THE ORIGIN OF $^{60}$Fe AND OTHER SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM

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Abstract. Establishing the origin of short-lived radionuclides (SLRs) with half-lives $\leq 100$ Myr has important implications for the astrophysical context of our Sun’s birth place. We review here the different origins proposed for the variety of SLRs present in the solar accretion disk 4.57 Ga ago. Special emphasis is given to an enhanced Galactic background origin for $^{60}$Fe which was inherited from several supernovae belonging to previous episodes of star formation, rather than from a nearby, contemporaneous supernova.

1 Introduction

Short-lived radionuclides (SLRs) are radioactive isotopes with half-lives $\leq 100$ Myr. Their presence in the solar protoplanetary disk is inferred from excesses in their daughter isotopes in various meteorite components such as Calcium-, Aluminium-rich Inclusions (CAIs), chondrules and planetary differentiates.

The abundance of some SLRs in the solar accretion disk is compatible with the expectations of continuous galactic nucleosynthesis, while some require a last minute origin, such as local production via irradiation in the solar accretion disk, or external stellar nucleosynthesis followed by injection. Additionally some SLRs such as $^{60}$Fe could be inherited from previous episodes of star formation in the immediate neighborhood of our nascent solar system. The origin of SLRs has many implications for the astrophysical context of our Sun’s birth, early solar system chronology, stellar nucleosynthesis models or irradiation processes around young stellar objects.

There have been many recent reviews covering different aspects of SLRs in the last years (e.g. Wadiwa et al. 2007; Goswami et al. 2005; McKeegan & Davis 2004). In the present work, aimed at students who followed Les Houches’ course, we wish to present the experimental situation focusing on the latest analytical
Fig. 1. Isochron diagram for the CAI MRS6 in Leoville (unpublished data obtained by the senior author at UCLA in Edward Young’s laboratory, using LA-ICPMS). Most points fall on an isochron corresponding to an initial $^{26}\text{Al}/^{27}\text{Al}$ ratio of $4.6 \times 10^{-5}$ (canonical ratio). Two spinel data points fall on an isochron corresponding to an initial $^{26}\text{Al}/^{27}\text{Al}$ ratio of $6 \times 10^{-5}$ (supercanonical ratio). It is obvious from the figure that a large fractionation between the radionuclide and its daughter element ($\text{Al}$ and Mg in the case of $^{26}\text{Al}$) is required to establish an isochron.
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aluminium abundance define an isochron and establish the past presence of \(^{26}\text{Al}\) in the solar system (Fig. 1).

To estimate the initial value of SLRs in the accretion disk, it is important to identify the most ancient phases which formed in the accretion disk. CAIs have the oldest Pb-Pb measured age of all extraterrestrial samples (e.g. Amelin et al. 2006). They are therefore believed to represent the first solids in the solar accretion disk, and their content in SLRs is taken as the solar system initial value. Some SLRs cannot be detected in CAIs, because the fractionation between the radionuclide and its daughter element is not strong enough to yield an isotopic effect that can be analytically resolved (see Fig. 1). The abundance of these SLRs is therefore measured in other phases/meteorites and the abundance in CAIs is calculated using an other isotopic system (another SLR or the Pb-Pb age) for which data are available both in CAIs and in the other phases/meteorites under investigation. An alternative to CAIs for determining the initial solar system ratio is to use bulk carbonaceous chondrites (see Table 1 and text below), assuming that their precursors separated from the accretion disk at time zero (i.e. the CAI formation time).

It is important to mention that the initial solar system value is for some SLRs poorly defined (Gounelle 2006). This is because, when two isotopic systems are used to calculate the abundance in CAIs (see above), it is implicitly assumed that the two isotopic systems record the same event. This assumption might be entirely flawed as, for example, diffusion coefficients can vary from element to element. In addition, if some SLRs were heterogeneously distributed in the protoplanetary disk, this very concept of an initial value would be meaningless (Gounelle & Russell 2005). Finally, it is worth noting that CAIs might not be the oldest solids, and that they might have formed contemporaneously with some chondrules (Markovski et al. 2006).

In the following paragraphs, we discuss the experimental situation in detail for some SLRs, either because of their special interest, or because some important progress was made recently. For the SLRs not discussed here, we adopted the numbers mentioned in Wadhwa et al. (2007), and the reader is referred to that review for an in-depth discussion. Initial values are summarized in Table 1. Despite the fact that one initial value is given for each radionuclide, one should keep in mind that there might be a variability and that the initial value is not necessarily precisely known (see above).

Evidence for the in situ decay of \(^{7}\text{Be}\) has been found in one CAI by Chaussidon et al. (2006), with an initial ratio \(^{7}\text{Be}/^{9}\text{Be}\) \(\approx 6 \times 10^{-3}\). \(^{10}\text{Be}\) has been identified in CAIs from CV3 and CM2 chondrite groups. Its initial abundance relative to \(^{9}\text{Be}\) varies between \(\approx 5 \times 10^{-4}\) and \(1 \times 10^{-3}\) (Liu et al. 2008 and references therein).

The initial abundance of \(^{26}\text{Al}\) is at the center of a vivid debate. For many years, it was considered that \(^{26}\text{Al}\) was present in the CAI forming region at a canonical level (\(^{26}\text{Al}/^{27}\text{Al} \approx 4.5 \times 10^{-5}\), MacPherson et al. 1995). Based on high precision, in situ data, Young et al. (2005) as well as Cosarinsky et al. (2006) proposed that it could be closer to 6 or \(7 \times 10^{-5}\) (supercanonical ratio). If CAIs formed originally with such a supercanonical ratio, the canonical ratio would be due to resetting...
Table 1. The initial value of SLRs in the early solar system

| R   | D   | S   | $T_{1/2}$ (Myr) | R/S       | Notes    |
|-----|-----|-----|-----------------|-----------|----------|
| $^7$Be | $^7$Li | $^9$Be | 53 days        | $6 \times 10^{-3}$ | CAI      |
| $^{10}$Be | $^{10}$B | $^9$Be | 1.5            | 0.5-1$ \times 10^{-3}$ | CAI      |
| $^{26}$Al | $^{26}$Mg | $^{27}$Al | 0.74           | 5-6$ \times 10^{-5}$ | CAI      |
| $^{36}$Cl | $^{36}$S/$^{36}$Ar | $^{35}$Cl | 0.3           | $> 1.6 \times 10^{-4}$ | CAI-ALT  |
| $^{41}$Ca | $^{41}$K | $^{40}$Ca | 0.1           | 0.1-4$ \times 10^{-7}$ | See text |
| $^{53}$Mn | $^{53}$Cr | $^{55}$Mn | 3.5           | $8 \times 10^{-6}$ | CCs      |
| $^{60}$Fe | $^{60}$Ni | $^{56}$Fe | 1.5           | $< 6 \times 10^{-7}$ | Irons    |
| $^{92}$Nb | $^{92}$Zr | $^{90}$Nb | 36            | $10^{-5}-10^{-3}$ | See text |
| $^{107}$Pd | $^{107}$Ag | $^{108}$Pd | 6.5           | $6 \times 10^{-5}$ | CCs      |
| $^{129}$I | $^{129}$Xe | $^{127}$I | 15.7          | $10^{-4}$ | Chondrites |
| $^{182}$Hf | $^{182}$W | $^{189}$Hf | 8.9           | $10^{-4}$ | CAIs     |
| $^{205}$Pb | $^{205}$Tl | $^{204}$Pb | 15            | $1-2 \times 10^{-4}$ | Irons    |
| $^{238}$U | fission Xe | $^{238}$U | 82            | $7 \times 10^{-3}$ | See text |

R is the radionuclide under consideration, D its daughter isotope, and S the reference stable isotope. CAI indicates that the initial value has been measured in a CAI. Irons indicates that the concerned SLR has been measured in iron meteorites and that the solar system initial value was calculated coupling the measured value with some other SLR whose initial abundance is known both in CAIs and in iron meteorites. In the case of $^{36}$Cl, its abundance was measured in an alteration phase (ALT) within a CAI, and the solar system initial ratio was calculated assuming this phase formed 1.5 Myr after time zero (Lin et al. 2005). CCs refer to initial abundances which were inferred from a set of carbonaceous chondrites (CCs).

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events (e.g. Young et al. 2005). A recent high precision study based on bulk CAIs (Jacobsen et al. 2008) suggests that the CAIs formed with the canonical ratio and that the supercanonical ratio is an analytical artefact. Although the exact value of the initial $^{26}$Al/$^{27}$Al ratio matters for early solar system chronology, it is of little importance as far as $^{26}$Al origin is concerned because the debate concerns variations of 20 %, far smaller than the precision of any reasonable model trying to account for the origin of SLRs.

Srinivasan & Goswami (1994) measured an initial abundance $^{41}$Ca/$^{40}$Ca = $1.5 \times 10^{-8}$ in an Efremovka (CV3) CAI. However, the CAIs initial abundance of $^{41}$Ca, which decays into $^{41}$K, might have been higher than previously thought. If Mg isotopes were reset by a secondary event, it is likely that K isotopes were too, lowering the now measured initial $^{41}$Ca/$^{40}$Ca ratio of CAIs. Assuming a similar temperature closure for K and Mg, and applying the exponential decay law to $^{41}$Ca and $^{26}$Al, the initial $^{41}$Ca/$^{40}$Ca ratio would have been as high as $4 \times 10^{-7}$ (see Gounelle et al. 2006).

Moynier et al. (2007) recently measured the Cr isotopic composition of bulk
carbonaceous chondrites and inferred an initial value $^{53}\text{Mn}/^{55}\text{Mn} = 8 \times 10^{-6}$ for the SLR $^{53}\text{Mn}$. This is lower than the initial value calculated by Lugmair & Shukolyukov (2001) based on measurements of angrites.

The initial abundance of $^{60}\text{Fe}$ in the solar system is not precisely known. Different estimates determined by Multi Collector -Inductively Coupled Mass Spectrometry (MC-ICPMS) or Secondary Ionization Mass Spectrometry (SIMS) vary between $5 \times 10^{-8}$ and $1 \times 10^{-6}$ for the initial $^{60}\text{Fe}/^{56}\text{Fe}$ ratio (see the discussion in Gounelle & Meibom 2008). Measurements performed with MC-ICPMS have so far failed to detect an isochron indicative of the past presence of $^{60}\text{Fe}$ (e.g. Dauphas et al. 2008). The most precise work performed to date on primitive carbonaceous chondrites by Regelous et al. (2008) constrained the initial $^{60}\text{Fe}/^{56}\text{Fe}$ ratio to be lower than $1 \times 10^{-7}$, suggesting that SIMS work might be plagued with unresolved interferences. We will conservatively adopt an upper limit of $6 \times 10^{-7}$ for the initial $^{60}\text{Fe}/^{56}\text{Fe}$ ratio (Dauphas et al. 2008).

Nielsen et al. (2006) measured in iron meteorites excesses of $^{205}\text{Tl}$ correlating with $^{204}\text{Pb}$, indicating the past presence of the SLR $^{205}\text{Pb}$ ($T_{1/2} = 15$ Myr). The initial solar system abundance was calculated using I-Xe ages for iron meteorites. Baker et al. (2007) failed to identify a Tl-Pb isochron for carbonaceous chondrites, although data from the latter fall close to the isochron defined for irons.

3 Models for the origin of short-lived radionuclides

3.1 A galactic background origin for some SLRs

On-going nucleosynthesis by a diversity of stars (supernovae, novae, AGB stars...) in the Galaxy continuously replenishes the interstellar medium with freshly made SLRs. At a given time in the history of the Galaxy, the background abundance of a given short-lived radionuclide $R$ relative to its stable reference isotope $S$ will depend on a diversity of parameters such as the number and nature of nucleosynthetic events responsible for the production of $R$ over the last few half-lives of $R$, the number and nature of nucleosynthetic events responsible for the production of $S$ during the history of the Galaxy, the respective yields of $R$ and $S$ in the nucleosynthetic events aforementioned, astration, the mixing timescales and processes of the different phases of the interstellar medium, the rate of decay of $R$... Final isolation of the average interstellar medium from nucleosynthetic events introduces an extra parameter, the isolation time $\Delta$, during which $R$ decays without further addition of freshly made matter. Because two different SLRs might originate from different nucleosynthetic events, $\Delta$ varies from radionuclide to radionuclide. In addition to the number of poorly constrained parameters mentioned above, a further complication occurs for those SLRs whose half-life is smaller than, or comparable to, typical recurrence times of relevant nucleosynthetic events. In such a case, granularity of nucleosynthesis becomes a key phenomenon (Meyer & Clayton 2000), and it becomes difficult to model a steady-state background interstellar medium abundance.

Despite the uncertainties discussed above, Wasserburg et al. (2006) present
Fig. 2. Abundances of SLRs injected by a nearby SN in the nascent solar system compared to the value observed in meteorites. Because the injected abundances depend only on two parameters (the mixing fraction $f$ and the decay time $\Delta$, see Eq. (1) of Gounelle & Meibom 2008), the calculation assumes that $^{60}\text{Fe}$ and $^{41}\text{Ca}$ are delivered at the correct abundance. Yields of massive stars are from Rauscher et al. (2002). Different lines correspond to supernovae of different masses.

some estimates of the background interstellar medium abundance of SLRs. According to these authors, $^{244}\text{Pu}$ and $^{182}\text{Hf}$ had solar system abundances compatible with the background interstellar medium value, while $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, $^{41}\text{Ca}$ and $^{60}\text{Fe}$ were in excess in the solar system relative to the expected background interstellar medium abundance, calling for a last minute origin. They use the abundance of $^{129}\text{I}$, which is a $r$-process only nuclide, to calculate the isolation time ($\Delta \sim 70$ Ma) since the last $r$-process nucleosynthetic event. If the same time delay is applied to $^{107}\text{Pd}$, which is also a $r$-process nuclide, they find that $^{107}\text{Pd}$ is overabundant in the solar system, and requires a last minute origin, which is attributed to the contribution of an AGB star by Wasserburg et al. (2006).

The estimated solar system abundance of $^{107}\text{Pd}$ and $^{129}\text{I}$ can however be reconciled with expectations from the continuous galactic nucleosynthesis. Still assuming that $^{107}\text{Pd}$ and $^{129}\text{I}$ are made in the same nucleosynthetic site, and considering
an isolation time of $\Delta = 43$ Ma, we calculated, using the Wasserburg et al. (2006) numbers, that $^{107}$Pd was underabundant in the solar system by a factor of 3, while $^{129}$I was overabundant in the solar system by a factor of 3. Given the uncertainties of the models and of the initial abundances of SLRs, it is quite reasonable to conclude that both $^{107}$Pd and $^{129}$I have abundances in line with that of the steady-state interstellar medium background.

Nielsen et al. (2006) and Wadhwa et al. (2007) proposed that $^{205}$Pb and $^{92}$Nb also originated from the galactic background. It could also be the case of $^{53}$Mn (Wadhwa et al. 2007). Beryllium-7, $^{10}$Be, $^{26}$Al, $^{36}$Cl, $^{41}$Ca and $^{60}$Fe cannot be explained by the continuous Galactic nucleosynthesis, and therefore require a special origin.

3.2 An enhanced galactic origin for $^{60}$Fe: The SPACE model

Iron-60 cannot originate by irradiation (Lee et al. 1998). As it is unlikely a nearby SN delivered it in the nascent solar system (see §3.3), it has recently been proposed that it is inherited from previous episodes of star formation (Gounelle and Meibom 2008).

In the last decade, it has been proposed that molecular clouds (MCs) are transient, dynamically evolving, dense ISM features produced by compressive motions of either gravitational or turbulent origin, or some combination thereof (Ballesteros-Paredes et al. 2007). MCs contain a mixture of atomic and molecular gas (e.g. Goldsmith et al. 2008) with density ranging from $1 \text{ cm}^{-3}$ to $10^5 \text{ cm}^{-3}$ with an average value of $\sim 100 \text{ cm}^{-3}$. This MC clumpiness means that in Giant Molecular Clouds (GMCs), some regions might actively form stars, while others are diffuse and undergo a latency phase (Elmegreen 2007).

OB associations are the outcomes of the star-forming process in molecular clouds. OB associations are divided into subgroups of different age (Blaauw 1964). A famous example is the Scorpio-Centaurus region which consists of the Lower Centaurus Crux (LCC, $\sim 16$ Myr), the Upper Centaurus Lupus (UCL, $\sim 17$ Myr) and the Upper Scorpions (Upper Sco, $\sim 5$ Myr) subregions (Preibisch & Zinnecker 2007; Mamajek et al. 2002). The range in ages within a given region has long been interpreted as indicative of sequential star formation (e.g. Elmegreen & Lada 1977).

Relatively high concentrations of $^{60}$Fe and other radioactivities with half-lives $\geq 1$ Myr are expected in second generation star-forming regions. This is because supernovae explosions from an older region, e.g. the LCC, enrich a younger region, e.g. the Upper Sco, with their nucleosynthetic products. It is therefore suggested that $^{60}$Fe in the solar system was inherited from previous episodes of star formation (SPACE model\textsuperscript{1}, Gounelle et al. 2008).

Two different astrophysical settings for the SPACE model are envisioned (Gounelle et al. 2008). In the first setting, it is considered that the entire molecular cloud is assembled via turbulent convergent flows (e.g. Hartmann et al. 2001).

\textsuperscript{1}Supernova Propagation And Cloud Enrichment.
In this scenario, the gas which will make the bulk of the MC is swept up by winds from massive stars and supernovae explosions. In an alternative setting, we assume that supernovae explode in a pre-existing molecular cloud which is large enough (such as a GMC) to have regions evolving at different paces. Winds from massive stars belonging to an older region accumulate a dense shell of gas as in the collect & collapse model (Elmegreen & Lada 1977). When massive stars explode as SNe, star formation is promoted in the dense shell. In both cases, $^{56}$Fe present in the SNe ejecta is delivered while dense gas is accumulating. Because star formation occurs rapidly (on a $\sim$ Myr timescale) once the gas is dense enough, $^{56}$Fe has no time to decay and is expected to be alive in the newly formed protoplanetary disks.

3.3 Nearby supernovae models

Of models based on a supernova (SN) origin for SLRs there are two types. Either a SN injects freshly synthesized SLRs into a nearby molecular cloud core, triggering its gravitational collapse (e.g. Cameron & Truran 1977), or directly into a nearby protoplanetary disk (Chevalier 2000; Hester & Desch 2005; Ouellette et al. 2005). The first SN scenario is now considered less likely because only very specific conditions allow a supernova shockwave to trigger the collapse of a molecular cloud core and, at the same time, inject SLRs (e.g. Boss & Vanhala 2000). In the second scenario, which is currently receiving a lot of attention (Chevalier 2000; Hester & Desch 2005; Ouellette et al. 2005; Ouellette, Desch & Hester 2007), the SN has to be very close ($\sim$ 0.3 pc) to the protoplanetary disk in order to allow the disk to intercept enough SN ejecta to account for the solar system inventory of SLRs. It is thus assumed that the massive star, which evolved into a SN, and the protoplanetary disk were coeval and formed in the same stellar cluster (e.g. Hester & Desch 2005).

The probability of direct injection of SN materials into a nearby protoplanetary disk has recently been estimated to be less than one in thousand (Williams & Gaidos 2007; Gounelle & Meibom 2008). A similar low probability can be assigned to the molecular cloud core model. In both cases, the evolution timescale of massive stars is too long compared to low-mass stars evolution timescales, given that SLRs incorporation happened in the earliest phases of the solar system. UV radiation emitted by massive stars create an HII region which can extend to a few pc or more after a few Myr of evolution (e.g. Reach et al. 2004), preventing star formation in that region. Low-mass stars formed in the enrichment zone ($\leq$ 1.6 pc) before the clearing of the molecular gas would have formed planets by the time of the first SN explosion ($\sim$ 5 Myr after the onset of star formation). Low-mass stars formed around the time of the SN explosion would be too far away from the massive stars (at least a few pc, more likely 10 pc) to have their disks or cores contaminated by $^{56}$Fe at the level observed in the solar system.

Regardless of its astrophysical implausibility, the injection of SLRs by a nearby SN also fails to quantitatively satisfy the cosmochemistry data (Fig. 3).
3.4 Irradiation models

Irradiation of nebular gas and/or dust by accelerated hydrogen or helium nuclei can result in the production of short-lived radionuclides. $^{10}\text{Be}$ has an irradiation origin since it cannot be made in stars (e.g. McKeegan, Chaussidon & Robert 2000). Beryllium-7 which has been identified in one Allende CAI (Chaussidon, Robert & McKeegan 2005) is an unambiguous tracer that some irradiation took place in the early solar system. Ubiquitous, thousand-fold enhanced, and flare-like X-ray activity of protostars provides firm evidence for the existence of accelerated particles in the vicinity of the early sun (Wolk et al. 2005). The issue is whether some other SLRs, such as $^{26}\text{Al}$, are co-produced during irradiation events. Some models, dedicated to calculate irradiation yields of SLRs, established that it is possible to produce $^7\text{Be}$, $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, $^{41}\text{Ca}$, $^{53}\text{Mn}$ at abundances in line with that of the early solar system (Leya et al. 2003; Gounelle et al. 2006) provided that proton and helium nuclei are accelerated by impulsive events. Assuming that $^{26}\text{Al}$ was ubiquitous in the entire protoplanetary disk, Duprat & Tatischeff (2007) proposed that irradiation could not account for the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio. There is however no positive evidence for $^{26}\text{Al}$ ubiquity in the protoplanetary disk.

4 Conclusions

Some SLRs such as $^{53}\text{Mn}$, $^{92}\text{Nb}$, $^{107}\text{Pd}$, $^{129}\text{I}$, $^{182}\text{Hf}$, $^{205}\text{Pb}$ and $^{244}\text{Pu}$ might originate from continuous Galactic nucleosynthesis (Wasserburg et al. 2006; Meyer & Clayton 2000). These correspond to the SLRs with the longest half-life. SLRs with intermediate half-life ($^{26}\text{Al}$, $^{60}\text{Fe}$) might be inherited from previous episodes of star formation in the molecular cloud progenitor from our solar system (Gounelle et al. 2008). $^7\text{Be}$, $^{10}\text{Be}$, $^{36}\text{Cl}$, $^{41}\text{Ca}$ might have an irradiation origin.

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