01 Mar 2000

# Conceptual Problems with Remote Element Synthesis

Oliver Manuel
*Missouri University of Science and Technology*, om@mst.edu

## Recommended Citation

O. Manuel, "Conceptual Problems with Remote Element Synthesis," *Journal of Earth System Science*, vol. 109, pp. 195-203, Indian Academy of Sciences, Mar 2000.
The definitive version is available at https://doi.org/10.1007/BF02719164

# Conceptual problems with remote element synthesis

O K Manuel

*Department of Chemistry, University of Missouri, Rolla, MO 65401, USA*
*email: om@umr.edu*

The notion of remote element synthesis has recently been modified to explain the presence of nucleogenetic isotopic anomalies and decay products of short-lived nuclides by injection of a small amount of *exotic* nucleogenetic material. Even with this modification, remote element synthesis seems inconsistent with the following observations:

- Evidence of coupled variations in the chemical and isotopic compositions of the source material for meteorites.
- Residual coupling of chemical and isotopic heterogeneities across planetary distances in the solar system today.
- The mass-fractionation relationship seen across isotopes of elements in the planetary system, in the solar wind, and in solar flares.
- Linkage of short-lived radioactivities with isotopic anomalies and with physical properties of their host grains, as expected for early condensate of fresh stellar debris.
- Temporal and spatial distributions of short-lived nuclides and their decay products.
- Mirror-image (+ and −) isotopic anomalies in meteorite grains that sum to "normal" isotopic ratios, as expected of unmixed products of the same nuclear reactions that produced our bulk elements.
- The lack of supporting evidence for "presolar" grains or nearby stars that injected *exotic* material into the early solar nebula.

---

## 1. Introduction

It has long been assumed that our elements were made elsewhere and collected from vast regions of space into a homogeneous cloud of material that somehow formed the solar system. The discovery of decay products of short-lived radioactivities and nucleogenetic isotopic anomalies in meteorites has forced modifications to this assumption. Begemann thus introduced his survey on isotopic anomalies, "The classical picture of the pre-solar nebula is that of a hot, well-mixed cloud of chemically and isotopically uniform composition. Recent measurements have shown this conception to be erroneous, however" (Begemann 1980, p. 1309).

The idea of homogeneous starting material for the solar system has been largely abandoned, while the idea of remote element synthesis has been retained. Late addition of a small amount of alien nucleogenetic matter to an otherwise homogeneous mix of elements from many stellar sources is now the popular explanation for meteorite grains that condensed before short-lived radioactivities decayed away, even before the isotopes of individual elements were mixed. However, this explanation neglects the possibility that these observations may indicate local element synthesis (Manuel and Sabu 1975, 1977; Lavrukhina 1980; Sabu and Manuel 1980).

For example, Fowler (1984) and Wasserburg (1987) endorsed the late addition of 0.0001 parts *exotic* nucleogenetic material to 0.9999 parts *normal* solar system material to explain decay products of short-lived nuclides and nucleogenetic isotopic anomalies

**Keywords.** Element synthesis; isotopes; solar system; meteorites; planets.

in meteorites. Their opinions, expressed in lectures given on receipt of the Nobel Prize in Physics and the Crafoord Prize in Geosciences, respectively, are especially influential.

Earlier, Clayton championed the idea that isotopic anomalies and short-lived nuclides were brought into the solar system in interstellar grains that became embedded in meteorites (e.g., R N Clayton *et al* 1973; D D Clayton 1975, 1982; D D Clayton and Hoyle 1976). Cameron and coworkers proposed, then refuted, and recently revived the idea of a nearby supernova that injected alien nucleogenetic material into an interstellar cloud of material and simultaneously triggered its collapse to form the Solar System (e.g., Cameron and Truran 1977; Cameron 1984; Cameron *et al* 1995).

The idea of interstellar grains embedded in meteorites has caught the fancy of many leading scientists. In an invited review, Anders and Zinner (1993) conclude that interstellar grains from outside the Solar System are the source of isotopically anomalous elements and decay products of short-lived nuclides found in diamonds, silicon carbide and graphite of primitive meteorites. On receiving the Leonard Medal from the Meteoritical Society, Professor Begemann (1996, p. 171) states that carbonaceous chondrites contain "stardust" with "undiluted nucleosynthesis products of individual stars".

Scientists from nuclear astrophysics, observational astronomy and cosmochemistry recently gathered in Saint Louis, Mo and endorsed the concept of presolar grains as carriers of exotic nucleogenetic material. The uniformity of this consensus is reflected in the 750-page Conference Proceedings (Bernatowicz and Zinner 1997) and in the opening statement of an ensuing news report on the conference, "Amazingly, individual grains of dust from stars that existed before the Sun was born have made their way to Earth in meteorites." (Bernatowicz and Walker 1997, p. 26).

The St. Louis conference was devoted to a discussion of short-lived nuclides and nucleogenetic isotopic anomalies, but the continued allure of remote element synthesis and an initially homogeneous nebula is obvious in papers selected for publication in the conference proceedings.

For example, on the first page of the conference overview Zinner (1997, p. 3) states that: "It was realized early on that the solar system not only is a very homogeneous mixture of material from many different stellar sources but that these stars themselves incorporated the debris of previous generations of stars ('galactic chemical evolution')." In the introduction to the second paper in the proceedings, Hoppe and Ott (1997, p. 27) note "While most of the material that went into the making of the solar system was thoroughly processed and mixed, thus losing isotopic heterogeneity and all memory of its origin, small quantities of refractory dust grains survived the formation of the solar system in the parent bodies of primitive meteorites" (Anders and Zinner 1993; Ott 1993).

Some problems with the concept of remote element synthesis and injection of alien nucleogenetic material into the early solar system are presented below. First, it seems appropriate to acknowledge that the author was among the first to champion an injection, noting trends in the experimental data which might suggest that anomalous Xe-X "represents material that has been added to our solar system from a nearby supernova, although no evidence for the addition of products from a separate nucleosynthesis event has been found in other elements." (Manuel *et al* 1972, p. 100). Xe-X, with excess $^{124,126}$Xe and $^{134,136}$Xe from the p- and r-processes of nucleosynthesis, is also called Xe-HL (Huss and Lewis 1995).

## 2. Primordial coupling of chemical and isotopic heterogeneities

Coupling of chemical and isotopic heterogeneities in meteorites was the first observation that could not be explained by remote element synthesis plus the addition of exotic nucleogenetic material.

### 2.1 *Primordial coupling of He and Ne with Xe-X*

A few years after suggesting an injection of alien nucleogenetic material from a nearby supernova (Manuel *et al* 1972), it was noticed that primordial (not produced *in situ*) He and Ne in meteorites are always trapped with isotopically anomalous Xe-X. Further, meteorite phases containing isotopically normal Xe were found to be almost totally devoid of primordial He and Ne (Manuel and Sabu 1975, 1977). Figure 1 shows the first recognized example of this linkage of elemental abundances of He with isotopically strange Xe. Later work showed that the coupling of He and Ne with Xe-X (and with isotopically strange Kr and Ar) is a common feature of noble gases in meteorites (Sabu and Manuel 1980).

The primordial linkage of light elements with specific isotopes of heavy elements, as shown in figure 1 for noble gases, may indicate that the solar system formed directly from debris of a single supernova (SN) (Manuel and Sabu 1975, 1977; Sabu and Manuel 1980).

According to that interpretation, nuclear fusion reactions in the stellar interior depleted He from the source region of isotopically normal Xe, Kr and Ar, shown on the left in figure 1. The supernova explosion produced Xe-X, shown on the right in figure 1, in outer stellar layers that remained rich in light elements like H, He, C, etc.

Since He is widely regarded as the second most abundant element in the solar system, remote element

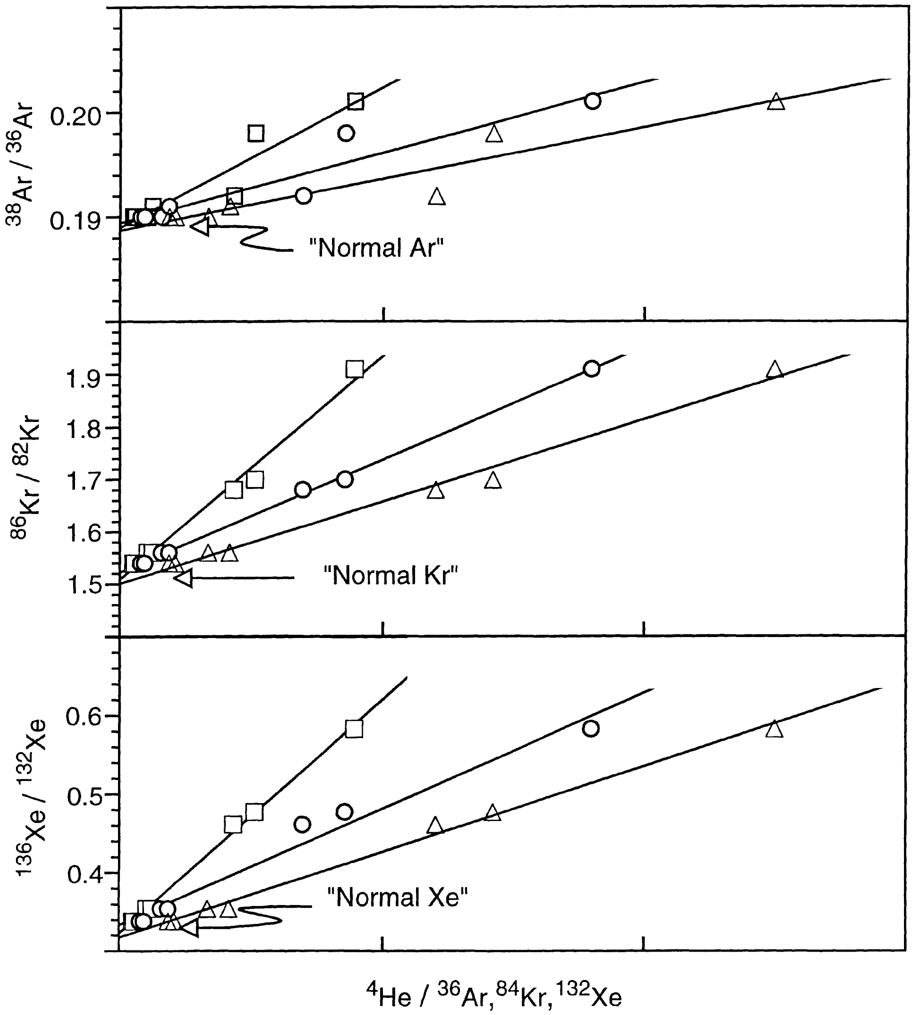

Figure 1. Elemental abundances of primordial He correlate with isotopic ratios of Ar, Kr and Xe in mineral separates of the Allende meteorite and extrapolate to zero at isotopic ratios of "normal" Ar, Kr and Xe. This primordial linkage of He with specific isotopes of the heavier noble gases is a common feature of noble gases in meteorites (Sabu and Manuel 1980). $^{132}$ Xe, $^{84}$Kr and $^{36}$Ar are represented by □, and ○, respectively.

synthesis plus the addition of a small quantity of exotic nucleogenetic material – in the form of interstellar grains or a nearby star – offers no explanation for the example of many experimental observations illustrated in figure 1: The ubiquitous linkage of primordial He with *exotic* Ar, Kr and Xe in meteorites (Sabu and Manuel 1980).

### 2.2 *Primordial coupling of He, Ne and Xe-X with C*

When the carrier of Xe-X was first partially isolated from the Allende meteorite, Anders *et al* (1975) suggested that the host mineral was probably chromite, enriched in "noble metals (congeners of elements 107–111) and volatiles (congeners of elements 113–118)." Such a composition was unexpected for condensate from the outer layers of a supernova, where the dominant elements are expected to be H, He, C, etc.

Subsequent work has shown, however, that the host phase is actually C in the form of nanometer-sized diamonds (Lewis and Anders 1988). It has also been shown that diamonds may form directly by chemical vapor deposition from a methane-hydrogen mixture (e.g., Shindo *et al* 1985). Thus, the diamond host phase of noble gases on the right of figure 1 is a plausible vapor condensation product from a region of the presolar nebula with high abundances of H, He and C.

This coupling of primordial He, Ne, and Xe-X with diamond has been confirmed in seven different classes of chondritic meteorites (e.g., Huss and Lewis 1995). The isotopic compositions of He, C, and Ne in these diamonds appear "normal" for solar system materials, unlike that expected if these were exotic imports from beyond the solar system.

### 2.3 *Primordial coupling of Silicon Carbide with Xe-S*

Xe-S is enriched in the intermediate mass isotopes, $^{128\text{-}132}$Xe, that are made by the s-process of nucleosynthesis. It is thus a complementary component to

Xe-X. Xe-S is found in SiC inclusions of meteorites, accompanied by Ne-E(H), a neon component that is enriched in $^{22}$Ne. This primordial coupling of isotopically anomalous Xe-S and Ne-E(H) with SiC has been confirmed in seven classes of chondritic meteorites (Huss and Lewis 1995). Indeed, the primordial coupling of noble gas isotopic ratios with the chemical compositions of their host minerals in chondrites was *apparently* pervasive throughout the presolar nebula. Thus, Huss and Lewis (1995) were able to estimate the abundances of diamond, as well as silicon carbide and graphite grains by isotopic analyses of the noble gases.

### 2.4 *Primordial coupling of Xe-T with Fe and S*

The occurrence of terrestrial-type xenon (Xe-T) in troilite (FeS) inclusions of iron meteorites was noted several years ago (Hwaung and Manuel 1982). More recently, Xe-T was identified as the trapped xenon component in FeS-rich mineral separates of the Allende carbonaceous chondrite (Lee *et al* 1996). It was also noted that Xe-T is the dominant xenon component in the atmospheres of Earth and Mars, two inner planets rich in Fe and S. It was concluded that Xe-T was the primary xenon ingredient in the central, Fe, S-rich region of the solar nebula, just as the main xenon component in the outer, He, C-rich region was Xe-X (Lee *et al* 1996).

Murty and Marti (1987) found isotope ratios of xenon in metal and in troilite inclusions of the Cape York iron meteorite that are closer to those in air than to those in stone meteorites (Marti 1967). Mathew and Begemann (1995) also report isotopic ratios of xenon in schreibersite, $(Fe, Ni)_3P$, and graphite inclusions from the El Taco iron meteorite that are close to Xe-T, whereas xenon in olivine, feldspar and pyroxene of the El Taco meteorite is closer to that found in stone meteorites (Marti 1967).

The above four examples of inter-linked isotopic and chemical abundances show the effects of nuclear fusion and evolution of a massive first generation star into chemical layers of successively higher atomic number, from an outer layer that remains rich in light elements to an inner layer that is rich in iron. Xe-X is associated with low-Z elements (He, C, etc.) expected in the outer layers of an evolved star. Xe-T is coupled with the high-Z elements (Fe, P, S, etc.) identified with the central region of an evolved star. Xe-S is linked with low-to-intermediate Z elements (C, Si) that might be abundant below the outer layers of an evolved star.

Remote element synthesis and the injection of exotic nucleogenetic material offers no explanation for the observed linkage of isotopic ratios of noble gases with the chemical compositions of their carrier phases, including both refractory and low-temperature minerals.

## 3. Residual coupling of chemical and isotopic heterogeneities

Large chemical heterogeneities exist in the planetary system today. Planets near the Sun are rich in high-Z elements like Fe and S, especially in the cores of these inner planets. Giant, low-density planets beyond the asteroid belt are rich in low-Z elements like H, He and C. If this diversity is the remnant of a heterogeneous solar nebula, then this coupling of chemical and isotopic abundances may still be observed as variations in the isotopic compositions of elements across the planetary system.

There are at least three indications of residual coupling of isotopically distinct xenon with chemical gradients in the planetary system, plus some intriguing isotopic compositions of elements that comprise the Sun.

Isotopically distinct primordial xenon was first found in carbonaceous chondrites many years ago (Reynolds 1960b). The term AVCC Xe was widely used to designate the isotopically distinct xenon in average carbonaceous chondrites. Later, it was shown that AVCC Xe is a mixture of Xe-X plus a mass fractionated form of Xe-T, the dominant xenon component in Mars, the Earth and the Sun (Manuel *et al* 1972). However, this early work by Reynolds clearly established that the average isotopic composition of primordial xenon on Earth is different than that in material which formed carbonaceous chondrites further away from the Sun.

The latest advancement in our understanding of isotopic diversity in the solar system resulted directly from Dr. Daniel S. Goldin's decision on January 7, 1998 to release isotopic data from the Galileo probe entry into Jupiter (Goldin 1998). The isotopic composition of xenon there is much closer to Xe-X than to that of xenon in the solar wind (Manuel *et al* 1998). Since Jupiter is rich in He and C – elements that were initially linked with Xe-X in the solar nebula (Sabu and Manuel 1980) – the presence of Xe-X in Jupiter today probably represents residual coupling of these elemental and isotopic components from the heterogeneous solar nebula.

Xe-T is dominant in the atmospheres of both Earth and Mars, which are also rich in Fe and S. This same type of primordial xenon is trapped in troilite (FeS) of diverse meteorites, including the very isotopically heterogeneous material incorporated into the Allende carbonaceous chondrite (Lee *et al* 1996). Today's presence of Xe-T in Earth and Mars is probably a remnant of the primordial coupling of Xe-T with Fe and S.

Residual coupling of elemental and isotopic abundances across the planetary system today is again unexplained by remote element synthesis.

If the various chemical and isotopic components in the solar nebula collectively formed the Sun, then the isotopic composition of its elements may indicate the relative abundances of these ingredients. Several groups (Boulos and Manuel 1971; Kaiser 1972; Bernatowicz and Podosek 1978) concluded that SW xenon is predominantly Xe-T, with the lighter mass isotopes selectively enriched by about 4% per mass unit. Manuel and Hwaung (1983) attempted to decipher the presence of mass fractionated Xe-T at the solar surface, where light elements (He, C) initially linked with Xe-X are much more abundant than the heavy elements (Fe, S) initially linked with Xe-T. This dilemma will be discussed below.

## 4. Fractionated isotopes in the solar wind and in solar flares

Isotopic anomalies are not only limited to elements found in meteorites or in other planets. Solar wind (SW) elements display one set of isotopic anomalies, for example, and those in solar flares display another.

Isotopic ratios of certain SW noble gases are selectively enriched in lighter mass isotopes, as expected from mass-dependent fractionation (Kuroda and Manuel 1970; Kaiser 1972; Manuel and Hwaung 1983). Manuel and Hwaung (1983) found that a systematic mass fractionation pattern could be discerned across the isotopes of all five SW noble gases if He, Ne and Ar in the Sun are predominantly type-X gases, if its xenon is Xe-T, and if its Kr is a mixture of these primordial noble gas components.

When resolved this way, lighter mass isotopes in the solar wind are enriched by ≈4%, 6%, 9%, 27% and 200% per amu for Xe, Kr, Ar, Ne and He, respectively. Manuel and Hwaung (1983) suggested that internal diffusion in the Sun enriches lighter nuclei at its surface. If so, the composition of the solar surface may conceal that of its interior. Noble gas atoms are volatile, but diffusive fractionation in an ionizing plasma would be independent of the chemical nature of atoms. They therefore suggested isotopic analyses of a refractory element like SW Mg to test this hypothesis.

Even before the results of isotopic analyses of Mg in the solar wind were reported, confirmation of diffusive fractionation in the Sun came from isotopic analyses of noble gases in solar flares (Rao *et al* 1991). Isotopic ratios of flare gases are systematically less enriched in lighter isotopes, as expected if internal diffusion in the Sun is disrupted by energetic events at the solar surface (Manuel and Ragland 1997).

Selesnick *et al* (1993) reported isotopic ratios for Mg in solar flare particles. Later, Boschler *et al* (1996) reported that isotopic ratios of SW Mg are consistent with terrestrial values. However, isotopic ratios of SW Mg vary systematically with velocity, and like SW He, Ne and Ar, heavier isotopes become increasingly abundant at higher velocities (Manuel and Ragland, 1997). It was also noted (Manuel and Ragland 1997) that hydride formation is an interference that apparently increases with SW velocity. The natural abundances of $^{25}$Mg and $^{26}$Mg are nearly equal, but lower than that of $^{24}$Mg by a factor of 8. Therefore, hydride formation of $^{24}\mathrm{MgH}^+$ contributes a much larger fraction of the signal from $^{25}\mathrm{Mg}^+$ than $^{25}\mathrm{MgH}^+$ contributes to the signal from $^{26}\mathrm{Mg}^+$.

To demonstrate that shifts in isotopic ratios of He, Ne, Mg and Ar are caused by internal solar diffusion, Manuel and Ragland (1997) tabulated the results of Geiss *et al* (1972), Rao *et al* (1991), Selesnick *et al* (1993) and Boschler *et al* (1996) in the manner shown in table 1. The top section compares values of $^3$He/$^4$He, $^{20}$Ne/$^{22}$Ne, $^{24}$Mg/$^{26}$Mg and $^{36}$Ar/$^{38}$Ar ratios in the solar wind with those in the solar flares. Note that these ratios are always higher in the solar wind than in solar flares. Shifts in these ratios, tabulated in the bottom section of table 1, follow values of $\Delta$m/m$_{\mathrm{avg.}}$, as expected if diffusion in the Sun is disrupted by the energetic events that produce solar flares (Manuel and Ragland 1997).

The results shown in table 1 are consistent with internal diffusion in the Sun that enriches lighter elements and the lighter isotopes of individual elements at the solar surface (Manuel and Hwaung 1983; MacElroy and Manuel 1986; Manuel and Ragland 1997). Thus, the presence of Xe-T in the solar wind is consistent with other measurements indicating that Fe may be the most abundant element in the Sun's interior (Hoyle 1975; Manuel and Hwaung 1983; Rouse 1983, 1985).

Isotopic anomalies in the solar wind and in solar flares, as shown in table 1, are unexplained by synthesis of elements in multiple stellar sources to produce an initially homogeneous solar nebula. Furthermore, this discrepancy between remote element synthesis and observation cannot be resolved by injecting a small amount of exotic nucleogenetic material.

## 5. Short-lived radioactivities, isotopic anomalies and host grains

If elements were made locally and the solar system condensed directly from chemically and isotopically

Table 1. *Fractionation relationship between isotopic ratios of He, Ne, Mg and Ar in the solar wind and in solar flares (Manuel and Ragland 1997)*

| A. Isotope Ratios | Solar Wind (SW) | Solar Flare (SEP) |
|---|---|---|
| $^3$He/$^4$He | $4.1 \times 10^{-4}$ | $2.6 \times 10^{-4}$ |
| $^{20}$Ne/$^{22}$Ne | 13.6 | 11.6 |
| $^{24}$Mg/$^{26}$Mg | 7 | 6 |
| $^{36}$Ar/$^{38}$Ar | 5.3 | 4.8 |
| **B. Isotope Ratios** | **SW/SEP** | **$\Delta$m/m$_{\mathrm{avg.}}$** |
| $^3$He/$^4$He | 1.58 | 0.29 |
| $^{20}$Ne/$^{22}$Ne | 1.17 | 0.09 |
| $^{24}$Mg/$^{26}$Mg | 1.17 | 0.08 |
| $^{36}$Ar/$^{38}$Ar | 1.1 | 0.05 |

heterogeneous SN debris (Manuel and Sabu 1975, 1977), natural mixing would decrease the diversity with time. Short-lived nuclide abundances would also decrease naturally with time. The magnitude of isotopic anomalies may be linked with the level of extinct radioactivity contained in condensate from a local supernova.

If the solar system condensed directly from SN debris, the earliest nucleation seeds would likely form grains with physical properties like those exhibited by other high-temperature condensation products.

All of these expectations are borne out by the five X-type grains of SiC recovered from the Murchison carbonaceous chondrite (Amari *et al* 1992). They apparently represent the earliest known condensate. These grains formed soon after the explosion of a supernova (Kuroda and Meyers 1997), over a period of time as the $^{26}$Al/$^{27}$Al ratio decayed from a value of 0.60 to a value of 0.10 (Amari *et al* 1992). As expected of early condensate from isotopically heterogeneous material, they contain very large isotopic anomalies in several elements, including C, N, Si, Ti and Ca.

Levels of extinct radioactivity in these SiC grains decrease with particle size, similar to fallout particles from nuclear weapons (Kuroda and Meyers 1997). Higher values of the $^{26}$Al/$^{27}$Al ratio are seen in SiC grains that started to nucleate early and grew larger; lower values of the $^{26}$Al/$^{27}$Al ratio are seen in smaller grains that started their growth later.

This linkage of isotopic anomalies with extinct radioactivity was first seen when Reynolds (1960a) discovered the decay product of extinct $^{129}$I embedded in xenon with a general isotopic anomaly pattern across all nine xenon isotopes (Reynolds 1960b). Remote element synthesis, even with a late injection of exotic material, does not explain the observed linkage of extinct radioactivity with isotopic anomalies and with the size of their host grains.

## 6. Short-lived nuclides and their decay products

The shorter-lived nuclides and their decay products are also an enigma for remote element synthesis. Lugmair *et al* (1996) found that excess $^{53}$Cr from the decay of $^{53}$Mn ($t_{1/2} = 3.7$ My) correlates with distance from the Sun. As noted above, abundances of elements like Fe and He also correlate with heliocentric distance, as do abundances of isotopically distinct forms of elements that were initially linked with those elements, e.g., Xe-T and Xe-X. Remote element synthesis does not explain radial heterogeneities in the primitive solar nebula.

Some of the earliest critics of local element synthesis (Lewis *et al* 1977) have recently discovered that "a single stellar source is responsible for generating" $^{53}$Mn and other short-lived nuclides with half-lives of 0.1–10 My, such as $^{41}$Ca, $^{26}$Al, $^{60}$Fe and $^{107}$Pd (Sahijpal *et al* 1998, p. 559). The presence of extant, even more short-lived nuclides requires shorter interstellar distances from the parent source, if these radioactivities are injected into the early solar nebula, as implied.

Although there is no convincing evidence that even shorter-lived radioactivities existed in the solar nebula, the presence of Ne-E requires an even shorter time scale if the decay of $^{22}$Na ($t_{1/2} = 2.6$ y) is the source of excess $^{22}$Ne in this neon component (see Black 1978 and references therein). Recent measurements at Mainz suggest that r-products in the isotopes of Kr, Te and Xe must have been separated from precursor nuclei like $^{83}$Br, $^{125}$Sb and $^{131}$I within $10^4$ seconds of the supernova event to explain the isotopically anomalous Kr, Te and Xe seen in diamonds of the Allende meteorite (Ott 1996; Richter *et al* 1998).

## 7. Complementary isotopic anomalies

If elements were made elsewhere and collected into a mostly homogeneous cloud that formed the solar system, then isotopic compositions of elements in the exotic component injected into that cloud are not expected to have any special relationship to the "normal" isotopic compositions of bulk elements in the well-mixed cloud. On the other hand, if elements were made locally and the solar system formed out of material that was isotopically heterogeneous, then material not thoroughly mixed to form isotopically "normal" elements may show "excesses" and "depletions" of any given isotope (Oliver *et al* 1981). Observations match the latter case.

This was first seen in xenon. For example, Xe-X is enriched in light and heavy isotopes, $^{124,126}$Xe and $^{134,136}$Xe, respectively, from the p- and r- processes of nucleosynthesis (Manuel *et al* 1972). A complimentary component, Xe-S, is enriched in the intermediate mass isotopes, $^{128\text{-}132}$Xe (Srinivasan and Anders 1978).

Recently, Begemann (1993) noted that the seven isotopes of Ba, Nd and Sm in grains separated from two different carbonaceous chondrites reveal the "mirror-image" anomaly patterns expected in unmixed products of the same nuclear reactions that made bulk Ba, Nd and Sm in the solar system. Inclusion EK-1-4-1 of the Allende carbonaceous chondrite is enriched in isotopes of Ba, Nd and Sm from the r- and p-processes of nucleosynthesis. SiC grains from the Murchison carbonaceous chondrite are depleted in these same isotopes. The relative depletions in SiC grains are in the same proportions as the enrichments in inclusion EK-1-4-1, i.e., the isotopic anomaly patterns are "mirror-images." This is illustrated in figure 2 for any element with seven stable isotopes.

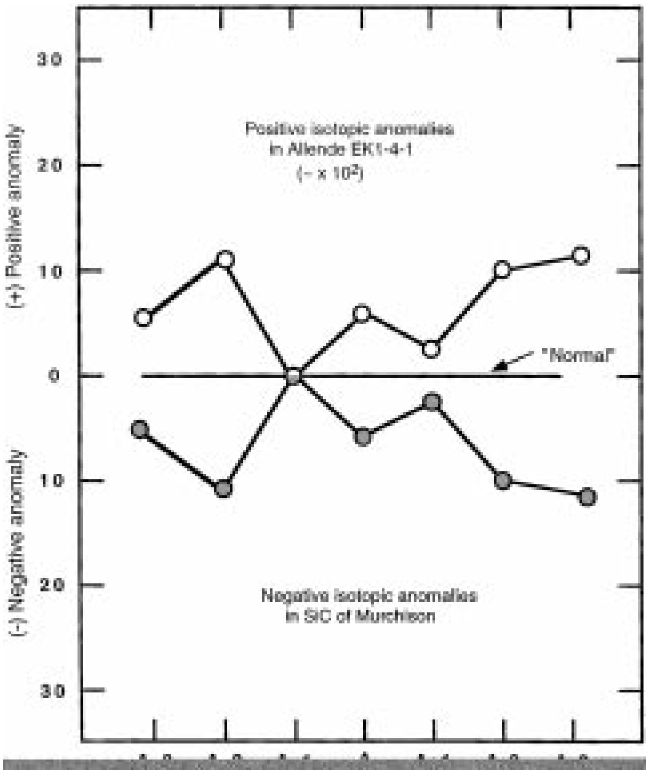

Figure 2. The enrichment pattern of isotopes of elements in the E-K-141 inclusion of Allende is the "mirror-image" of the depletion pattern of these same isotopes in SiC grains from the Murchison meteorite. Individual plots for the stable isotopes of Ba, Nd and Sm are shown in figure 2 of Begemann (1993) and in figure 3 of Zinner (1997).

The "mirror-image" isotopic anomaly patterns observed in Ba, Nd and Sm are expected in poorly mixed products of the same nuclear reactions that made bulk Ba, Nd and Sm in the solar system. These "mirror-image" anomaly patterns are unexpected if elements in the bulk solar system were well mixed and the isotopic anomalies came from an injection of *exotic* nucleogenetic material.

## 8. Mystical interstellar grains and nearby stars

Interstellar carrier grains from distant stars and/or direct injections of material from nearby stars were proposed in an effort to explain how the findings of heterogeneities from fresh nucleosynthesis products might be compatible with the concept of remote element synthesis and an initially homogeneous nebula (see articles in Bernatowicz and Zinner 1997). However, both of these mechanisms are *ad hoc* and lacking in corroborative evidence.

These solutions leave several questions unanswered. There is no convincing evidence, for example, that any "presolar" grains are older than the solar system. Neither is there any convincing evidence for their bombardment by cosmic rays during a journey across interstellar distances before becoming embedded in meteorites. Likewise, it is reasonable to ask what happened to the nearby star(s) that was so conveniently present at the birth of the solar system to inject exotic nucleogenetic material.

Thus, supporting evidence of presolar grains and/or nearby stars that might have injected material into the solar system is lacking. Decay products of short-lived nuclides and nucleogenetic isotopic anomalies are more easily understood as products of local element synthesis.

For these reasons, local element synthesis and an initially heterogeneous solar nebula seem a more plausible explanation for the chemical and isotopic heterogeneities that we observe in the solar system today.

## Acknowledgements

I am indebted to my colleagues here at the University of Missouri-Rolla for assuming a heavier teaching responsibility this semester while I prepared this manuscript and to my current and former students whose hard work and perseverance played such a key role in our understanding of the origin and early history of the solar system. This paper benefitted from external reviewers' comments by Drs. I P Wright, M N Rao, and an anonymous reviewer, in addition to internal reviews by Daniel Ragland, Anthony Humberbolt and Gary Bertrand.

## References

Amari S, Hoppe P, Zinner E and Lewis R S 1992 Interstellar SiC with unusual isotopic compositions: Grains from a supernova? *Ap. J.* **394** L43–L46

Anders E, Higuchi H, Gros J, Takahashi H and Morgan J W 1975 Extinct superheavy element in the Allende meteorite; *Science* **190** 1262–1271

Anders E and Zinner E 1993 Interstellar grains in primitive meteorites: Diamonds, silicon carbide and graphite; *Meteoritics* **28** 490–514

Begemann F 1980 Isotopic anomalies in meteorites; *Rep. Prog. Phys.* **43** 1309–1356

Begemann F 1993 Isotope abundance anomalies and the early solar system: MuSiC vs. FUN; In *Origins and Evolution of the Elements* (eds.) E N Prantzos, E Vangioni-Flam and M Casse pp. 518–527, (Cambridge: Cambridge Press)

Begemann F 1996 Noble gases and meteorites. (The Leonard Award Address); *Meteoritics* **31** 171–176

Bernatowizc T J and Podosek F A 1978 Nuclear components in the atmosphere; In: *Terrestrial Rare Gases* (eds.) E C Alexander and M Ozima 99–135, (Tokyo: Center for Academic Publications Press)

Bernatowicz T J and Walker R M 1997 Ancient stardust in the laboratory; *Physics Today* **50** no. 12 26–32

Bernatowicz T J and Zinner E (editors) 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials*, AIP Conference Proceedings 402, American Institute of Physics, Woodbury, N.Y., 750 pp.

Black D C 1978 Isotopic anomalies in solar system material – What do they tell us?; In: *The Origin of the Solar System* (ed.) S F Dermott 583–596, (New York: John Wiley and Sons)

Boschler P, Gonin M, Sheldon R B, Zurbuchen Th, Gloeckler G, Hamilton D C, Collier M. R. and Hovestadt D 1996 Abundance of solar wind magnesium isotopes determined with WIND/MASS; In: *Solar Wind 8 Proceedings* pp. 1–4

Boulos M S and Manuel O K 1971 The xenon record of extinct radioactivities in the Earth; *Science* **174** 1334–1336

Cameron A G W and Truran J W 1977 The supernova trigger for formation of the Solar System; *Icarus* **30** 447–461

Cameron A G W 1984 Star formation and extinct radioctivity; *Icarus* **60** 416–427

Cameron A G W, Höflich P, Myers P C and Clayton D D 1995 Massive supernovae, Orion gamma rays, and the formation of the Solar system; *Ap. J.* **447** L53–L57

Clayton D D 1975 Extinct radioactivities: Trapped residuals of presolar grains; *Ap. J.* **199** 765–769

Clayton D D 1982 Cosmic chemical memory: a new astronomy; *Q. Jl R. Astr. Soc.* **23** 174 212

Clayton D D and Hoyle F 1976 Grains of anomalous isotopic composition from novae; *Ap. J.* **203** 490–496

Clayton R N, Grossman L and Mayeda T K 1973 A component of primitive nuclear composition in carbonaceous chondrites; *Science* **182** 485–488

Fowler W A 1984 Experimental and theoretical nuclear astrophysics: the quest for origin of the elements; *Rev. Mod. Phys.* **56** 149–179

Geiss J, Bühler F, Cerutti H, Eberhardt P. and Filleaux C H 1972 Solar-wind composition experiment; In: *Apollo 15 Preliminary Science Report, Section 15* NASA SP-289

Goldin D S 1998 *Future of Space Science.* Talk presented to the 191st Meeting of the American Astronomical Society, January 7, 1998, Washington, D.C. C-SPAN tape: 98-01-07-22-1, available from Purdue University Public Affairs Video Archives, Lafayette, IN, USA.

Hoppe P and Ott U 1997 Mainstream silicon carbide grains from meteorites; In: *Astrophysical Implications of the Laboratory Study of Presolar Materials* (eds.) T J Bernatowicz and E Zinner pp. 27–58. AIP Conference Proceedings 402, (Woodbury, N.Y.: American Institute of Physics)

Hoyle F 1975 A solar model with low neutrino emission; *Ap. J.* **197** L127–L131

Huss G R and Lewis R S 1995 Presolar diamond, SiC and graphite in chondrites: Abundances as a function of meteorite class and petrologic type; *Geochem. Cosmochim. Acta* **59** 115–160

Hwaung G and Manuel O K 1982 Terrestrial-type xenon in meteoritic troilite; *Nature* **299**, 807–810

Kaiser W A 1972 Rare gas studies in Luna-16-G-7 fines by stepwise heating technique. A low fission solar wind Xe; *Earth Planet. Sci. Lett.* **13** 387–399

Kuroda P K and Manuel O K 1970 Mass fractionation and isotope anomalies in neon and xenon; *Nature* **227** 1113–1116

Kuroda P K and Myers W A 1997 Aluminum-26 in the early solar system; *J. Radioanal. Nucl. Chem.* **211** 539–555

Lavrukhina A K 1980 On the nature of isotopic anomalies in meteorites; *Nukleonika* **25** 1495–1515

Lee J T, Li B and Manuel O K 1996 Terrestrial-type xenon in sulfides of the Allende meteorite. *Geochemical Journal* **30** 17–30

Lewis R S, Srinivasan B and Anders E 1977 Reply to Manuel and Sabu; *Science* **195** 209–210

Lewis R S and Anders E 1988 Xe-HL in diamonds from the Allende meteorite-composite nature; *Proc. Lunar Planet. Sci. Conf.* **19** 679–680

Lugmair G W, Shukolyukov A and MacIsaac Ch 1996 Radial heterogeneity of $^{53}$Mn in the early solar system and the place of origin of ordinary chondrites; *Lunar Planet. Sci.* **27** 785–786

MacElroy J M D and Manuel O K 1986 Can intrasolar diffusion contribute to isotopic anomalies in the solar wind?; *J. Geophys. Res.* **9** D473–D482

Manuel O K, Hennecke E W and Sabu D D 1972 Xenon in carbonaceous chondrites; *Nature* **240** 99–101

Manuel O K and Hwaung G 1983 Solar abundances of the elements; *Meteoritics* **18** 209–222

Manuel O K and Ragland D E 1997 Diffusive mass fractionation effects across the isotopes of noble gases and magnesium in the solar wind and in solar flares. Abstract 281, 1997 *Midwest Regional Meeting of the American Chemical Society*, Osage Beach, Missouri, USA.

Manuel O, Ragland D, Windler K, Zirbel J, Johannes L, Nolte A 1998 Strange isotope ratios in Jupiter. Paper to be presented at 192nd Meeting of the American Astronomical Society, June 7–11, 1998, San Diego, CA, USA.

Manuel O K and Sabu D D 1975 Elemental and isotopic inhomogeneities in noble gases: the case for local synthesis of the chemical elements; *Trans. of the Missouri Acad. of Sci.* **9** 104–122

Manuel O K and Sabu D D 1977 Strange xenon, extinct superheavy elements, and the solar neutrino puzzle; *Science* **195** 208–209

Mathew K J and Begemann F 1995 Isotopic composition of xenon and krypton in silicate-graphite inclusions of the El Taco, Campo del Cielo, IAB iron meteorite; *Geochim. Cosmochim. Acta* **59** 4729–4746

Marti K 1967 Isotopic composition of trapped krypton and xenon in chondrites; *Earth Planet Sci. Lett.* **3** 243–248

Murty S V S and Marti K 1987 Nucleogenetic noble gas components in the Cape York iron meteorite; *Geochim. Cosmochim. Acta* **51** 163–172

Oliver L L, Ballad R V, Richardson J F and Manuel O K 1981 Isotopically anomalous tellurium in Allende: Another relic of local element synthesis; *J. Inorg. Nucl. Chem.* **43** 2207–2216

Ott U 1993 Interstellar grains in meteorites; *Nature* **364** 25–33

Ott U 1996 Interstellar diamond xenon and timescales of supernova ejecta; *Ap. J.* **463** 344–348

Rao M N, Garrison D H, Bogard D D, Badhwar G and Murali A V 1991 Composition of solar flare noble gases preserved in meteorite parent body regolith; *J. Geophys. Res.* **96** 19321–19330

Reynolds J H 1960a Determination of the age of the elements; *Phys. Rev. Lett.* **4** 8–10

Reynolds J H 1960b Isotopic composition of primordial xenon; *Phys. Rev. Lett.* **4** 351–354

Richter S, Ott U and Begemann F 1998 Tellurium in pre-solar diamonds as an indicator for rapid separation of supernova ejecta; *Nature* **391** 261–263

Rouse C A 1983 Calculation of stellar structure III. Solar models that satisfy the necessary conditions for a unique solution to the stellar structure equations; *Astron. Astrophys.* **126** 102–110

Rouse C A 1985 Evidence for a small, high-Z, iron-like solar core; *Astron. Astrophys.* **149** 65–72

Sabu D D and Manuel O K 1980 Noble gas anomalies and synthesis of the chemical elements; *Trans. Mo. Acad. Sci.* **9** 104–122

Sahijpal S, Goswami J N, Davis A M, Grossman L and Lewis R S 1998 A stellar origin for the short-lived nuclides in the early solar system; *Nature* **391** 559–561

Selesnick R S, Cummings A C, Cummings J R, Leske R A, Mewalt R A, Stone E C and von Rosenbinge T T 1993 Coronal abundances of neon and magnesium isotopes from solar energetic particles; *Ap. J.* **418** L45–L48

Shindo H, Miyamoto M, Matsuda J and Ito K 1985 Vapor deposition of diamond from methane-hydrogen mixture and its bearing on the origin of diamond in urelite: A preliminary report (abstract); *Meteoritics* **20** 754

Srinivasan B and Anders E (1978) Noble gases in the Murchison meteorite: Possible relics of s-process nucleosynthesis; *Science* **201** 51–56

Wasserburg G J 1987 Isotopic abundances: inferences on solar system and planetary evolution. *Earth Planet. Sci. Lett.* **86** 129–173

Zinner E 1997 Presolar material in meteorites: an overview. In *Astrophysical Implications of the Laboratory Study of Presolar Materials* (eds.) T J Bernatowicz, and E Zinner pp. 3–26. AIP Conference Proceedings 402, (Woodbury, N.Y.: American Institute of Physics)

*The author wishes to apologise for the anger expressed in some of his comments here. Any perceived misbehaviour by others does not excuse misbehaviour in me.*