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# Nucleosynthesis Updates for Isotopic Anomalies

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**NUCLEOSYNTHESIS UPDATES FOR ISOTOPIC ANOMALIES:** Clayton, Donald D., Dept. Physics and Astronomy, Clemson Univ., Clemson, SC 29634

I am in the process of summarizing some advanced aspects of modern nucleosynthesis theory that seem relevant to the measured isotopic anomalies in meteorites. The stable general anomalies seem to occur in two classes of samples--macroscopic objects formed in the solar system, and single presolar grains. For the solar objects, which were discovered first, specifically the CAI with their rich suite of endemic anomalies, the historical argument has concerned whether those anomalies reflect the *cosmic chemical memory* of the aggregation and alteration of presolar-dust aggregates (1,2) or an inhomogeneous admixture into the solar cloud followed by inhomogeneous condensation (most papers). For anomalous single crystals of diamond or SiC, on the other hand, which manifestly *are* presolar grains, the chemical memory theory is clearly the relevant one. But that does not in itself imply that cosmic chemical memory is the relevant factor in endemic CAI anomalies. Reconsider first oxygen.

**Why 16 Oxygen?:** For CAI the major data remain the endemic enrichment of Ox16. Because modern theory makes it clear that Ox16, Ox17 and Ox18 have distinct nucleosynthetic origins, we must ask afresh why it is that nature has selected specifically the mass-16 isotope for enhancement within the refractory anhydrous minerals formed in the solar system. Each isotope has equal *a priori* probability to appear anomalous.

Ox16 is almost entirely synthesized within He cores of presupernova stars and is the dominant specie in ejecta bearing it, without significant cohort of Ox17 or Ox18. Thus 99% of Ox16 originates monoisotopically.

Ox18 is almost entirely synthesized within the slightly burned convective He shell of massive type II supernovae, from  $^{14}\text{N}(\alpha, \gamma)$  within the He burning base, and is there the most abundant reactive atom save  $^{12}\text{C}$ , as shown in detailed models of SN1987A (3,4). Even Ox16 is of only comparable abundance and Ox17 is even more negligible. Thus Ox18 is also *virtually monoisotopic* when compared to solar isotopic composition, and, considering the carbon richness of that shell, may begin chemically as the CO molecule or as partial oxides of carbon SUNOCONS that form only in this shell (5). Thus Ox18 and Ox16 both come from massive supernovae, but from separate shells having distinct characteristics for molecular and solid chemistry and having distinct expansion speeds. But negligible Ox17 accompanies them. These Ox16 and Ox18 yields eventually mix at the molecular level, but only *after the epoch of SUNOCON formation that fixes the Ox16 but not the Ox18 with aluminum* (1,2).

Ox17 originates in hydrogen burning, as part of the CNO cycles. Its appreciable overabundance factor of 15 in the hydrogen-burning shells of presupernova stars (4) is inadequate for its primary source because of the limited mass of that shell in comparison with the great mass of Ox16 to come from the interior. We expect it also in abundance in intermediate-mass asymptotic-giant-branch stars that also dredge up overabundances of  $^{13}\text{C}$  and  $^{14}\text{N}$  that are indeed seen in the atmospheres of such giants, which are hundredfold more common than Type II supernovae. These atmospheres subsequently become carbon-rich and then are lost as the star bares its white-dwarf core of locked-up C and O. A significant fraction of Ox17 may also originate from subsequent hydrogen thermonuclear runaways on the surfaces of white dwarfs. These are the novae. In both latter cases the oxygen appears approximately as monoisotopic Ox17 when normalized to solar composition, and mostly from different objects than Ox16 and Ox18.

How in this picture can we imagine that the refractory CAI have excess of only Ox16, with the volatile Ox17/Ox18 ratio being almost constant at normal? This is not so easy to answer, but I find it almost inconceivable that Ox17 variations would not be the largest in the warm interstellar medium owing to the mechanism of incomplete mixing alone. I therefore reject mixing models, at least until a believable one is put forward. Surely the clue, as I frequently argue, is the association with aluminum and other refractory oxides. But why? We must focus on the mechanisms for this. I find only two credible mechanisms in the literature to date: *either* refractory interstellar dust is Ox16-rich owing to SUNOCON formation (1,2) which removes refractory metals from the gas phase while they are bathed in monoisotopic Ox16 *or* refractory atoms have resided longer in

interstellar dust so that the bulk oxygen associated with those refractory metals was on average more deficient in both secondary isotopes of oxygen (6,7). Both mechanisms require interstellar aluminum oxides to survive for almost 1Gyr even if bulk volatile dust cannot. The distinct slope-1 mixing lines in chondrites, on the other hand, perhaps reflect differing Ox17 or Ox18 concentrations in their bulk parent bodies owing to the differing dust profiles that went into those bodies. Those chemical memories are evidently weaker than those of the CAI, owing either to solar processing of the dust or to the much more complete sampling of volatile dust types.

Isotopic anomalies are not "explained" when the nucleosynthesis mechanisms responsible for observed patterns are identified. Such successes are only the beginnings. We must equally ask why nature has not selected the other isotopes available, why a pattern carries the observed algebraic sign, and why the pattern occurs in specific chemical contexts. Expressions such as "inhomogeneous admixture" or "incomplete mixing" are but empty words until modelled.

**Why not 44 Calcium ?** The recent detailed calculations(3,4) of nucleosynthesis in supernova 1987A have clarified the 44Ca nucleosynthesis a good deal. Both groups find the shock wave so strong near the oxygen burning shell that matter there is broken down into a helium bath whose reassembly into attempted nuclear equilibrium is unable to complete. The resulting "alpha rich freezeout" (8) produces about 1 E(-4) Msun of 44Ti, the 47yr progenitor of 44Ca. The resulting bulk TypeII yields 40Ca/42Ca/44Ti are close to solar and so large as to preclude doubt of these stars as the primary origin for these nuclei (but augmented about 25% by Type I supernovae). But does this not suggest that normalizing isotopic data to solar 40Ca/44Ca is presumptuous? Not only does any SUNOCON formation predate 44Ti decay, prompting the initial predictions of 44Ca anomalies(9), but the metal-chemistry dominated(5) inner zones are the anticipated sites for 48Ca, rather than for 40,42Ca. It seems that 44Ti and 48Ca are linked dynamically and by chemical surroundings as well(5). And yet no workers report 44Ca anomalies to be correlated with 48Ca anomalies. But why not ? Perhaps we are learning that the neutronized NSE zones(5,10) do not escape from Type IIs, as indeed they do not from these recent calculations. Is there then some different nucleosynthesis site for the observed 48Ca/50Ti/54Cr/58Fe/62Ni/64Ni correlation that has also been expected on nuclear grounds (5,10). I here suggest that the electron capture in TypeIa cores(white dwarfs) is more profound than it is normally thought to be, in which case they may provide the neutron-rich NSE zones of nucleosynthesis. Should that prove to be the actual case, a totally new twist in the observed correlations becomes plausible. Because the yield ratio TypeI/TypeII may logically be expected to have increased as the Galaxy has aged, the enrichments in their products should be time dependent, with the TypeI yield delayed similarly to secondary nucleosynthesis products(6). Thus the 48Ca/50Ti correlation would be similar to secondary 17Ox and 18Ox, leading to a similar interpretation in terms of dust ages(6,7). But instead of the "oldest oxygen" from ISM condensed early, one would have the "youngest metal" from ISM condensed late. I am seeking a logical reason for this difference to appear in CAI constituents.

**42Ca/40Ca.** Large TypeII yields of 40Ca emerge from the silicon quasiequilibrium(8) after Ox16 exhaustion, whereas the remainder of 40Ca from TypeIIs carries excess 42Ca/40Ca, about 2-to-5 times solar, bathed still in unburned Ox16(8). The mix is close to solar. Oxidized SUNOCONS therefore carry excess 42Ca/40Ca and Ox16(1, zone IV). Because 42Ca is secondary moreover, 42Ca/40Ca enrichments can also be interpreted as "young ISM". But mixing inhomogeneities are untenable. If the neutron-rich NSE is indeed from TypeI cores, as I speculated above, a correlation of 42Ca, 48Ca and 50Ti is predicted in "young ISM"(6).

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