solar system ultimately formed. Others, however, may reflect isotopic inhomogeneity within this cloud, and the variable abundance of exotic gas and grains of material synthesized at various times and places in the galaxy. Still other isotopic anomalies may reflect chemical fractionations within this cloud. It is these anomalies we focus on in this lecture.

**Neon Alphabet Soup and ‘Pre-Solar’ Noble Gases in Meteorites**

Noble gases were the first group of elements in which isotopic variations were identified, and they occur in virtually all of the carbonaceous chondrites that have not experienced extensive metamorphism. In contrast to the isotopic anomalies of metals mentioned above, most of the isotopically distinct noble gas is contained in the matrix that accreted at low temperature (below 100-200°C), specifically in highly unreactive carbon species, including organic carbon, graphite, diamond, and silicon carbide. Noble gases are present in meteorites at concentrations that are often as low as 1 part in $10^{10}$. Although they can be isolated and analyzed at these concentrations, their isotopic compositions are nonetheless partly sensitive to change due to processes such as radioactive decay (for He, Ar, and Xe), spallation and other cosmic-ray induced nuclear processes, and solar wind implantation. In addition, mass fractionation can significantly affect the isotopic compositions of the lighter noble gases (He and Ne). Up to the late 1960’s, it was thought that all isotopic variations in meteoritic noble gases were related to these processes. For example, Ne isotopic variations could be described as mixtures of three components, “Neon A” or “planetary” (similar in composition to the Earth’s atmosphere), “Neon B”, or solar, and “Neon S”, or spallogenic (cosmogenic) (Figure 12.1). In 1969, evidence of a $^{22}\text{Ne}$-rich component, named “Neon E” was found in the high temperature (900-1100°C) release fractions of six carbonaceous chondrites. Its release at high temperature indicated it was efficiently trapped in a phase that breaks down only at high

![Figure 12.1. Neon isotopic compositions in a step-heating experiment on Orgueil CI chondrite, which produced the first evidence of ‘pre-solar’ or exotic Ne. The points connected by the line show the changing Ne isotope ratios with increasing temperature. Shaded area was the original estimate of the composition of the pure Ne-E component. Also shown are the compositions of Ne-A (‘solar’), Ne-B (‘planetary’), and Ne-E (‘spallogenic’). After Black and Pepin (1969).](image)
temperature.

The carrier of Neon-E proved difficult to identify. Many scientists participated in an intensive search over nearly 2 decades for the carrier phase of these components. The search quickly focused on the matrix, particularly that of CM2 meteorites. But the fine-grained nature of the matrix, together with the abundance of sticky and refractory organic compounds, made work with the groundmass difficult. In the late 1980’s, E. Anders and his colleagues at the University of Chicago (e.g., Tang and Anders, 1988) found that Neon-E is associated with fine-grained (<6 µm) graphite and SiC (silicon carbide) of the matrix. Ne-E actually consists of two isotopically distinct components: Ne-E(L), which was found to reside in graphite, and Ne-E(H) which resides in SiC. The $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of Ne-E(H) is less than 0.01, while that of Ne-E(H) is less than 0.2.

The origin of Ne-E, and Ne-E(L), which is almost pure $^{22}\text{Ne}$, posed something of a mystery. It was originally thought that it was a decay product of $^{22}\text{Na}$, which has a half-life of 2.6 years, produced in red giants. Na could readily separate from Ne and other noble gases by condensation into grains. However, this hypothesis has now largely been rejected. For one thing, Huss et al. (1997) found that SiC grains in Orgueil (CI), had far too little Na to account for the observed amount of $^{22}\text{Ne}$. More detailed analytical work (Lewis et al., 1990) found that the Ne isotopic abundances actually match rather well that expected for nucleosynthesis in the He-burning shells of low mass, carbon-rich, thermally pulsing red giants called Asymptotic Giant Branch (AGB) stars. $^{22}\text{Ne}$ is synthesized from $^{14}\text{N}$, which is synthesized from C, N, and O nuclei during the previous hydrogen burning phase, through the sequence $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+,\nu)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$ (Gallino et al., 1990).

The other key noble gas in this context is xenon. Having 9 isotopes rather than 3 and with contributions from both $^{129}\text{I}$ decay and fission of various heavy elements, isotopic variation in xenon are bound to be much more complex than those of Ne. On the other hand, its high mass minimizes mass frac-

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Figure 12.2. Isotopic composition of Xe-S (relative to normal solar Xe with $^{130}\text{Xe}=1$). Xe-S is found in silicon carbide and associated with Ne-E(H). $^{128}\text{Xe}$ and $^{130}\text{Xe}$ are synthesized only in the s-process, hence the most likely site for its synthesis is red giants.

Figure 12.3. A presolar SiC grain. From Nittler (2003).

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* More specifically, AGB stars are low to modern mass stars (i.e., 0.6 to 10 solar masses) that have completed the He-burning phase of their post-main sequence evolution. They have enormously strong stellar winds, enough to lose 50 to 70% of their mass during this phase.
tionation effects, so “solar” (more properly solar wind) and “planetary” Xe are isotopically similar. The first evidence of other isotopic variations in Xe came in the early 1960’s, but these variations were thought to be fissogenic (at one time it was argued they were produced by fission of short-lived super-heavy elements). Subsequently, several isotopically distinct Xe components were identified. One of these is associated with Ne-E(H) in SiC and is enriched in the s-process-only isotopes of Xe ($^{128}$Xe and $^{130}$Xe) and is called, appropriately enough, Xe-S. The isotopic pattern of Xe-S is shown in Figure 12.2. This is most likely synthesized in red giants. Indeed, there is a striking similarity of the isotopic abundances to the calculated production of s-process nuclides in AGB stars. Comparison of the isotopic composition of Kr, which is also anomalous in the SiC, with theoretical calculations further narrows the site of synthesis to low-mass (1-2 solar masses) AGB stars, consistent with the inferences made for $^{22}$Ne synthesis. SiC grains are thus apparently condensed from material ejected from red giant stars, which have very strong solar winds. Thus in a very real sense, these grains are truly stardust.

The Ne in the SiC is a little richer in $^{21}$Ne than the predicted products of AGB stars. This is presumably due to cosmogenic production of $^{21}$Ne. If so, some 130 Ma of cosmic ray irradiation would be required to produce the observed $^{21}$Ne, indicating the grains predate meteorite parent body formation by this amount of time (Lewis et al., 1994). If they had been degassed, however, the grains could be much older.

Another isotopically distinct component, identified in acid-dissolution residues of Allende (CV3) named Xe-HL because it is enriched in both heavy and light Xe isotopes was released in the 700-1000°C temperature step. This particular enrichment pattern can apparently by produced only by a combination the p- and r-processes (Figure 12.4). These processes, of course, operate only in supernovae. Unlike Ne-E, Xe-HL is accompanied by the other noble gases, of which Ne, Ar, and Kr all show enrichment in their heavier isotopes. Eventually, Anders’ group identified the carrier of Xe-HL as microdiamonds. These diamonds are extraordinarily fine, averaging only 1 nm in diameter and containing typically only $10^3$ or so atoms. Roughly one in every four atoms is at the surface. As a result, the properties of this material differ significantly from normal diamond, which considerably complicated the effort to isolate it. Analysis of the noble gases in the SiC, graphite

### Table 12.1. Isotopic Characteristics of Interstellar Grains

<table>
<thead>
<tr>
<th>Phase</th>
<th>Diamond</th>
<th>SiC</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotopic Component</td>
<td>Xe-HL</td>
<td>Xe-S, Ne-E(H)</td>
<td>Ne-E(L)</td>
</tr>
<tr>
<td>Enriched in Isotopes</td>
<td>$^{124}$Xe, $^{126}$Xe</td>
<td>$^{128}$Xe, $^{130}$Xe, $^{22}$Ne</td>
<td>$^{22}$Ne</td>
</tr>
<tr>
<td>Nuclear Process</td>
<td>p, r</td>
<td>s, $^{21}$Na($\beta^+$,v)$^{20}$Ne</td>
<td>$^{14}$N + 2α→$^{22}$Ne</td>
</tr>
<tr>
<td>Grain Size, µ</td>
<td>0.001</td>
<td>0.03-10</td>
<td>0.8-7</td>
</tr>
<tr>
<td>Abundance in C2 chondrites, ppm</td>
<td>400</td>
<td>7</td>
<td>&lt;2</td>
</tr>
<tr>
<td>($^{13}$C/$^{12}$C)/($^{13}$C/$^{12}$C)$_o$</td>
<td>0.96</td>
<td>0.03 – 50</td>
<td>0.012 – 50</td>
</tr>
<tr>
<td>($^{15}$N/$^{14}$N)/($^{15}$N/$^{14}$N)$_o$</td>
<td>0.66</td>
<td>0.015 – 20</td>
<td>0.55 – 6.7</td>
</tr>
</tbody>
</table>

and diamond by step-heating was comparatively easy, since each of these decompose at distinct temperatures. Identifying the carriers proved more difficult. However, once the carrier grains were identified and isolated, it became possible to analyze the isotopic composition of other elements. The isotopic compositions of other elements have also proved to be anomalous to varying degrees. The noble gas, C and N isotopic compositions are summarized in Table 12.1. Also shown in the table is the abundance of these phases, which is quite low.

Many of the SiC and graphite grains are large enough so the isotopic compositions of the major elements in individual grains can be analyzed by ion probe. These analyses (e.g., Figure 12.5) reveal a diversity of isotopic compositions as well as correlations between grain size and isotopic composition. Clearly, the SiC grains do not form a single population, but represent a number of populations of grains, each produced in a different astronomical environment. The majority of grains have isotopically heavy C and light N (relative to solar), which are the compositions expected from production in the CNO cycle (Lecture 2). However, compositions produced by other mechanisms are also represented. Si isotopic compositions are also anomalous. Anomalies have also been identified in the isotopic compositions of Ti, Sr, Zr, Mo, Ba, Nd, Sm, and Dy in these grains. These have further helped to identify the stellar production environments of these grains (Figure 12.6). For example, graphite and most SiC grains display enrichment in $^{96}$Mo, which is an s-process isotope. This enrichment pattern is that expected for s-process nucleosynthesis in the He-burning shell of AGB stars. A subset of the SiC grains, the so-called SiC X grains, show enrichment in $^{95}$Mo and $^{97}$Mo, which are r-
process isotopes, and were likely produced in the neutron burst of supernovae.

Mg isotopic compositions in both graphite and SiC are also anomalous. A fourth refractory phase identified in the groundmass (but poor in noble gases) is corundum (Al₂O₃). The graphite, SiC, and corundum have inferred initial 26Al/27Al ratios of \(5 \times 10^{-5}\) to \(1 \times 10^{-1}\). In contrast, we found in the previous lecture that CAI’s had inferred initial 26Al/27Al ratios up to \(5 \times 10^{-5}\), and that most other meteoritic materials showed no excess 26Mg. More recently, presolar grains have been shown to include Si₃N₄, spinel, hibonite, a variety of metal carbides, and perhaps TiO₂ and Fe-Ni metal.

Up until 2004, all the presolar grains identified in meteorites and in interstellar dust particles (IDP’s) collected by spacecraft and high-altitude aircraft were non-silicates. This puzzled cosmochemists as spectroscopic observations of young stars reveal that silicates are abundant, meaning they should be abundant in molecular clouds like the one in which the solar system formed. In 2004, several research groups reported not only finding silicates (olivine) with highly anomalous O isotope ratios, hence indicating a presolar provenance, they reported that that presolar silicates were actually more abundant than non-silicate presolar grains. In the exceptionally primitive carbonaceous chondrite Acfer, Nagashima et al. (2004) and Nguyen and Zinner (2004) found presolar silicates were present in the groundmass at an abundance of about 30 to 40 parts per million, compared to 14 parts per million for presolar SiC. This late discovery most likely reflects the approaches used to isolate the presolar grains. The high-temperature of release of the anomalous noble gases suggested the carrier grains were quite refractory. Anders and coworkers attacked the problem with a brut-force method: dissolving away whatever could be dissolved, then studying the residue. This led to acid-resistance phases such as SiC, graphite, and diamond. The most recent approaches use ion microprobes to produce isotopic ratio maps of thin sections of meteorites. Once an isotopic anomalous grain is identified, its composition is readily determined \textit{in situ} with an electron microprobe.

A Late Injection of Supernova Debris?

Bizzaro et al. (2007) found a subset of early-formed differentiated meteorites, including the angrites, ureilites, and some irons and pallasites (stony-irons thought to be asteroidal core-mantle boundaries), have ⁶⁰Ni deficits of around 25 ppm (0.2 epsilon units) compared to terrestrial material, an enstatite, ordinary and carbonaceous chondrites, and a Martian meteorite. ⁶⁰Ni is the daughter of ⁶⁰Fe, which as a half-life of 1.5 Ma. They suggested that a type Ib supernova injected ⁶⁰Fe into the solar nebula after the parent bodies of the early-formed objects had accreted, but before the terrestrial planets and the parent bodies of the terrestrial planets had accreted. Type Ib and Ic supernovae result from core collapse of massive stars that have thrown off their outer layers during earlier red giant phases. Such a supernova would not have injected ²⁶Al produced during the red giant phase (unlike a type II supernova).

Other Exotic Components in Meteorites

Besides isotopic anomalies apparently produced by decay of short-lived radionuclides such as ²⁶Al, ¹²⁹I, and ²⁴⁴Pu, and those associated with the interstellar grains in the matrix, other isotopic anomalies have been identified in CAI’s. Some of these have been observed only in a few CAI’s from Allende: Ca, Ba, Sm, Nd, and Sr. They have been termed FUN anomalies: fractionation and unknown nuclear. Other variations are widespread, but appear to be due to fractionation, e.g., Si and Mg. A systematic search by G. Lugmair and colleagues at the University of California at San Diego has revealed that isotopic variations of the iron peak elements (elements clustered around the cosmic abundance peak at Fe), Ca through Zn, are ubiquitous in many CAI’s. Variations are up to per mil size relative to terrestrial isotope ratios, and are characterized by overabundance of the most neutron-rich nuclides (⁶⁰Ca, ⁵⁰Ti, ⁵⁴Cr, ⁶⁴Ni, and ⁶⁰Zn), often accompanied by under-abundance of the most neutron-poor isotopes. In some instances, isotopic variations within single mineral grains have been observed with the ion microprobe. In general, these isotopic variations are most readily explained if the inclusions contain an admixture of neutron-rich e-process material from a supernova.
With the exception of these dramatic isotopic variations on very fine scales and of oxygen, discussed below, decades of research has shown that the isotopic composition of the solar system is strikingly uniform on larger scales. The conclusion has been that the solar nebula was very well mixed. But as precision in isotopic measurement improves, this picture may be breaking down. Based in part on variations in \(^{142}\text{Nd}/^{144}\text{Nd}\), Andreasen and Sharma (2006) have suggested that carbonaceous chondrites have a roughly 100 ppm deficit of the p-process isotopes \(^{146}\text{Sm}\) and \(^{144}\text{Sm}\) relative to ordinary chondrites. Ranen and Jacobsen (2006) found that chondrites have small excesses in \(^{137}\text{Ba}\) and \(^{138}\text{Ba}\), which are r-process isotopes, relative to the Earth. Thus small amplitude isotopic heterogeneities might have existed in the solar nebula as the Earth and meteorite parent bodies were forming.

**Ubiquitous Oxygen Isotope Variations**

Another element commonly showing isotopic variations is O. Until 1973, O isotope variations in meteorites were thought to be simply the result of fractionation, as they generally are on Earth. But when R. Clayton of the Univ. of Chicago went to the trouble of measuring \(^{17}\text{O}\) (0.037% of O) as well as \(^{18}\text{O}\) and \(^{16}\text{O}\), he found that these variations were not consistent with simple mass-dependent fractionation. This is illustrated in Figure 12.7. On a plot of \(^{17}\text{O}/^{16}\text{O}\) vs. \(^{18}\text{O}/^{16}\text{O}\), variations created by fractionation should plot along a line with slope of 1/2. Terrestrial and lunar samples do indeed define such a line, but

![Figure 12.7](image-url)

**Figure 12.7.** Variation of O isotope ratios in meteorites and terrestrial and lunar samples. Most of the data from Allende inclusions is off the plot to the left. From the work of R. N. Clayton.

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other meteorites or their components fall along a line with slope = 1. One interpretation is that this reflects mixing between a more or less pure $^{18}$O component, such as might be created by helium burning, and a component of 'normal' isotopic composition. However, Thiemens and Heidenreich (1983) conducted experiments in which ozone produced by a high frequency electric discharge showed "mass independent fractionation", i.e., where the ozone was equally enriched in $^{17}$O and $^{18}$O (Figure 12.8) relative to $^{16}$O. The experiment demonstrates that a slope of 1 on the $\delta^{17}$O — $\delta^{18}$O diagram could be produced by chemical processes. Thiemens suggested this kind of fractionation results from a kinetic fractionation mechanism, which arises because non-symmetric (e.g., $^{16}$O$^{17}$O or $^{18}$O$^{16}$O) molecules have more available energy levels than symmetric (e.g., $^{16}$O$^{16}$O) molecules (as we will see later in the course, symmetry enters into the partition function, which governs isotope fractionation). Subsequent studies have suggested it results from asymmetric molecules having a greater number of quantum states than symmetric ones. Others have suggested it results from the collision process itself.

Subsequent to Thiemens and Heidenreich’s work, mass-independent fractionations have been discovered in O and S isotopes of terrestrial materials; we’ll consider the details latter in the course. Mass-independent fractionation in oxygen has been found in atmospheric ozone. In the case of sulfur, photodissociation of atmospheric sulfur compounds appears to cause mass-independent fractionation.

The explanation for mass-independent O fractionation in the solar nebula may also involve photodissociation. Clayton (2002) suggested that the anomalies arose through radiation self-shielding in the solar nebula. In his model, ultraviolet radiation from the early proto-Sun dissociated carbon monoxide, which would have been among the most abundant gases in the solar nebula. Because C$^{18}$O rather than C$^{17}$O or C$^{18}$O was the dominant oxygen-bearing species, the radiation of the wavelength necessary to dissociate C$^{18}$O would have been quickly absorbed as it traveled outward from the Sun. At greater distance from the Sun, radiation of the frequency necessary to dissociate C$^{16}$O would have been absent, while that needed to dissociate C$^{17}$O and C$^{18}$O would still be available. Thus at these distances, C$^{17}$O and C$^{18}$O are preferentially dissociated, and equally so, making $^{17}$O and $^{18}$O preferentially available for reaction to form silicates and other meteorite components. Since the solar nebula would have been fairly opaque at this time, this isotopic fractionation would have occurred in the inner part of the nebula, near the forming star, and then expelled back out by the “X-wind”. The implication of this is that most of the solid matter that makes up the Earth and it neighbors must have cycled through this inner region at one point. Clayton’s model also predicts that the Sun itself should be poor in $^{18}$O and $^{17}$O compared to meteorites and the Earth – closer in composition to the CAI’s. This prediction appears to have recently been confirmed based on analysis of solar wind implanted in lunar soil. Hashizuma and Chaussidon (2005) found that surfaces of lunar soil particles have oxygen isotope compositions up to $20\%$ enriched in $^{18}$O. This solar-wind-implanted oxygen presumably represents the O isotopic composition of the Sun, which has most of the mass, and most of the O in the solar system. It would thus seem that it is meteorites and planets that are anomalously and variably depleted in $^{18}$O, just as Clayton’s theory predicts.

As Figure 12.9 shows, while variations between classes are mostly mass-independent, variations within groups of meteorites fall along mass-dependent fractionation lines. This strongly suggests that, for the most part, different meteorite groups probably formed in different parts of the presolar nebula. There are a few exceptions: IIE irons fall on a mass-dependent fractionation line (MDFL) with H-chondrites, IVA irons plot on a MDFL with L and LL chondrites, basaltic and hypersthene achondrites plot on a MDFL with IAB irons and some stony-irons, and the moon and the Earth plot on a MDFL together with enstatite chondrites and achondrites. This suggests a genetic relationship between these objects, perhaps derivation from a single a single parent body in some cases.

Oxygen isotope compositions of the minerals of the FUN inclusions of Allende are erratic and do not fall on any line. These are certainly nuclear effects.

Mass-independent effects have not been found among isotopes of other elements such as Si, S and Mg in meteorites (except in some inclusions, groundmass phases, and chondrules as noted above),
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though large mass-dependent fractionations are ubiquitous. Thus oxygen appears unique. The reason may be related to the partition of oxygen between the gaseous and solid phases of the presolar nebula. Over a large temperature range, only about 17% of oxygen will condense, the remainder being in the gas, principally as CO and H₂O. Hydrogen and carbon have only two stable isotopes so mass-dependent and mass-independent effects cannot be distinguished.

EXPOSURE AGES OF METEORITES

Cosmogenic nuclides have been used for many years to determine cosmic-ray exposure ages of meteorites. Meteorites experience a much higher cosmic ray flux because they have no atmospheres to shield them. Unstable and stable nuclides are sometimes used together to determine such ages. The rate of change of abundance of an unstable cosmogenic nuclide is given by:

\[ \frac{dN}{dt} = P - \lambda N \]  

where \( P \) is the production rate. If we consider the case of the production of a stable nucleus, the number of stable nuclei produced at the surface of the body over some time \( t \) is simply given by:

\[ N = P t \]  

Combining these equations, we may obtain an expression for \( t \) that is independent of variations production rate:

\[ N = \frac{N_u \left( \frac{P_u}{P_u} \right)}{N_u \left( \frac{P_u}{P_u} \right)} \frac{t}{\lambda} \]  

Cosmic ray exposure ages of meteorites have been found to be on the order of millions or tens of millions of years for stony meteorites and hundreds of millions of years for iron meteorites. Ages for the 3 classes of ordinary chondrites are shown in Figure 12.10. These ages are much less than their formation ages as determined by conventional radiometric dating. This implies that through most of their histories, meteorites must have been shielded from cosmic rays. Hence they must have come from much large bodies that were broken up by collisions. The similarity of exposure ages for all meteorites of a given class

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Figure 12.9. O isotope variations among minerals of various meteorite classes (Clayton et al., 1976).

Figure 24.10. Cosmic ray exposure ages for three classes of ordinary chondrites. Filled histogram is for meteorites with regolith histories (i.e., brecciated meteorites). After Crabb and Schultz (1981).
implies individual meteorite classes are derived from single parent bodies.

REFERENCES AND SUGGESTIONS FOR FURTHER READING


