17. O. Khaner and F. Wilt, *Development* **112**, 881 (1991).
18. B. T. Livingston and F. H. Wilt, *ibid.* **108**, 403 (1990).
19. C. Nocente-McGrath, C. A. Brenner, S. G. Ernst, *Dev. Biol.* **136**, 264 (1989).
20. A. Ransick, S. G. Ernst, R. J. Britten, E. H. Davidson, *Mech. Dev.*, in press.
21. C. A. Ettensohn, *Science* **248**, 1115 (1990).
22. _____ and D. R. McClay, *Dev. Biol.* **117**, 380 (1986).
23. In the normal 16-cell embryo, the four micromeres abut the four macromeres, their sister cells after the fourth cleavage (Fig. 2). However, because the next division of the micromeres is delayed relative to that of the macromeres, the fourth-cleavage micromeres also underlie the eight, fifth-cleavage macromere progeny (Fig. 1B). The macromere progeny divide horizontally at the sixth cleavage, separating the eight vegetal-plate founder cells, known as the veg_2 ring (*12*) (Fig. 1, A and C), from an overlying veg_1 ring that gives rise only to portions of the oral and aboral ectoderm (*24*). When the micromeres do finally divide, it is by an unequal cleavage that produces a skeletogenic founder blastomere and a small micromere From these four skeletogenic founder cells, several cleavages generate the 32 skeletogenic mesenchyme cells present at the late blastula stage. The small micromeres divide only once more to produce eight cells that ultimately contribute to postembryonic imaginal development [R. A. Cameron, S. E. Fraser, R. J. Britten, E. H. Davidson, *Development* **113**, 1085 (1991), J. R. Pehrson and L. H. Cohen, *Dev Biol.* **113**, 522 (1986).] It is unlikely that the small micromeres play a role in this process, because they lack the inductive capabilities of the (skeletogenic) micromeres in blastomere recombination experiments (*17*).
24. R. A. Cameron, B. R. Hough-Evans, R J. Britten, E. H. Davidson, *Genes Dev* **1**, 75 (1987).
25. The supra-anal ectoderm is a region of the aboral ectoderm located between the oral ectoderm and the anus. It is derived from the VO macromere, as described (*24*), discussed in (*24*), this region expresses molecular aboral ectoderm marker genes
26. J Hardin and D. R. McClay, *Dev. Biol.* **142**, 86 (1990).
27. M. A. Harkey, H. R. Whiteley, A. H. Whiteley, *Mech. Dev.* **37**, 173 (1992)
28. We are pleased to thank R J. Britten and R A. Cameron for their critical and helpful reviews. Supported by NIH grant HD-05753; and an NIH training grant HD-07257 (A.R.).

RESEARCH ARTICLE

Live Iron-60 in the Early Solar System

A. Shukolyukov and G. W. Lugmair

Isotopic analyses of nickel in samples from the differentiated meteorite Chervony Kut revealed the presence of relative excesses of ^{60}Ni ranging from 2.4 up to 50 parts per 10^4. These isotopic excesses are from the decay of the now extinct short-lived nuclide ^{60}Fe and provide clear evidence for the existence of ^{60}Fe over large scales in the early solar system. Not only was ^{60}Fe present at the time of melting and differentiation (that is, Fe-Ni fractionation) of the parent body of Chervony Kut but also later at the time when basaltic magma solidified at or near the surface of the planetesimal. The inferred abundance of ^{60}Fe suggests that its decay alone could have provided sufficient heat to melt small (diameters of several hundred kilometers) planetary bodies shortly after their accretion.

An important parameter for describing the earliest stages of the evolution of the solar system is the time interval between the last event of nucleosynthesis contributing to solar system matter and formation of the first solid bodies. Nucleosynthetic production and subsequent rapid introduction into the nascent solar system of relatively short-lived radionuclides with half-lives of millions to hundreds of millions of years could provide information on the extent of this time interval provided that the short-lived species, although now extinct, were still alive at the time of the formation of solids. Thus, ancient solid bodies such as meteorites would reveal evidence for the original presence and subsequent decay of these short-lived radionuclides in the form of isotopic anomalies on the daughter isotopes.

These thoughts were formulated almost half a century ago by Brown (*1*) and Süss (*2*) and later were further developed by Urey (*3*) and Kohman (*4*). Evidence for the first such short-lived radionuclide, ^{129}I [half-life $T_{1/2}$ of 16 m.y. (million years)], was discovered in 1960 by Reynolds (*5*). Since then the presence in the early solar system of several short-lived species has been well established: ^{244}Pu ($T_{1/2}$ = 82 m.y.) (*6*), ^{26}Al (0.7 m.y.) (*7*), ^{107}Pd (7 m.y.) (*8*), ^{146}Sm (103 m.y.) (*9*), and ^{53}Mn (3.7 m.y.) (*10*). Together with long-lived radionuclides, such as ^{87}Rb, ^{40}K, ^{147}Sm, ^{235}U, and ^{238}U, the abundance of these short-lived radionuclides has already provided extensive information and constraints on the nature of nucleosynthesis and the chronology of the early evolution of the solar system. In this article, we present evidence for the presence in the early solar system of another short-lived radionuclide, ^{60}Fe, and discuss its usefulness as a chronometer and its importance as a heat source for early planetary melting.

History. The composition and texture of differentiated meteorites such as achondrites, irons, and pallasites reflect igneous differentiation processes within asteroidal-sized parent bodies. This igneous differentiation can only be the result of extensive melting of these planetesimals. However, these bodies, which had radii of 500 km or less, are much too small to have melted extensively as a result of accretional energy or radioactive decay of long-lived nuclei (*11*). Thus, the nature of the heat source has remained uncertain, although heating by both external [electromagnetic induction (*12*)] and internal [radioactive decay of short-lived nuclei (*3, 4, 13*)] mechanisms has been suggested. Urey (*3*) proposed that the decay of ^{26}Al (3.18 MeV) could have been an efficient heat source for the processing of meteorites; Kohman and Saito (*4*), in consideration of the high iron content of many meteorites, suggested that a yet unknown nuclide, ^{60}Fe, might be an important heat source if it had a suitable half-life and sufficient primordial abundance. Roy and Kohman (*13*) subsequently discovered the nuclide ^{60}Fe, which has a total decay energy of 3.04 MeV, and estimated its half-life as ~0.3 m.y. with an uncertainty of a factor of 3. However, at that time both ^{26}Al and ^{60}Fe were discounted as useful chronometers and adequate heat sources because of their short half-lives. Nevertheless, extensive efforts were made to find the vestiges from extinct ^{26}Al in meteorites. The first clear evidence for the presence in the early solar system of ^{26}Al was found by Lee *et al.* (*7*) in refractory Ca-Al–rich inclusions (CAI) from the Allende meteorite in the form of relative excesses of its daughter, ^{26}Mg. Thereafter, ^{26}Al again attracted attention as a possible heat source [see, for example, (*14*)]. Further studies on other meteorite inclusions, however, showed that not all samples of comparable antiquity contain excess ^{26}Mg; this evidence suggested that ^{26}Al was heterogeneously distributed in the early solar

---

The authors are at the Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093.

system (*15, 16*). In addition to CAI, products from ^{26}Al decay were found in a hibonite clast from an H3 chondrite (*17*), in a basaltic chondrule from the unequilibrated ordinary chondrite Semarkona (*18*), and most recently in feldspars from the H4 chondrite Ste. Marguerite (*19*). This last result considerably strengthens the possibility that ^{26}Al could indeed have been sufficiently abundant to melt early accreting planetesimals because H4 chondrites are believed to originate from a small planetary object (*19*).

The half-life of ^{60}Fe has been recently redetermined to be 1.49 ± 0.27 m.y. (*20*), much longer than the earlier estimate (*21*). Its importance as a potential heat source, however, was still unclear because the nucleosynthetic production rate of ^{60}Fe is poorly constrained. Clayton (*22*) had argued that rapid neutron capture by ^{56}Fe during explosive carbon burning is the most probable mode of production, but the amount of ^{60}Fe produced is still uncertain. According to multizone-mixing model calculations of Hartmann *et al.* (*23*), most ^{60}Fe was produced in nuclear statistical equilibrium at neutron enrichments intermediate to those for ^{50}Ti and ^{48}Ca, for which ubiquitous excesses are observed in CAI. However, no quantitative estimate on the ^{60}Fe/^{56}Fe production ratio is yet available.

^{60}Fe decays by β^- emission and forms, by way of ^{60}Co, the stable nuclide ^{60}Ni. Until recently no direct evidence had been found that ^{60}Fe was alive in the early solar system although several attempts have been made to detect traces of its existence in the form of excess ^{60}Ni. These attempts mainly indicated that the abundance of ^{60}Fe must have been low (*24*). However, Birck and Lugmair (*25*) showed that the isotopic composition of Ni in Allende inclusions exhibits small but, in several instances, clearly resolved excesses of ^{60}Ni (^{60}Ni*) of about 1 part in 10,000 [1 ϵ unit (*26*)]. On the basis of theoretical considerations, these excesses are unlikely to have been caused by coproduction of ^{60}Ni with the neutron-rich nuclei for which larger excesses were found. Rather, it was deemed more likely that ^{60}Ni* is the result of the decay of ^{60}Fe and is related to the bulk Fe/Ni ratio in the samples. If so, then the amount of ^{60}Ni* would suggest that the ratio of ^{60}Fe/^{56}Fe at the time these inclusions formed was (1.6 ± 0.5) × 10^{-6}. Uncertain Fe-Ni fractionation in the precursor material and other assumptions rendered this interpretation rather speculative, however. Furthermore, it was not clear whether these ^{60}Ni excesses were attributable to in situ decay of ^{60}Fe.

Sample selection. The earlier work (*25*) indicated that results for ^{60}Ni* obtained on Allende inclusions, although the most ancient solar system material now available, may be of limited value because of the small ^{60}Ni excesses and the uncertainties associated with constraining their origin (*27*). We thus chose to study eucrites because this class of material meets most of the important criteria for a search for effects from ^{60}Fe decay. Eucrites are meteorites of basaltic composition and originate from a differentiated asteroidal-size planetesimal. During metal-silicate segregation and core formation in the eucrite parent body, the bulk of siderophile Ni must have been removed into the core. Thus, the remaining silicate mantle and lavas derived from the mantle were strongly depleted in Ni. Indeed, the Ni content of eucrites is only several parts per million, and Fe/Ni ratios, on the order of 10^4 to 10^5 (*28*), are extremely high relative to the solar value of ~20 (*29*). Chemical equilibration of the eucrite material occurred on a planetary scale. Thus, any ^{60}Ni* would show that ^{60}Fe was present on a large scale in the solar system at the time of Fe-Ni fractionation in the eucrite parent body. Variations of ^{60}Ni* between different subsamples of a eucrite would indicate that ^{60}Fe was still extant at the time of basalt crystallization. Furthermore, a correlation of ^{60}Ni* and Fe/Ni in phases with different Fe/Ni ratios would allow determination of the ^{60}Fe/^{56}Fe ratio at that time (*30*). Of course, in order to detect these effects, the Ni depletion process must have occurred early in solar system history. Lugmair and Galer (*31*) recently obtained a precise Pb-Pb age for angrites of 4.5578 ± 0.0005 Ga (billion years ago). They argued on the basis of the identical ^{87}Sr/^{86}Sr initial ratios of eucrites and angrites that their solidification ages are within ~2 m.y. of one another. Thus, eucrites clearly are early magmatic differentiates, and if live ^{60}Fe played any significant role in the early solar system one should be able to find vestiges of its presence in these samples.

Table 1. Ni and Fe concentrations, Fe/Ni ratios, and relative ^{60}Ni excesses, expressed in ϵ units (*26*), measured in samples from the eucrite Chervony Kut; nd, not determined.

Sample	Weight (g)	Ni (ppm)	Fe (%)	10^{-4} ^{56}Fe/^{58}Ni	^{60}Ni* (ϵ units)
Bulk 1	0.0861	6.1	15.1	3.50	6.6 ± 0.6
Bulk 2	0.2159	3.6	18.3	7.18	14 +3/−6
Bulk 3	0.4775	0.59	15.2	36.4	39.4 ± 3.0
Px 1	0.1948	6.1	24.5	5.67	2.4 ± 0.5
Px 1 wash	0.0065	91.3	18.3	0.283	3.2 ± 0.8
Px 2	0.2032	~0.8	nd	nd	nd
Px 2 wash	0.0062	102.6	24.3	0.335	3.3 ± 0.5
Px 3	0.0340	4.5	21.1	6.62	3.0 ± 1.0
Troilite	0.0361	12.7	30.9	3.43	50.4 ± 0.9
Troilite residue	0.0702	~0.3	10.7	50.4	nd
Mixed fraction	0.1430	2.84	12.1	6.02	17.7 ± 0.9

We first studied the relatively unbrecciated eucrite Chervony Kut (CK). Its well-preserved igneous texture distinguishes CK from other more brecciated eucrites (*32*) and clearly indicates that it had an igneous origin. It is a noncumulate eucrite and resembles the less brecciated parts of the eucrite Juvinas. CK is composed of approximately 32 modal percent orthopyroxene, 19 percent clinopyroxene, 41 percent plagioclase, and 7 percent silica. The accessory minerals are troilite, chromite, ilmenite, and magnetite. It has a gabbroic texture and medium grain size (0.5 to 3 mm) (*32*). Several bulk samples and mineral fractions of pyroxene (Px), plagioclase (Pl), and troilite from CK were prepared (*33*) for mass spectrometric measurement of Ni isotopic abundances (*34*) and determination of Ni and Fe concentrations (*35*).

The Rb-Sr and Sm-Nd ages of CK (*36*) are old but highly uncertain. We measured ^{87}Sr/^{86}Sr and Rb/Sr ratios for a bulk sample of CK. The calculated initial ^{87}Sr/^{86}Sr ratio agrees within uncertainty with the initial ^{87}Sr/^{86}Sr ratio of 0.698970 ± 0.000015 obtained for the angrites (*31*). Thus, we can infer an age for CK of 4.558 ± 0.002 Ga. Ages based on initial ^{87}Sr/^{86}Sr values are model-dependent and require the assumption that Rb depletion occurred during magma differentiation on the eucrite and angrite parent bodies.

Evidence for ^{60}Fe. The initial analysis of the first fine-grained bulk sample of CK (bulk 1) (*37*) revealed a distinct and well-resolved excess on the ^{60}Ni/^{58}Ni ratio of 6.6 ± 0.6 ϵ units (Table 1 and Fig. 1). We argued (*37*) that this excess was a result of the decay of ^{60}Fe. Alternative modes of production such as by spallation or n-γ reaction on ^{59}Co can be excluded: The abundance of any target element for production of ^{60}Ni by spallation is insufficient; the low Co concentrations in eucrites [several parts per million (*38*)] and a low secondary thermal neutron fluence (<1 × 10^{15} neutrons per square centimeter) obtained from measurement of the ^{150}Sm/^{149}Sm ratio in this sample rule out ^{60}Ni production in neutron capture reactions. Thus, ^{60}Fe was alive at least at the time of Ni depletion (that is, core formation) in

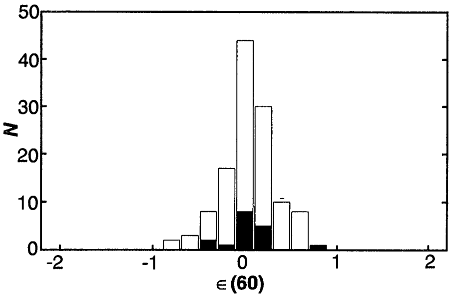

Fig. 1. Distribution of laboratory standard (open bars) and terrestrial rock standard (JB-1, JB-2, closed bars) measurements of ^{60}Ni/^{58}Ni, expressed in relative deviations [as ϵ units (*26*)] from the mean. The total population covers a range of ±0.8 ϵ units; for a single measurement the typical (internal) precision corresponds to ~±0.6 ϵ units or 95 percent of the total population (2σ).

the CK parent body. Relative to the solar value, the high Fe/Ni ratio in bulk 1 of CK (Table 1) leads to an ^{60}Fe/^{56}Fe ratio at the time of Fe-Ni fractionation of about 7.5×10^{-9}. The only assumption entering this calculation is that the measured Fe/Ni ratio in the bulk sample is close to that in its source magma.

In order to confirm this result and investigate the possibility that ^{60}Fe was still alive at the time of solidification of CK, we analyzed other samples from this basaltic achondrite. We found that Ni is heterogeneously distributed in the meteorite and may reside mainly in tiny metal or troilite grains rather than in the major mineral phases. The Ni concentrations in the relatively large bulk samples (86, 216, and 478 mg) ranged from 6 to 0.6 ppm. Mild HCl washes of pyroxene separates contained more Ni than the actual pyroxene fractions. For example, washing of a 200-mg portion of the Px2 separate (Table 1) in 1.8 N HCl for 6 minutes removed about 80 percent of total Ni in the sample (the remaining Ni content was too low for isotopic analysis). Nevertheless, all bulk samples and mineral fractions with sufficient amounts of Ni for isotopic analysis showed ^{60}Ni excesses from ~2.4 up to ~50 ϵ units (Table 1 and Fig. 2).

These data confirm and extend the earlier result that ^{60}Fe was extant during planetary differentiation. If we assume that CK represents a closed system with respect to Ni and that all the ^{60}Fe had decayed at the time of solidification, then ^{60}Ni* in all samples should be the same regardless of the Fe/Ni ratio; this is not the case (Fig. 2). Variable ^{60}Ni excesses can be understood only if some ^{60}Fe was present at the time of crystallization of CK. In that case, however, ^{60}Ni* in the samples should be correlated with the respective Fe/Ni ratios (*30*), a relation not evident from the data (Fig. 2).

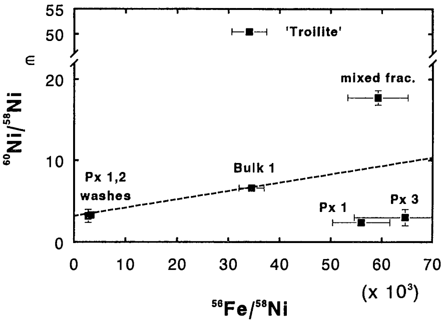

Fig. 2. Relative excesses of the ^{60}Ni/^{58}Ni ratio (in ϵ units) from the decay of ^{60}Fe in a bulk sample, several mineral fractions, and washes from the eucrite Chervony Kut. Although isotopic anomalies are ubiquitous in all measured samples, there is no correlation with their respective Fe/Ni ratios. This scatter is believed to be due to a small scale redistribution of Ni caused by a thermal event in the meteorite's history after all ^{60}Fe had decayed. The dashed line is the least squares fit from Fig. 3. The axis breaks between 20 and 50 ϵ units.

Redistribution of Ni relative to Fe among the mineral phases after crystallization, at a time when essentially all ^{60}Fe had decayed, must have partly obliterated any direct relation between ^{60}Ni* and the Fe/Ni ratios. Indeed, textural relations show that some pyroxene recrystallized late (*32*). The cause of this redistribution was most likely a thermal metamorphic event that did not destroy the original igneous texture of CK but resulted in diffusion of Ni from the high-Fe silicates where ^{60}Ni* had been formed by ^{60}Fe decay. The disturbed Rb-Sr systematics and, in particular, the ^{40}Ar/^{39}Ar results also indicate a late (≤1.5 Ga) metamorphic event (*36*).

Another conclusion that can be derived from the data in Fig. 2 is that the initial ^{60}Ni/^{58}Ni ratio at the time of CK solidification could not have been higher than the lowest value obtained for ^{60}Ni* from some mineral fractions because any closed system redistribution of Ni after solidification would tend to increase the observed initial ^{60}Ni/^{58}Ni ratio. Thus, the lowest obtained ^{60}Ni/^{58}Ni ratio of 2.4 ± 0.5 ϵ units is an upper limit for the initial ^{60}Ni/^{58}Ni.

The incompatibility of Ni in the major mineral phases, its obvious heterogeneous distribution within CK, and its apparent high mobility give rise to several questions with regard to the usefulness of the ^{60}Fe-^{60}Ni system as a chronometer. Did Ni diffuse only over a range of tens to hundreds of micrometers and did the radiogenic Ni (that is, ^{60}Ni*) remain in close proximity to the phases where it was originally accumulated, or did diffusion occur on a scale of millimeters or even centimeters? In the first case we can expect that millimeter-sized "bulk" samples from different parts of the meteorite having different Fe/Ni ratios could still be considered to be individual closed systems; their ^{60}Ni* should then correlate with the respective Fe/Ni ratios. In the second case, however, a correlation, even for relatively large (≥100 mg) bulk samples, would be degraded. Unequivocal resolution of this question requires data on the origin, properties, and distribution of the Ni-bearing phases in CK that are not yet available.

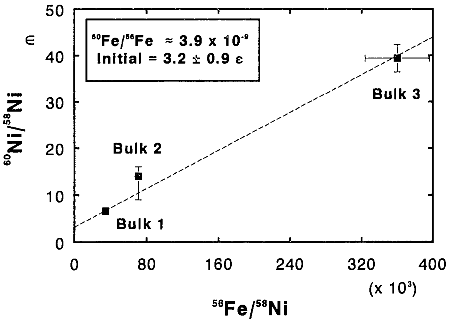

Fig. 3. Variation of the ^{60}Ni/^{58}Ni ratio with a large range of Fe/Ni ratios in three bulk samples of Chervony Kut. The linear relation suggests that Ni mobility during the thermal redistribution was limited enough to preserve this feature on a bulk rock basis. The slope of the best fit line through the data points corresponds to the ^{60}Fe/^{56}Fe ratio at the time the meteorite had solidified on its parent planetesimal. Ni was depleted from the source region of the meteorite (silicate mantle of the parent body) in an event (core formation) some time (1 to 4 m.y.) before basalt formation, giving rise to an initial ^{60}Ni/^{58}Ni ratio of ~3 ϵ units.

In order to ascertain whether bulk samples do represent or at least approximate closed systems with respect to Ni, we analyzed two more bulk samples, one of which was from a different part of CK (Fig. 3). The ^{60}Ni excesses in all bulk samples range from 6.6 to 40 ϵ units and vary with the Fe/Ni ratio, which approaches 4×10^5 in sample bulk 3. If this correlation is taken as an isochron, then the initial ^{60}Ni/^{58}Ni ratio is significantly elevated above the normal (terrestrial) ratio. This initial value of 3.2 ± 0.9 ϵ coincides within error with the ^{60}Ni* data obtained from the pyroxene fractions and their washes (Fig. 2). Thus, if the linear correlation is not coincidental, then the CK bulk samples acted as closed systems with respect to Ni. The slope of this isochron determines the ^{60}Fe/^{56}Fe ratio at the time of solidification. This ratio is $(3.9 \pm 0.6) \times 10^{-9}$.

Another large ~6-cm section of CK (sample 1290) included an area ~0.5 cm across containing an unusual material highly enriched in sulfide, probably troilite. The troilite content in this area was about 20 to 30 percent. We treated several fragments from this sample with 6 N HCl and analyzed the dissolved portion (with a sulfide

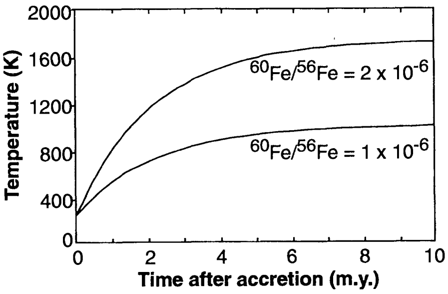

Fig. 4. A simple model for heat production resulting from the decay of ^{60}Fe during the first few million years after accretion in a several hundred kilometer size planetesimal of CI chondrite chemical composition. A starting temperature of 0°C and no heat loss were assumed. The starting parameters for the ^{60}Fe/^{56}Fe ratio correspond to values derived from earlier results obtained from Allende meteorite inclusions that are consistent with an ~10 m.y. interval between commencement of planetesimal accretion and basalt formation on an already differentiated body. These estimates suggest that the ^{60}Fe/^{56}Fe ratios as derived from this study are consistent with ^{60}Fe abundances in the early solar system that could have caused melting of relatively small planetesimals shortly after their accretion.

content of greater than 50 percent) for Ni isotopic composition. The observed ^{60}Ni* of 50.4 ± 0.9 ε units is the highest among all CK samples (Table 1) but falls far above the isochron (Fig. 2). Because the residual silicate fraction contained only ~0.3 ppm of Ni or ~4 percent of the Ni present in the dissolved portion (it was too small for Ni isotope measurement), we estimate that ^{60}Ni* in the total sample must be close to 50 ε units. In order for this value to fall onto the isochron an ^{56}Fe/^{58}Ni ratio of about 4.5×10^5 would be required. However, by mass balance the Fe/Ni ratio in the total sample is only 5.3×10^4. Therefore, this ^{60}Ni enrichment of troilite can only be explained by migration of Ni into this part of the meteorite over a scale of close to 1 cm.

Chronological considerations. The observed heterogeneous Ni distribution obviously hampers the determination of a precise ^{60}Fe/^{56}Fe ratio at the time of Ni depletion in the source of CK because it does not allow the Fe/Ni ratio of the total rock to be established from bulk samples of some 100 mg in size. For simplicity we assume that there was no significant change of the Fe/Ni ratio during basalt extraction from the source magma and use the value of 7.5×10^{-9} that we obtained from bulk 1 as a reasonable upper limit for the ^{60}Fe/^{56}Fe ratio at the time of the main Fe-Ni fractionation. The time difference (δT) between planetary differentiation and basalt formation, based on the ^{60}Fe decay from an ^{60}Fe/^{56}Fe ratio of $\leq 7.5 \times 10^{-9}$ to 4×10^{-9}, is then ≤1.4 m.y. If some Fe-Ni fractionation occurred during partial melting of the source and some Ni was retained in residual olivine, δT could be 3 to 4 m.y. Thus, regardless of the precise value of the ^{60}Fe/^{56}Fe ratio at the time of Ni depletion, the data imply that the time interval between the planetary Ni depletion event (core formation) and the solidification of CK was short (~1 to 4 m.y.).

We now consider the time interval between the formation of early solar system condensates and the solidification of igneous planetary differentiates. Allende CAI have Pb-Pb ages of 4.566 ± 0.002 Ga (*39*). A recent study (*31*) indicates a time difference of ~10 m.y. between formation of CAI and angrites. As discussed above, the initial ^{87}Sr/^{86}Sr ratios suggest that eucrites and angrites formed within 2 m.y. of one another. Thus, eucrites are about 10 ± 2 m.y. younger than Allende CAI. For an initial ^{60}Fe/^{56}Fe ratio of $(1.6 \pm 0.5) \times 10^{-6}$ in CAI (*25*), the ^{60}Fe/^{56}Fe ratio after 10 ± 2 m.y. would be 0.4×10^{-8} to 5.2×10^{-8}. This estimate is in good agreement with the value of 4×10^{-9} obtained for CK. However, we cannot exclude the possibility that some of the ^{60}Ni* in CAI is fossil rather than only from in situ decay of ^{60}Fe. If so, the true ^{60}Fe/^{56}Fe ratio at the time of CAI formation would be lower and in even better agreement with the CK results.

A reliable estimate of ^{60}Fe production during stellar nucleosynthesis is not available (*22, 23*), but it is expected to be low. In addition, because of its short half-life, freshly synthesized ^{60}Fe must have been introduced and mixed with solar system matter shortly (at most a few million years) before the formation of early condensates (CAI).

Heat production. We have established that ^{60}Fe existed in the early solar system and that it was present on at least a planetary scale. Some ^{60}Fe was still alive during planet melting and differentiation and, even later, when CK cooled and crystallized. To evaluate the extent that planets might have been heated by the decay of ^{60}Fe, which yields 3.04 MeV per nucleon, we estimated the temperature in a planetary body during the first few million years after accretion. We assumed that the planetesimal had a CI chondritic chemical composition with 19 percent Fe by weight (*29*). Heat loss by conduction from the interior and radiation into space was assumed to be negligible. The ^{60}Fe/^{56}Fe ratio at the time of accretion is not known. Because solar nebula condensation models (*40*) suggest that the time between formation of early condensates and accretion of asteroidal-sized bodies was less than 1 m.y., we used initial ^{60}Fe/^{56}Fe ratios of 1×10^{-6} and 2×10^{-6}, values that are close to those observed for CAIs. The curves in Fig. 4 indicate that the heat provided by the decay of ^{60}Fe could lead to planetary melting a few million years after accretion. If the ^{26}Al distribution was homogeneous, the ^{26}Al/^{27}Al ratio was 5×10^{-5} (*7*) at the time of accretion, and Al and Fe abundances were chondritic, then the proportions of the total heat provided by the decay of ^{26}Al and ^{60}Fe would be similar (≳70 and ≲30 percent, respectively) (*41*). Thus, if during the first ~2 m.y., additional energy is provided by ^{26}Al decay, rapid melting of small planets following accretion cannot be avoided. The large-scale planetary occurrence of ^{26}Al has yet to be established, however. Under certain favorable conditions, such as a higher initial temperature (we used 0°C), additional accretional energy, and particularly an H chondrite chemical composition [~26 percent Fe (*38*)], the decay of ^{60}Fe alone would provide sufficient energy to melt these bodies. For small planetesimals (<100 km) heat loss becomes significant, and total planetary melting and differentiation may not occur. However, the remaining energy may be sufficient to account for early thermal metamorphism in some chondrite parent bodies. In large bodies, particularly those covered by an insulating regolith blanket, high temperatures would have been maintained for several tens of millions of years, long enough for ^{60}Fe and ^{26}Al to have completely decayed.

REFERENCES AND NOTES

1. H. Brown, *Phys. Rev.* **72**, 348 (1947).
2. H. E. Suss, *Z. Phys.* **125**, 386 (1948).
3. H. Urey, *Proc. Natl. Acad. Sci. U.S.A.* **41**, 127 (1955); R. A. Fish, G. G. Goles, E. Anders, *Astrophys. J.* **132**, 243 (1960).
4. T. Kohman and N. Saito, *Annu. Rev. Nucl. Sci.* **4**, 401 (1954); T. Kohman, *Ann. N.Y. Acad. Sci.* **62**, 21, 503 (1956).
5. J. H. Reynolds, *Phys. Rev. Lett.* **4**, 8 (1960).
6. M. W. Rowe and P. K. Kuroda, *J. Geophys. Res.* **70**, 709 (1965).
7. T. Lee, D. A. Papanastassiou, G. J. Wasserburg, *Geophys. Res. Lett.* **3**, 109 (1976).
8. W. R. Kelly and G. J. Wasserburg, *ibid.* **5**, 1079 (1978).
9. G. W. Lugmair, T. Shimamura, R. S. Lewis, E. Anders, *Science* **222**, 1015 (1983).
10. J.-L. Birck and C. J. Allegre, *Geophys. Res. Lett.* **12**, 745 (1985).
11. A. T. Hsui and M N. Toksöz, *Proc Lunar Sci. Conf.* **8**, 447 (1977).
12. F. Herbert and C. P. Sonett, *Astrophys. Space Sci.* **55**, 227 (1978).
13. J.-C. Roy and T. P. Kohman, *Can. J. Phys.* **35**, 649 (1957).
14. J. M. Herndon and M. A. Herndon, *Meteoritics* **12**, 459 (1977); M. Miyamoto, N. Fujii, H. Takeda, *Proc. Lunar Planet. Sci.* **12**, 1145 (1981).
15. G. J. Wasserburg, in *Protostars and Planets II*, D. C. Black and M. Shapley Matthews, Eds. (Univ. of Arizona Press, Tucson, 1985), pp. 703–737.
16. F. A. Podosek and T. D. Swindle, in *Meteorites and the Early Solar System*, J. F. Kerridge and M.

Shapley Matthews, Eds. (Univ. of Arizona Press, Tucson, 1988), pp. 259–275.

17. R W. Hinton and A. Bischoff, *Nature* **308**, 169 (1984).
18. I. D. Hutcheon and R. Hutchison, *ibid.* **337**, 238 (1989).
19. E. Zinner and C. Göpel, *Meteoritics* **27**, 311 (1992); P. Pellas and D. Storzer, *Proc. R. Soc. London Ser. A* **374**, 253 (1981).
20. W. Kutschera *et al.*, *Nucl. Inst. Meth. Phys. Res. Sect. B* **5**, 430 (1984).
21. T. P. Kohman and M. S. Robinson [*Proc. Lunar Planet. Sci.* **11**, 564 (1980)] re-addressed the question of ^{60}Fe as a potential heat source and chronometer for the early solar system based on a possibly much longer half-life than previously assumed (up to 10 m.y.).
22. D. D. Clayton, *Nature* **234**, 291 (1971).
23. D. Hartmann, S. E. Woosley, M. F. El Eid, *Astrophys. J.* **297**, 837 (1985).
24. P. Morand and C. J. Allegre, *Earth Planet. Sci. Lett.* **63**, 167 (1983); T. Shimamura and G. W. Lugmair, *ibid.*, p. 177; R. W. Hinton, D. E. Scatena-Wachel, A. M. Davis, *Lunar Planet. Sci.* **XV**, 365 (1984).
25. J.-L. Birck and G. W. Lugmair, *Earth Planet. Sci. Lett.* **90**, 131 (1988).
26. $\epsilon_{Ni} \equiv [(^{60}Ni/^{58}Ni)_{sample}/(^{60}Ni/^{58}Ni)_{standard} - 1] \times 10^4$.
27. Limitations of CAI include their high Ni content and thus low Fe/Ni ratio, uncertain origin of ^{60}Ni* considering the presence of other isotopic anomalies (*25*), the possibility that ^{60}Ni* is the result of admixture of grains carrying the ashes of earlier ^{60}Fe decay (fossil origin), uncertain chemical and physical history of CAI, and extensive evidence for disequilibrium among mineral phases.
28. M. B. Duke, *J. Geophys. Res.* **70**, 1523 (1965).
29. E. Anders and N. Grevesse, *Geochim. Cosmochim. Acta* **53**, 197 (1989).
30. Present-day ^{60}Ni/^{58}Ni ratios in subsamples (*i*) from material that had crystallized from a chemically and isotopically equilibrated magma when ^{60}Fe was still present will have values given by $(^{60}Ni/^{58}Ni)_i = (^{60}Ni/^{58}Ni)_o + (^{60}Fe/^{56}Fe)_o(^{56}Fe/^{58}Ni)_i$ where (o) denotes the isotopic ratios at the time of equilibration (or "initial" values).
31. G. W. Lugmair and S. J. G. Galer, *Geochim. Cosmochim. Acta* **56**, 1673 (1992).
32. J. L. Gooding, M. Prinz, K. Keil, *Lunar Planet. Sci.* **10**, 446 (1979); A. M. Zavaritsky and L. G. Kvasha, in *Meteorites of the USSR* (USSR Academy of Sciences Press, Moscow, 1952), pp. 223–225 (in Russian).
33. The samples were crushed in a boron carbide mortar. Mineral separates of Px and Pl were obtained with a clean Franz Isodynamic magnetic separator followed by hand picking. The two pyroxene fractions, Px1 and Px2, were washed in cold 1.8 N HCl for 6 min under ultrasonication to remove potential contamination. Other samples were analyzed without washing in HCl because we found that this procedure removed easily soluble Ni phases. For the troilite analysis, a fragment of the meteorite highly enriched in troilite (≥20%) was attacked with 6 N HCl under ultrasonication for ~30 hours. Analysis of the major elements in the dissolved sample showed, however, that in addition to troilite some fraction of the silicate phases was also dissolved by this treatment. The chemical separation procedures for Ni, performed under clean lab conditions, were similar to those in (*25*). They included separation on cation exchange columns and Ni extraction with dimethylglyoxime in chloroform. Total chemical yields for Ni were 80 to 90 percent.
34. The isotopic compositions of Ni from standards and CK were measured on a multicollector VG-Sector mass spectrometer in a multidynamic operation mode with 100 to 800 ng of Ni per sample load. A mixture of silica gel and germanium oxide was used as an emitter. The samples were loaded on prebaked W filaments. Ionization efficiencies ranged from 2×10^{-4} to 5×10^{-4}. All Ni isotopes were normalized to ^{58}Ni and corrected for mass fractionation according to an exponential law with the use of ^{62}Ni/^{58}Ni = 0.052545 as internal standard. A Ni shelf standard solution (*25*) and chemically processed geological standards with relatively low Ni content (JB-1, JB-2) were used as a terrestrial reference material and test samples. The distribution of the ^{60}Ni/^{58}Ni ratios obtained from these standards are presented in Fig. 1. Internal precision for the ^{60}Ni/^{58}Ni ratio ranged from 0.4 to 0.8 ϵ units ($2\sigma_{int}$) and the mean value for the VG-Sector instrument is 0.382139 ± 0.000002 ($2\sigma_m$). For the ^{61}Ni/^{58}Ni ratio we obtained 0.0165449 ± 0.0000001 ($2\sigma_m$). All results from the standard measurements covered a total range of ±0.8 ϵ units, and the external precision (95 percent of the population) was ±0.6 ϵ units (Fig. 1). Thus, the reproducibility is about the same as one can expect from the errors of individual measurements.

    For each sample isobaric interferences were monitored before and during the experiment with the use of a Daly detector. The species that might interfere with Ni isotopes are Fe$^+$, KF$^+$, CaF$^+$, CaO$^+$, TiO$^+$, and Zn$^+$. For mass 58 we found that interferences from KF$^+$ and Fe$^+$ were always negligible. For mass 60, the interference from ^{44}Ca^{16}O$^+$ can be monitored at mass 56 (where both ^{56}Fe$^+$ and ^{40}Ca^{16}O$^+$ are located). The contributions to mass 60 from these species were negligible—they were $<1 \times 10^{-5}$ to 5×10^{-5} even if the total signal at mass 56 was assumed to be from ^{40}Ca^{16}O$^+$. The measurement of ^{60}Ni can also be affected indirectly by contributions from ^{43}Ca^{19}F$^+$ and ^{46}Ti^{16}O$^+$ on mass 62 through the mass-fractionation correction. ^{40}CaF$^+$ was monitored at mass 59, and TiO$^+$ at masses 63 and 65. In almost all cases [except for CK bulk 2, where 50 percent of the correction was included in the error (see Table 1 and Fig. 3)] the contributions to mass 60 from these isobaric species were significantly less than the precision of the measurements. The interference from ^{42}CaF$^+$ on ^{61}Ni was also found to be negligible. The interferences on mass 64 from ^{48}Ti^{16}O$^+$ and ^{64}Zn$^+$, however, were significant. Because of the nature of the samples and the goal of our study, accurate knowledge of the relative abundance of ^{64}Ni was not important, and no steps were taken to remove these impurities from silica gel (their main source). Experiments indicated that any additional purification would have decreased the ionization efficiency enhancing properties of the silica gel; this effect would have been undesirable considering the low Ni amounts in the samples.

    For many analyses Ni blanks were found to be negligible relative to the precision of the measurements and usually ranged from 6 to 12 ng depending on sample amounts and the chemical procedure used. However, some samples of extremely low Ni concentration (<3 ppm) required processing of large amounts of sample. For these, reagent blank corrections ranging from 3 to 15 percent were applied to concentration and isotopic data and are included in the error estimates. The main source for the blank was found to be citric acid. Subsequent to the analyses citric acid was cleaned by passing it through a cation exchange resin column; this treatment decreased the blank by a factor of 4.
35. Concentration measurements of Fe and Ni were made by flame atomic absorption (AA) spectroscopy and graphite furnace AA using standard addition techniques. The concentration data are estimated to be precise within 2 to 10 percent and, for Ni, depend on available sample amounts (Table 1).
36. J. L. Wooden *et al.*, *Lunar Planet. Sci.* **X**, 1379 (1979).
37. A. Shukolyukov and G. W. Lugmair, *ibid.* **XXIII**, 1295 (1992).
38. E. Jarosewich, *Meteoritics* **25**, 323 (1990).
39. C. Göpel, G. Manhès, C. J. Allègre, *ibid.* **26**, 338 (abstr.) (1991).
40. J. A. Wood and G. E. Morfill, in *Meteorites and the Early Solar System*, J. F. Kerridge and M. Shapley Matthews, Eds. (Univ. of Arizona Press, Tucson, 1988), pp. 329–347; S. J. Weidenschilling, in *ibid.*, pp. 348–371.
41. Other short-lived radionuclides, such as ^{53}Mn and ^{107}Pd, can provide only minor amounts of heat because of their low decay energies and abundances.

42. Supported by NASA grant NAG 9-49. A. Sh. is a postdoctoral fellow. We thank C. MacIsaac for his help in the laboratory, H. Wanke for discussions, and D. A. Papanastassiou for a helpful review. We are grateful to M. Petaev and the Meteoritical Committee of the Russian Academy of Science for providing the various samples of Chervony Kut.

13 October 1992, accepted 11 January 1993