We have recently presented evidence for the existence of live \(^{60}\)Fe in the early solar system \([1-3]\). This evidence comes from the observation of 2.4 to 50 \(\epsilon\) unit \((1 \text{ part in } 10^4)\) relative excesses of \(^{60}\)Ni \((^{60}\text{Ni}^*)\) measured in samples from the eucrite Chervony Kut (CK). These isotopic excesses have been produced by the decay of the now extinct short-lived radionuclide \(^{60}\)Fe \((T_{1/2} = 1.5 \text{ Ma})\). Because CK originates from a planetesimal which was totally molten and its high Fe/Ni ratio is due to a planet-wide Fe - Ni fractionation during metal-silicate segregation, the presence of the \(^{60}\)Fe decay product indicates the large scale abundance of \(^{60}\)Fe in the early solar system and its presence during differentiation of this planetesimal. The observed variable \(^{60}\text{Ni}^*\) excesses in different bulk samples and mineral separates (and their washes) from CK can only be understood if some \(^{60}\)Fe was still alive at the time when basaltic magma had solidified on the eucrite parent body. The lack of a correlation between \(^{60}\text{Ni}^*\) and the respective Fe/Ni ratios in different mineral fractions from CK indicates a metamorphic remobilization of Ni after essentially all \(^{60}\)Fe had decayed. However, \(^{60}\text{Ni}^*\) from three bulk samples from different locations within the meteorite appears to correlate reasonably well with the respective Fe/Ni ratios. If we regard this correlation as an isochron then its slope yields a \(^{60}\text{Fe}/^{56}\text{Fe}\) ratio of \((3.93\pm0.6) \times 10^{-2}\) and an initial \(^{60}\text{Ni}^*\) of \(3.2\pm0.9 \epsilon\) units at the time of crystallization of CK \([3]\). Estimates based on these values and a \(-10\) Ma time interval between CK solidification and formation of the earliest condensates in the solar system followed by rapid accretion of planetary bodies indicate that the decay of \(^{60}\)Fe could produce sufficient heat to melt these planetesimals. If \(^{26}\)Al was present on a planetary scale as \(^{60}\)Fe and at abundances close to values observed in Allende inclusions \([4]\) then melting of small early formed planets is inevitable.

As an attempt to further explore the \(^{60}\text{Fe}-^{60}\text{Ni}^*\) isotope system as an early solar system chronometer we studied another noncumulate eucrite, Juvinas (JUV) \((\text{sample USNM 1051})\), which belongs to the same subgroup as CK \([5]\). In contrast to CK, JUV is generally more brecciated, contains clasts, and has more than a century longer terrestrial residence time. Several samples of matrix, ranging from 130 to 500 mg, from two clasts (CL A and B) and several \(\text{H}_2\text{O}, \text{methanol, and HCl}\) washes have been analyzed for Ni isotopic composition and Fe/Ni ratios. Most importantly, clear evidence for the decay of \(^{60}\)Fe was found in all unwashed and washed samples. As in CK, Ni is very heterogeneously distributed within the meteorite: Ni concentrations in unwashed bulk samples vary from 1.2 ppm up to 10.7 ppm. However, there are important differences between JUV and CK. In JUV, the \(^{60}\text{Ni}\) excesses in bulk samples range from \(-1.6\) to \(-8 \epsilon\) units \((\text{up to } 40 \epsilon\ in \ CK)\) while the spread in Fe/Ni ratios is similar. \(^{60}\text{Ni}/^{58}\text{Ni}\) ratios in \(\text{H}_2\text{O}\) and 1.8N HCl washes are all very close to the normal terrestrial value \((\text{Fig. 1})\) while the washes of CK samples have \(^{60}\text{Ni}^* close to the initial ratio \((+3 \epsilon)\) obtained from a CK bulk sample isochron. If JUV and CK originate from the same parent body, which is most likely, the JUV samples should not have any \(^{60}\text{Ni}/^{58}\text{Ni}\) ratios lower than the initial ratio found in CK. Moreover, 30 to 60% of the total Ni in the washed samples was found in the \(\text{H}_2\text{O}\) (and methanol) washes. Thus, the normal Ni isotopic composition of the large amount of readily removable Ni could most plausibly be explained by contamination of JUV during its terrestrial exposure, consistent with other observations \([6]\). However, introduction of normal Ni at
some time in its pre-terrestrial history (e.g. brecciation event) cannot be excluded.

So far two washed bulk samples, Bulk 2 and 4, have been analyzed. Although their very high Fe/Ni ratios are different, they have the same $^{60}$Ni of $\sim 8 \times 10^{-8}$ (Fig. 1). $^{60}$Ni in all unwashed samples are distinctly lower. Thus, it is reasonable to assume that these low $^{60}$Ni values are due to contamination with normal Ni. Since the cleaned matrix samples with the highest Fe/Ni ratios have the same $^{60}$Ni a line through these two points has a slope of $-0$ and an initial $^{60}$Ni of $-8.3 \pm 1$ units. This implies that all $^{60}$Fe had decayed at the time when JUV crystallized. If we assume that JUV and CK were produced by similar degrees of partial melting then the intercept of the two ‘isochrons’ (Fig. 1) yields a good approximation for their total rock $^{56}$Fe/$^{58}$Ni ratios of $5 \times 10^{-4}$. From this we calculate that JUV has crystallized at least 5 Ma after CK. This time difference suggests a deeper burial for JUV than for CK.

The new estimate for the total rock Fe/Ni ratio also affords a better approximation for the $^{60}$Fe/$^{56}$Fe ratio ($6.3 \times 10^{-5}$) at the time of parent body differentiation and the time difference ($\Delta T \approx 1.1$ Ma) until CK formed, in good agreement with our earlier upper limit of 1.4 Ma [3]. If some Fe/Ni fractionation occurred during partial melting of the CK source, a conservative upper limit for $\Delta T$ of 3 to 4 Ma can be estimated. Regardless of the precise conditions, a short time interval of 1 to 4 Ma between core formation and solidification of CK is indicated.


We thank G. MacPherson for sample USNM 1051.

Figure 1: Relative $^{60}$Ni/$^{58}$Ni excesses ($^{60}$Ni') from the decay of $^{60}$Fe in the Juvinas (JUV) eucrite, expressed in $\varepsilon$ units ($1 \times 10^{-4}$). H$_2$O and HCl washed bulk (Blk) samples are indicated by (w). All washes have $^{60}$Ni close to zero, suggesting contamination with normal (terrestrial) Ni, which appears to have affected the clasts (CL A, B) as well. The dashed line (marked JUV) through the data points corresponding to the washed samples has zero slope which indicates closure of the $^{60}$Fe-$^{60}$Ni system after $^{60}$Fe had totally decayed. The solid line (marked CK) shows the Fe-Ni ‘isochron’ for Chervony Kut (CK) which yields $^{60}$Fe/$^{56}$Fe $= 3.9 \times 10^{-9}$ at the time of closure of the $^{60}$Fe-$^{60}$Ni system in CK. From this we calculate a formation time interval for CK and JUV of $\geq 5$ Ma. The time between core formation on the eucrite parent body and CK crystallization is 1 to 4 Ma.