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Xenon isotope record of nucleosynthesis and the early solar system

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ISOTOPIC abundances of Xe were determined as two FeS separates of the Allende (C3V) carbonaceous chondrite were heated, stepwise. A tracer Xe isotope was first produced in one sample by $^{130}\text{Te}(n, \gamma 2\beta^-)^{131\text{r}}\text{Xe}$ reaction to monitor the degassing of Xe from the sample. The FeS melted at 950°C , releasing a spike of $^{131\text{r}}\text{Xe}$ and terrestrial-type Xe, Xe-T. This confirms that trapped Xe in Allende's FeS is indeed Xe-T, which is also in the atmospheres of the earth and Mars, in the sun, and in FeS of diverse meteorites^[1, 2]. These results imply that Xe-T was in the central, Fe, S-rich region of the protoplanetary nebula, and challenge the main

stream hypothesis of the formation of the solar system. Formation of planetary systems from supernova debris^[3] provides a mechanism for (1) large-scale chemical and isotopic heterogeneities and decay products of short-lived radioactivities (e. g. ^{26}Al , ^{107}Pd , ^{129}I), (2) mirror-image (+ and -) isotopic anomalies in several other elements of meteorites^[4], and (3) planets orbiting pulsar PSR1257 + 12^[5], the only other confirmed planetary system.

1 Experimental method

A total of 60 mg of FeS was separated from a 120-g sample of the Allende meteorite that had been crushed and disaggregated by cyclic exposure to liquid N_2 , boiling water, and ultrasonication. Sulfide particles were handpicked under a microscope from the coarse (50 μm —1 mm), high-density fraction. EDX analysis showed the atomic ratio, $\text{Fe}/\text{S} \approx 1$. Half of the sample was irradiated with an integrated thermal neutron flux of 1.69×10^{18} n/cm². The unirradiated FeS(u) and the irradiated FeS(i), samples were mounted in individual side-arm chambers of the gas extraction system. After the pressure had been reduced to about 133.332×10^{-9} Pa, Xe was extracted, cleaned and analyzed in a Reynolds-type, a noble gas mass spectrometer for each sample was heated stepwise to progressively higher temperatures: 600, 800, 950, 1 000 and 1 050°C. More detailed information on the experimental methods is given elsewhere^[2].

2 Results and discussion

Figure 1 shows the release of trapped ^{132}Xe and the tracer isotope, $^{131\text{r}}\text{Xe}$, generated within FeS(i) by the irradiation. The release patterns of ^{132}Xe and $^{131\text{r}}\text{Xe}$ are very similar for 600—950°C, as Xe is released from the sulfides. A peak release occurs at 950°C, when the sulfides melt. Trace silicate minerals with little Te start to degas above 950°C.

FeS(u) also gave off the largest amount of Xe at 950°C. Therefore, this fraction best represents Xe trapped in Allende's FeS. Isotopic ratios of Xe released from FeS(u) and FeS(i) at 950°C are shown in fig. 2 as $(^{131}\text{Xe}/^{132}\text{Xe})_{\text{FeS}} / (^{131}\text{Xe}/^{132}\text{Xe})_{\text{AVCC}}$, where AVCC represents Xe in average carbonaceous chondrites^[2]. Solid horizontal lines indicate AVCC Xe; dashed lines indicate terrestrial Xe, Xe-T. Excess ^{128}Xe and ^{131}Xe from neutron capture on ^{127}I and ^{130}Te are shown as filled symbols. Xe from Allende's FeS is closer to Xe-T than to AVCC Xe, in spite of a slight excess of cosmogenic ^{126}Xe in both samples and a slight deficiency of ^{130}Xe , beyond the 1σ error limit, in FeS(u).

We interpret Xe-T in Allende's FeS as evidence that this formed in a region of the proto-planetary nebula where the earth acquired its Xe, and it was later transported and mechanically

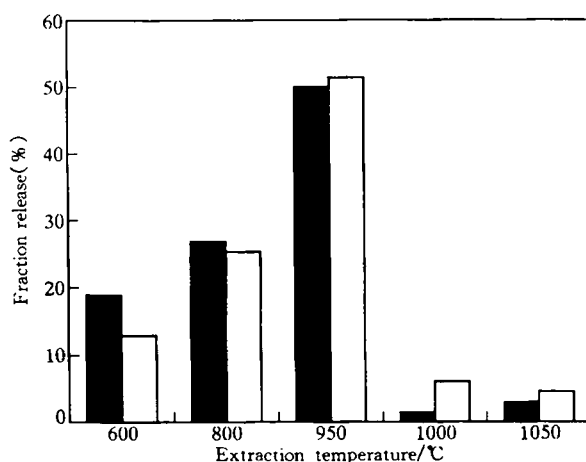


Fig. 1. Release patterns of trapped ^{132}Xe and pile-produced $^{131\text{r}}\text{Xe}$ from the irradiated sample, FeS(i), during stepwise heating. The similar release patterns for both isotopes at 600—900°C indicate degassing of the chalcophile phase. ■, $^{131\text{r}}\text{Xe}$; □, ^{132}Xe .

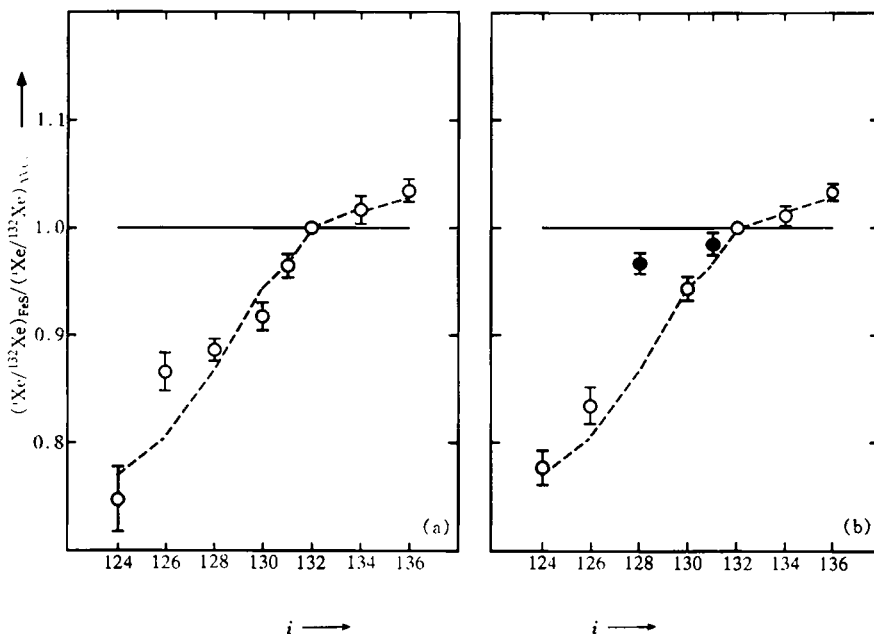


Fig. 2. A comparison of atmospheric and AVCC Xe with that released from the unirradiated sample (a) and irradiated sample (b) at 950°C. The darkened symbols (b) show excesses of ^{128}Xe and ^{131}Xe from neutron capture on ^{127}I and ^{130}Te , respectively. For both samples, the Xe isotopic ratios are closer to Xe-T than to AVCC Xe. (a) \circ , FeS(u); —, AVCC; ---, air. (b) \circ , FeS(i); —, AVCC; ---, air.

mixed with other phases in the region where Allende agglomerated. Niemeyer^[1] observed Xe-T in FeS from the Mundrabilla IAB iron meteorite, noted that Mundrabilla's troilite predates its high melting silicates, and concluded that Mundrabilla's FeS also formed in a different nebular region than the other phases with which it aggregated. Xe-T was also observed in FeS of other iron meteorites^[2], and it was suggested that this formed in a central, Fe- and S-rich region of the protoplanetary nebula where Xe-T was the dominant form of xenon.

Xe-T occurs in other Fe- and S-rich objects in the central part of the solar system. In addition to the earth's atmosphere, Lec *et al.*^[2] cited earlier work showing that martian Xe in meteorite EETA 79001 "is consistent with addition of neutron-capture, radiogenic and fissionogenic isotopes to a base composition resembling terrestrial atmospheric Xe" and that solar wind Xe is also closer to fractionated Xe-T than to fractionated AVCC Xe, with lighter isotopes enriched by about 4% per mass unit.

Two other isotopically distinct forms of Xe are from different regions of the protoplanetary nebula. The outer region where diamond^[6] formed was rich in He, C, Ne and Xe-X^[3] characterized by excess $^{124}, ^{126}\text{Xe}$ and $^{134}, ^{136}\text{Xe}$. The intermediate region where SiC^[7] formed was enriched in a complementary type of xenon, enriched in $^{128-132}\text{Xe}$.

Correlations between abundances of the low-Z rare gases, He and Ne, with isotopic ratios of the high-Z ones, Ar, Kr and Xe, provided the first evidence of correlated chemical and isotopic heterogeneities in the protoplanetary nebula^[3]. Fig. 3 shows these correlations for diamond-rich mineral separates of the Allende meteorite. Xe-T, Kr-T and Ar-T are identified, although barely distinguishable from AVCC Xe, Kr and Ar on the scale used there. Fig. 3 (a-c) shows correlations between elemental abundances of ^4He , expressed as $^4\text{He}/^{36}\text{Ar} (\times 5)$, $^4\text{He}/^{84}\text{Kr} (\times 0.08)$ and $^4\text{He}/^{132}\text{Xe} (\times 0.15)$, and values of $^{38}\text{Ar}/^{36}\text{Ar}$, $^{86}\text{Kr}/^{82}\text{Kr}$ and

$^{136}\text{Xe}/^{132}\text{Xe}$ isotopic ratios. All excess ^{38}Ar , ^{86}Kr and ^{136}Xe are accompanied by primordial ^4He ; "normal" values of $^{38}\text{Ar}/^{36}\text{Ar}$, $^{86}\text{Kr}/^{82}\text{Kr}$ and $^{136}\text{Xe}/^{132}\text{Xe}$ isotopic ratios occur at the intercept where elemental abundances of $^4\text{He} \approx 0$. Fig. 3(d) shows correlations of primordial ^4He and ^{20}Ne , expressed as $^{20}\text{Ne}/^{36}\text{Ar} (\times 3\ 800)$, $^{20}\text{Ne}/^{84}\text{Kr} (\times 40)$, $^{20}\text{Ne}/^{132}\text{Xe} (\times 60)$. Normal isotopic ratios of Ar, Kr and Xe occur at $^{20}\text{Ne} \approx ^4\text{He} \approx 0$. The correlations in fig. 3 are a common feature of meteoritic noble gases^[8], as expected if Ar-X, Kr-X and Xe-X are from outer layers of a supernova where low-Z elements like He, C and Ne are abundant and isotopically "normal" Ar, Kr and Xe are from its interior, where fusion consumed low-Z elements.

Formation of the solar system from heterogeneous debris of a single supernova^[3] may explain these correlations and some otherwise puzzling observations: (1) "Mirror-image" isotopic anomalies are observed in several elements^[4, 8]. Begemann^[4] notes that the (ant)-match of Ba, Nd and Sm isotopic anomalies "appears too good to be serendipitous". (2) Levels of extinct radionuclides in meteorites (e.g. ^{26}Al , ^{107}Pd , ^{129}I) do not define a consistent, post-nucleosynthesis chronology. An intense irradiation in the immediate vicinity of a supernova provides a mechanism for continued production of these after stellar synthesis has ceased. (3) A local irradiation might also explain the production of D, Li, Be and B, and the observation^[9] of correlations between isotopic enrichments of ^{11}B and values of the B/Si and Be/Si elemental ratios.

3 Conclusions

Our finding of Xe-T in FeS from Allende and the finding of Xe-X in diamonds from this same meteorite^[6] illustrate the chemical and isotopic diversity of material that formed Allende. The occurrence of Xe-T in FeS of diverse meteorites^[1, 2] and in the atmospheres of Fe, S-rich planets^[2] suggests heterogeneities on a larger, planetary scale.

The presence of Xe-T in the He-rich solar wind^[2] is one observation which does not fit the correlation of Xe-T with Fe- and S-rich material. However, Xe-T in the solar wind is enriched in lighter isotopes by about 4%/amu^[2], and this may be caused by diffusion that enriches light nuclei at the solar surface. Heavy ions in a plasma diffuse to the high-pressure and high-temperature region, as noted^[10] in Chapman and Cowling's conclusion that "This must happen in the sun and stars, where thermal diffusion will assist pressure diffusion in concentrating the heavier nuclei towards the hot central regions." If intrasolar diffusion causes selective enrichment of light isotopes of Xe, Ne, He, etc. in the solar wind, then Fe and S are the first and fifth most abundant elements in the bulk sun^[10] and the high abundances of H and He at the solar surface are an artifact of diffusion.

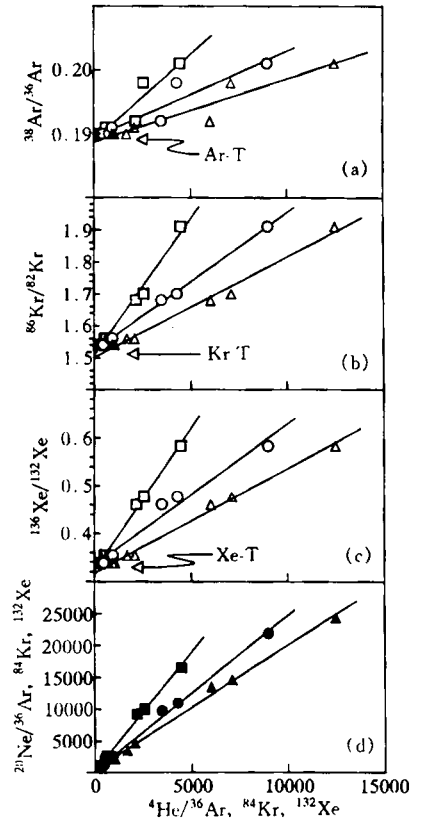


Fig. 3. Isotopic ratios of Ar, Kr and Xe correlate with elemental abundances of He (a), (b), (c). Elemental abundances of Ne also correlate with He (d).

The suggestion that the solar system formed directly from debris of a single supernova^[3], with the sun forming on the collapsed supernova core, was once considered too extreme to merit discussion. However, the possibility of forming a planetary system from a supernova became more attractive with the finding^[5] of a planetary system orbiting pulsar PSR-1257 + 12, a neutron star produced as the remnant collapsed core of a supernova. Three earth-like planets orbit PSR1257 + 12 within a distance of 0.2—0.5 AU from the pulsar^[5]. Our solar system and the planets orbiting PSR1257 + 12 were the first planetary systems known. Axial collapse and explosion of a spinning supernova, as shown in fig. 6 of Oliver *et al.*^[8], may explain both systems, as well as the preservation of nucleogenetic chemical and isotopic heterogeneities in material which formed the solar system.

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