INITIAL DISTRIBUTION OF ^{60}Fe AND HETEROGENEITY OF Ni ISOTOPES IN THE EARLY SOLAR SYSTEM. G. Quitté[1], F. Albarède[1], [1]Laboratoire de Géologie de Lyon: Terre, Planètes, Environnement, CNRS, ENS de Lyon, Université Lyon 1, 46 allée d'Italie, 69364 Lyon Cedex 07, France (Ghylaine.Quitte@ens-lyon.fr).

Introduction: Determining the timescales for the accretion and early evolution of asteroids and terrestrial planets is essential for evaluating planetary accretion models and understanding the relationships between the different processes involved in the early solar system history. Short-lived nuclides have proven particularly useful for obtaining such age constraints. However, the use of these isotopic systems as chronometers relies on the assumption that the distribution of the parent isotopes was homogeneous throughout the source region of the objects under scrutinity. One way to test this hypothesis is to compare the timescales inferred from different chronometers: if ages are consistent, the initial distribution must have been homogeneous. ^{60}Fe is of particular interest since this radionuclide has a short half-life (2.62 Ma), a stellar origin (which means it cannot be produced in the solar system by irradiation and spallation reactions) and ^{60}Fe, together with ^{26}Al, is a possible heat source for planetary melting.

Despite many efforts in the field, no self-consistent ^{60}Fe-^{60}Ni chronology for various kinds of objects could be established over the last few years. The reasons may be: (1) a disturbed ^{60}Fe-^{60}Ni system, or (2) an initial heterogeneous distribution of ^{60}Fe in the solar system. Experimental data in meteorites point towards the second hypothesis as detailed below. Several isotopically distinct Ni reservoirs have also been identified.

New estimates of the initial ^{60}Fe/^{56}Fe ratio and initial distribution of ^{60}Fe: We analyzed Ni isotopes in differentiated meteorites and recalculated the initial ^{60}Fe/^{56}Fe ratio of the solar system using the known age of the samples. The Ni data obtained for eucrites combined with their ^{53}Mn-^{53}Cr age yield an initial of ~7.7×10^{-9} for the start of the solar system [1], comparable to another recent estimate also based on eucrites [2]. However, the associated uncertainty is large and the ^{60}Fe-^{60}Ni systematics has been disturbed in these basaltic meteorites [1], so that the initial value is not very robust.

Angrites represent a better sample choice as they are old, they cooled down rapidly and remained undisturbed since their formation. A bulk rock isochron has a slope of 3.1×10^{-9}. Given the ^{53}Mn-^{53}Cr age (4563.2 Ma [3]) for the global differentiation event on the angrite parent body, an initial of $(8.5 \pm 3.3) \times 10^{-9}$ is calculated for the start of the solar system, in agreement with [2,4] within uncertainty. This value is however much lower than the lower limit inferred from CAIs (4×10^{-7} [5]) and the initial deduced from chondrules (e.g. [6-7]), which points toward a heterogeneous distribution of live ^{60}Fe at the start of the solar system even if chondrule data may need to be revised [8]. To test the hypothesis of a heterogeneous distribution of ^{60}Fe further, samples from two other types of meteorites that formed contemporaneously with angrites have been studied.

CB chondrites are metal-rich and formed 4562.7 Ma ago [9]. Gujba and MIL05082 contain silicate nodules and large FeNi metal nodules with some sulfides. The three analyzed metal nodules from Gujba and one from MIL05082 show sub-chondritic Fe/Ni ratios. The samples all present the same clear 10-20 ppm deficit in ^{60}Ni relative to the terrestrial standard and the data point do not fall on an isochron [10]. Thus, CBs formed in the absence of live ^{60}Fe, which is confirmed by the ^{64}Ni-deficit observed as predicted [11].

Ureilites are ultramafic rocks constituted of olivine, pyroxene and also 10% of carbon, metal and sulfide-rich veins. They seem to be differentiated but at the same time show very primitive characteristics such as their oxygen isotope composition. Bulk rocks, silicate-rich fractions, and vein material were separated out of 8 ureilites and analyzed. The Fe/Ni ratio is higher than 45 in bulk rocks and spans up to 890 in the silicate-rich fractions. Small ^{60}Ni excesses are then expected in silicates if they formed in the presence of live ^{60}Fe. However, all silicates are depleted in ^{60}Ni, no isochron can be defined, and the ^{60}Ni/^{58}Ni and ^{61}Ni/^{58}Ni ratios are correlated indicating that metal and silicate come from two isotopically distinct Ni reservoirs [10].

As angrites crystallized in the presence of live ^{60}Fe while CB chondrites formed – at the same time – in the absence of ^{60}Fe, we conclude that ^{60}Fe was heterogeneously distributed in the early solar system. This conclusion is reinforced by the initial deduced for the angrites, which is several orders of magnitude lower than the lower limit inferred from CAIs, and by the diversity of values proposed for the initial of the solar system based on different types of objects and meteorites.

To further explore the variability of the ^{60}Fe/^{56}Fe ratio in the early solar system, various types of chondrules must be (re-)analyzed. No ^{60}Ni anomaly has been detected so far in Allende (CV3) chondrules and only two Tieschitz (H/L 3.6) chondrules show a resolvable excess [12]. The best explanation is most likely a remobilisation of Fe and/or Ni during alteration and metamorphism. The Ni isotope measurements of chondrules extracted from more primitive meteorites (CR2 chondrites) are currently under progress; the results will be discussed at the workshop.

Isotopically distinct Ni reservoirs: Nickel nucleosynthetic anomalies have been found in various meteorites (e.g. in ureilite silicate, see above) but the carrier phases have not been fully identified yet. Stepwise dissolution of carbonaceous chondrites is a powerful tool to characterize the fine-scale isotope heterogeneities of the solar system and to identify the presolar carrier phases, even if such a procedure may induce some mixing between the various nucleosynthetic components. Nickel is a suitable element as ^{61}Ni is overproduced by s-process (AGB stars) when excesses of ^{62}Ni and ^{64}Ni witness nucleosynthesis in a neutron-rich environment (for instance SN explosion). Besides, possible correlations between different isotopes or different elements in the same leachates potentially bring stronger and more precise constraints on the astrophysical setting where the nuclides have been produced. Nickel isotope analyses have been performed on leachates for the three carbonaceous chondrites Allende, Murchison, and Orgueil. Most of the Ni is dissolved by concentrated acetic acid and nitric acid confirming that metal is a major carrier phase. Nickel is not isotopically uniform among the various host phases. In Orgueil, the ^{60}Ni-deficit increases with increasing acid strength, which is consistent with the s-process component being carried by SiC presolar grains. All fractions in Orgueil and most leachates in Murchison tend to be depleted in ^{60}Ni and ^{62}Ni, when all Allende fractions but one are rather enriched. As ^{58}Fe is the most neutron-rich Fe isotope, a correlation is expected with the neutron-rich Ni isotopes that also belong to the iron peak elements and are co-produced in the same nucleosynthetic environment. Hint towards negative $\varepsilon(^{58}Fe/^{54}Fe)$ values indeed exist in Orgueil fractions but the anomalies are not resolvable from the standard [16].

Many meteorites and meteorite components such as ureilite mineral fractions, CAIs, CB metal nodules, sulfide inclusions found in iron meteorites fall on a mixing line between an s-process and a e-process (neutron rich environment) components [5,10,13]. Besides, some samples are devoid of nucleosynthetic anomalies but registered the past presence of life ^{60}Fe. Thus, meteorites come from multiple isotopically distinct Ni reservoirs [10,14]. Altogether, at least 3 distinct reservoirs can be identified: (1) a high ^{60}Ni,^{62}Ni (i.e. neutron-rich) reservoir containing fossil ^{60}Fe, sampled by some CAIs or more widely dispersed silicate phase; (2) a low ^{60}Ni,^{62}Ni (i.e. neutron-poor) reservoir with no ^{60}Fe, corresponding to the metal phase of carbonaceous chondrites, ureilite silicates, sulphides in iron meteorites; and (3) a reservoir where live ^{60}Fe was present, as supported by data of chondritic components (sulphides, some CAIs, chondrules). These conclusions are consistent with [11]: irons and carbonaceous chondrites may well come from the same well-mixed homogeneous reservoir while other types of meteteorites come from distinct reservoirs. Noteworthy, ^{54}Cr and ^{62}Ni anomalies are positively correlated and the three Ni reservoirs are compatible with the (at least) two Cr nebular reservoirs: a ^{54}Cr-poor reservoir for achondrites, ordinary chondrites and irons, and a ^{54}Cr-rich reservoir for carbonaceous chondrites and CAIs [15].

There is also clear evidence for isotope heterogeneity for many other elements, both in CAIs and at the mineral scale (due to the presence of presolar grains in different relative proportions), and also at the planetary scale. In many cases, data can be explained by a mixing of s-process and r-process components. A common feature is also the difference between carbonaeous chondrites on one side and the other meteorites on the other side. Considering all the data together, it appears that the radionuclides were most likely heterogeneously distributed in the solar nebula, except in the region between 1 and 2.4-2.7 AU, which brings strong constraints on the dynamics and is consistent with recent simulations of formation of terrestrial planets that suggest extensive radial mixing of the material between 1 and 2.5 AU (e.g. [17]).

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