EVIDENCE FOR NEUTRON IRRADIATION IN THE EARLY SOLAR SYSTEM;
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Chondritic metal from types H3 and H4 reveals a distinct Xe component: FVM-Xe (Forest Vale Metal Xe) (1). Since this represents a new Xe isotopic signature, we carried out a detailed investigation of its origin and of the implications.

The new FVM-Xe component is apparently surface correlated and generally is released at intermediate temperatures. The concentration in the metal depends on petrographic type. The main characteristic of FVM-Xe is an $\sim 3.4\%$ shift in the ratio $^{134}\text{Xe}/^{136}\text{Xe}$ when compared to that of FVC-Xe (2). We can rule out the possibility that the observed shift in the $^{134}\text{Xe}/^{136}\text{Xe}$ ratio between FVC and FVM xenon is due to cosmic-ray reactions. There is no correlation between spallation $^{38}\text{Ar}_s$ and FVM-Xe. Figure 1 shows that FVM-Xe cannot be obtained from any of the known solar system reservoirs by either mass dependent fractionation or by the addition of HL-Xe (3). It can not be due to solar (or stellar) wind ion implantation, because the observed element ratio $^{36}\text{Ar}/^{132}\text{Xe} = \sim 100$ in metal differs grossly from solar abundances ($\sim 25,000$). However, FVM-Xe is a minor component when compared to FVC-Xe, the major trapped Xe reservoir in chondritic metal and released at all temperature steps.

In order to understand the origin of FVM-Xe, it is necessary to define solar and solar nebular Xe isotopic signatures. The Sun represents the major reservoir in the solar system and a knowledge of the isotopic signature of solar Xe is essential for an understanding of solar system components. No Xe isotopic shifts are expected between solar and solar wind abundances as a result of non-mass-dependent effects (4). Therefore, the solar Xe can be inferred from solar-wind Xe data. The difference between solar nebular Xe and solar Xe isotopic signatures depends on the mixing ratio with exotic Xe. The amounts of exotic Xe in carbonaceous chondrites are less than 2% of total Xe (relative to Q-Xe, 5). Because the Q-Xe is elementally depleted by a factor of $10^5$ relative to solar Xe, the exotic Xe contribution to solar nebula gas from solid carriers is negligible ($<10^{-6}$ of solar nebu lar Xe). Therefore, the concentrations of HL-Xe are much too small to change the isotopic make-up of initial solar nebular Xe and the solar Xe isotopic signature is not expected to differ from solar-nebula Xe.

Several possible sources for FVM-Xe have been postulated (1): addition of Xe due to $^{248}\text{Cm}$ spontaneous fission, from $^{235}\text{U}$ neutron induced fission, or due to $^{244}\text{Pu}$ fission. In Fig. 1, the data (6) which show evidence for FVM-Xe components are plotted. The largest shifts (largest relative abundances of FVM-Xe) are observed in three fractions: 1200°C pyrolysis step in Dhajala <40μm, 1100°C pyrolysis step in Forest Vale 160-280μm and 1200°C pyrolysis step in Forest Vale 280-450μm. In the following discussion we will use only these three points, since the others can be understood to represent mixtures. As shown in Fig. 1, we can eliminate the $^{244}\text{Pu}$ fission option as an end-member because in that case we would need a trapped Xe component which plots beyond the upper right corner. For the $^{248}\text{Cm}$ option, using solar Xe as the trapped component, it is marginally possible, within error limits, to explain the FVM-Xe measurements as mixtures. For the $^{235}\text{U}_{nf}$ fission-Xe end-member option, the signature of the trapped component is reasonably well constrained. It could be solar Xe or slightly fractionated ($<1$/amu) solar Xe. However, the above listed three data points could be affected by an additional FVC-Xe component. Therefore, the $^{248}\text{Cm}$ fission option is only marginally acceptable. The most plausible source of FVM-Xe is neutron-induced fission Xe from $^{235}\text{U}$ added to solar Xe (or slightly fractionated solar Xe). A mixture of solar Xe (94% $^{136}\text{Xe}$) and $^{235}\text{U}_{nf}$ fission Xe (6% $^{136}\text{Xe}$) agrees well with FVM-Xe for all nine Xe isotopes. The neutron fluency required to produce the observed fission component from $^{235}\text{U}$ (88x more abundance at this time) can be estimated, if we make the following assumptions: (a) The FVM-Xe (3.4 x $10^{-12}$ cm$^3$ STP g$^{-1}$ $^{136}\text{Xe}$) in the finest grain-size fraction of Dhajala
metal was not lost during its history. (b) The $^{136}$Xe$_{nf}$ produced in $^{235}$U fissions was implanted in metal (20%) as well as in silicates in nebular dust (80%). With the above assumptions, a neutron fluence of $\sim 1 \times 10^{16}$ n/cm$^2$ was required in the location where metal in H-chondrites was exposed.

We do not know how the required neutron flux was produced, but we report experimental evidence for its existence. This presents evidence of neutron irradiation in the solar nebula. It is interesting to note, that recently Nichols et al. (7) reported unexplainable neutron effects on $^{127}$I in highly oxidized acid residues of Inman (L3.4). Possible sources of neutrons include: secondary neutrons produced by proto-solar activity, neutrons produced by fission of transuranic elements. From track studies in olivine microcrystals from ordinary chondrites, Kashkarov et al. (8) reported traces of pre-accretion irradiation of low-energy nuclei by solar cosmic rays and possibly secondary neutrons could be produced. Since this neutron-induced fission component was so far observed only in the metal phase, the following possible scenario is suggested. Before or during the accretion in the solar system, nebular materials were exposed to a neutron fluence ($>10^{16}$ n/cm$^2$). The U in small silicate or oxide particles ($<10 \mu m$) (or in the gas phase), reacted with neutrons and released fission Xe fragments which were then implanted into existing surfaces of nebular particles, such as presolar metal grains. After aggregation, some of the fission Xe is trapped in the interior of the resulting grains, but relict grain boundaries (9) control the Xe release by diffusion into pores or channels, which would explain the release temperature (800-1200°C). After accretion of these early metal grains, secondary processing and metamorphism occurred, and high petrographic types (H6) lost most of their FVM-Xe together with trapped gases. The release of substantial amounts of $^{244}$Pu-derived fission Xe at low temperatures ($\leq 600°C$) in H4 metal implies that the metal carriers of these fossil fission recoil fragments were never heated to 600°C for time periods of hours (the laboratory time scale) after the decay of $^{244}$Pu. These fission records provide important new constraints on the genesis and the thermal history of chondritic metal.

Fig. 1. Three isotope correlation plot of $^{134}$Xe/$^{136}$Xe vs. $^{132}$Xe/$^{136}$Xe using only data which reveal FVM-Xe components. Most of the data show mixtures of several components: FVC-Xe, Pu fission-Xe and FVM-Xe.