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Short-lived nuclides in the early solar system: The stellar connection

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Abstract

Fossil evidence for the presence of short-lived nuclides with half-life ranging from 100,000 years to ~100 million years (Ma) in the early solar system has been found in primitive meteorites. The nuclides with half-life less than a couple of million years (^{41}Ca, ^{26}Al, ^{10}Be, ^{60}Fe) must have been produced either shortly before or during the very early evolution of the solar system. Two plausible sources of these nuclides are proposed; a single stellar source (e.g., a TP-AGB star, supernova or a W-R star) or energetic particle production in solar, presolar or stellar environments. The presence of ^{10}Be, which is not a product of stellar nucleosynthesis, argues for an energetic particle production mechanism. However, correlated presence of ^{41}Ca and ^{26}Al with well-defined initial abundances in early solar system objects cannot be explained in the energetic particle production model and it also fails to account for the presence of ^{60}Fe. Recent experimental data demonstrate that the source of ^{10}Be is decoupled from that of ^{26}Al and ^{41}Ca and suggest that both a stellar source as well as energetic particle production contributed to the inventory of the short-lived nuclides in the early solar system. New data for initial abundance of ^{60}Fe in the solar system tend to favor a SN source. The presence of freshly synthesized short-lived nuclides from an evolved star in the early solar system led to the hypothesis of a triggered origin of the solar system. Numerical simulation studies indicate dynamical feasibility of such a process and there are indirect observational evidences for triggered formation of sun-like stars.

Keywords: solar system: formation; meteoroids, Sun: flares; Stars: AGB, supernovae; PACS 96.10+i; 96.40.Fg; 96.50.Mt; 97.10.Cv

1. Introduction

Isotopic studies of early solar system objects present in primitive meteorites have revealed the presence of a large number of short-lived now-extinct nuclides with half-life ranging from 10^5 to 10^8 years at the time of formation of these objects (see, e.g. Goswami and Vanhala, 2000; McKeegan et al., 2000). The former presence of the now-extinct nuclides is based on the observation of excess abundances of their decay products in suitable meteorite samples. Correlation of such an excess with abundance of the stable isotope of the parent element (e.g., correlation of the excess in ^{26}Mg/^{24}Mg ratio with ^{27}Al/^{24}Mg ratio in the case of the short-lived nuclide ^{26}Al that decays to ^{26}Mg) conclusively establishes that the nuclide was incorporated “live” into the analyzed object at the time of its formation and decayed in-situ. A list of short-lived nuclides whose presence in the early solar system has been established unambiguously is shown in Table 1.

In this paper the focus will be on nuclides with half-life less than a couple of million years (^{41}Ca, ^{26}Al, ^{60}Fe, and ^{10}Be). Two plausible sources of these nuclides have been proposed. They could be freshly synthesized stellar material injected into the protosolar cloud at the time of its collapse or they are products of interactions of solar energetic particles with gas and dust in the solar nebula. The possibility that some of them (e.g., ^{26}Al and ^{60}Fe) could be products of continuous galactic nucleosynthesis can be ruled out from the estimated steady state production rate of these nuclides as well as measured fluxes of interstellar ^{26}Al and ^{60}Fe gamma ray lines (see, e.g. Timmes et al., 1995;

Prantzos and Diehl, 1996; Plüschke et al., 2001; Smith, 2003 and this volume). Although there was a general consensus for a stellar source for these short-lived nuclides (see, e.g. Goswami and Vanhala, 2000), the discovery of ^{10}Be in early solar system objects (McKeegan et al., 2000) revived the energetic particle production model because ^{10}Be is not a product of stellar nucleosynthesis.

It is important to resolve the question of the source(s) of these short-lived nuclides to understand the origin and early evolution of the solar system. If they are of stellar origin their short half lives allow us to explore a possible stellar connection for understanding the origin of the solar system. On the other hand if they are products of interactions of solar energetic particles with material in the solar nebula, they may only be used for understanding the energetic environment in the early solar system. In this paper I review the current status of the field with emphasis on recent results that strengthens the case for a stellar source for the short-lived nuclides (other than ^{10}Be).

2. Source(s) of short-lived nuclides in the early solar system

Even though a stellar source for the short-lived nuclides was generally favoured, the possibility of energetic particle production was proposed (Heymann and Dziczkaniec, 1976) soon after the discovery of ^{26}Al in early solar system objects (Lee et al., 1976). This was further investigated by Wasserburg and Arnould (1987) following the identification of ^{53}Mn decay product in refractory objects from a primitive meteorite (Birck and Allègre, 1985). They concluded that it is not possible to simultaneously produce ^{26}Al and ^{53}Mn in the required amounts using the same set of parameters for the energetic particles (flux and energy spectrum), irradiation duration and target composition. However, there was some uncertainty about the inferred initial abundance of ^{53}Mn in the solar system (the currently accepted value given in Table 1 is five times lower than the value proposed initially). Further, the relatively longer half-life of ^{53}Mn (3.7 Ma) also allows for the possibility that continuous galactic nucleosynthesis may contribute towards the inventory of this short-lived nuclide (see, e.g., Wasserburg et al., 1996). The discovery of the short-lived nuclide ^{41}Ca ($T_{1/2}$ = 0.1Ma) in early solar system object (Srinivasan et al., 1994, 1996) provided a new possibility to check the energetic particle production hypothesis. Sahijpal et al., (1998, 2000) showed that the initial abundances of ^{41}Ca and ^{26}Al in early solar system objects are strongly correlated (see Fig. 1), suggesting that they had a common origin and followed the same pathways from the source to the protosolar cloud before getting incorporated into early solar system solids where their fossil records are present. It was also shown that production of these nuclides in amounts necessary to match their initial abundances in the early solar system is not possible in an energetic particle production scenario (Goswami et al., 1997; Sahijpal et al., 1998). Production of the required amount of ^{26}Al will lead to more than an order of magnitude higher abundance of ^{41}Ca than seen in early solar system objects. On the other hand models suggesting injection of freshly synthesized radioactivities from various stellar objects (SN, TP-AGB and W-R stars) could provide modest to good agreement with the experimental data (Wasserburg et al., 1994, 1995;

Table 1. Short-lived now-extinct nuclides present in the early solar system*

Radio-Nuclide	Half-life (Ma)	Daughter Nuclide	Reference Nuclide	Initial Ratio (w.r.t.Ref.Nucl.)
^{41}Ca	0.10	^{41}K	^{40}Ca	1.5×10^{-8}
^{26}Al	0.74	^{26}Mg	^{27}Al	5×10^{-5}
^{10}Be	1.5	^{10}B	^{9}Be	$(5\text{-}10)\times10^{-4}$
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$(2\text{-}10)\times10^{-7}$
^{53}Mn	3.7	^{53}Cr	^{55}Mn	$\sim10^{-5}$
^{107}Pd	6.5	^{107}Ag	^{108}Pd	4.5×10^{-5}
^{182}Hf	9	^{182}W	^{180}Hf	10^{-4}
^{129}I	16	^{129}Xe	^{127}I	10^{-4}
^{244}Pu	81	Fission Xe	^{238}U	$(4\text{-}7)\times10^{-3}$
^{146}Sm	103	^{142}Nd	^{144}Sm	$(5\text{-}15)\times10^{-3}$

* For sources of data, see text and Goswami and Vanhala (2000). Weak and strong hints for the presence of several additional nuclides [^{99}Tc (0.21 Ma), ^{36}Cl (0.3 Ma), ^{205}Pb (15 Ma), ^{92}Nb (35 Ma)] are also reported.

Cameron et al., 1995; Arnould et al. 1997). Thus both experimental and analytical data favoured the case for a stellar source for ^{41}Ca and ^{26}Al.

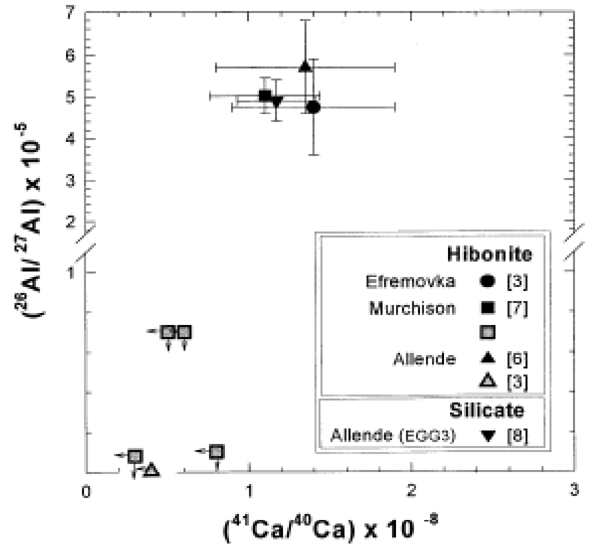

Fig. 1 Measured initial ^{26}Al/^{27}Al ratios in early solar system objects [hibonite (Ca-Al-oxide) from the Murchison, Allende and Efremovka meteorites and refractory silicate from the Allende meteorite] plotted against the measured initial ^{41}Ca/^{40}Ca ratios in them. Abundances of both ^{26}Al and ^{41}Ca, when present, are close to their canonical early solar system values (Table-1). The numbers within parentheses refer to the number of data points in each case (from Sahijpal et al., 2000).

A very novel concept for an origin of the short-lived nuclides via energetic particle irradiation was proposed during this period (Shu et al., 1997; Lee et al., 1998). In this model, christened the "X-wind" model, both the formation of early solar system objects as well as irradiation of their solid precursors were proposed to have taken place very close to the proto-Sun in a high energy, high temperature environment. Calculation of energetic particle production of short-lived nuclides within the framework of this model showed that it is possible to match the observed initial abundances of ^{41}Ca and ^{26}Al only if very specific compositions of the energetic particles as well as that of the irradiated targets are considered (Lee et al., 1998). However, the proposed composition of the targets and their evolution with time were rather ad-hoc and appeared to be very unlikely. Nonetheless, the evidence for the presence of the short-lived nuclide ^{10}Be in the early solar system (McKeegan et al., 2000) led to a renewed interest in this model. In particular, Gounelle et al. (2001) carried out a detailed study to check whether the energetic particle interactions responsible for production of ^{10}Be can concurrently produce several other short-lived nuclides, e.g., ^{41}Ca, ^{26}Al, ^{60}Fe and ^{53}Mn in the required amounts. Unfortunately, the requirement of an ad-hoc target composition remained and significant production of ^{60}Fe can be ruled out because of the absence of suitable targets.

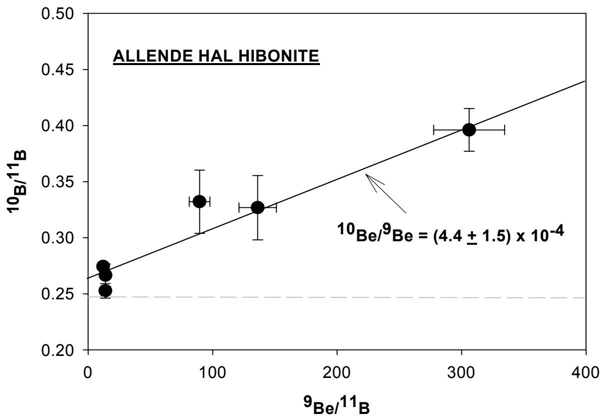

Fig. 2. Measured ^{10}B/^{11}B ratio in a hibonite (HAL) from the Allende meteorite plotted against measured ^{9}Be/^{11}B ratio (from Marhas and Goswami, 2003). The dashed line represents the normal ^{10}B/^{11}B ratio. The data show clear evidence for the presence of ^{10}Be at the time of formation of HAL hibonite. The initial ^{26}Al/^{27}Al in this object is three orders of magnitude below the canonical early solar system value given in Table 1 (see, Fahey et al., 1987).

Although the possibility of energetic particle production of short-lived nuclides other than ^{10}Be appeared to be unlikely, it was necessary to demonstrate experimentally that the source of ^{10}Be is decoupled from the primary source of the other short-lived nuclides because ^{10}Be is found to be present in many early solar system solids that host ^{26}Al and ^{41}Ca (McKeegan et al., 2000, 2001;

Sugiura et al., 2001; MacPherson et al., 2003). This has been accomplished in recent studies carried out by Marhas et al. (2002) and Marhas and Goswami (2003) who have analyzed a special set of objects (hibonite from Murchison and Allende meteorites) that have all the characteristic signatures of early solar system solids but are devoid of the short-lived nuclides ^{26}Al and ^{41}Ca at a detectable level. The data obtained by them showed presence of ^{10}Be in all the analyzed hibonites [see, e.g. Fig. 2]. This result conclusively demonstrated that the source responsible for production of ^{10}Be did not produce the other two nuclides, ^{26}Al and ^{41}Ca, at a detectable level.

3. Plausible source of ^{10}Be

Production of ^{10}Be by energetic particle interactions can take place in various settings where copious flux of low to intermediate energy particles (tens to hundreds of MeV) is present. These include interaction of energetic particles with infalling disk material very close to the proto-Sun (in the X-wind model; Gounelle et al., 2001) or with solar nebula material at asteroidal distances (2-4 AU; Goswami et al., 2001), interaction of galactic cosmic rays with protosolar cloud material prior to or during its collapse (Gounelle et al., 2001; see also Ramaty et al., 1996 and Desch et al., 2003) and spallation reactions induced by passage of r-process jets through expanding SN envelopes (Cameron, 2001). Production in SN envelopes may be ruled out as one would expect coupled presence of spallation produced ^{10}Be and SN produced ^{41}Ca and ^{26}Al (Marhas et al., 2002).

It is possible to characterize the flux and spectral shape of the interacting energetic particles that will be consistent with the observation of ^{10}Be in early solar system objects devoid of detectable ^{26}Al and ^{41}Ca (Marhas et al., 2002). If one considers interactions of solar energetic particles with nebular material with solar composition, a harder energy spectrum with a spectral index $\gamma \leq 2$ in a power-law representation in kinetic energy ($dN/dE \propto E^{-\gamma}$) and an effective irradiation dose of $\sim 2\times10^{18}$ cm^{-2} protons (E≥10MeV) is compatible with the data (see Fig. 3). The possibility that ^{10}Be present in the early solar system could be ambient galactic cosmic ray ^{10}Be that got trapped within the protosolar cloud at the time of its collapse has also been suggested (Desch et al., 2003).

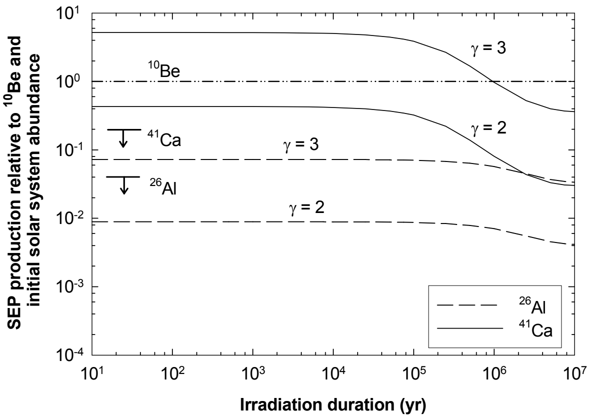

Fig. 3. Production of ^{41}Ca (solid line) and ^{26}Al (dashed line), relative to ^{10}Be and initial solar system initial abundances, by solar energetic particles for different spectral parameters (γ = 2 and 3; $dN/dE \propto E^{-\gamma}$) as a function of irradiation duration. The SEP flux is adjusted to match ^{10}Be production with an initial ^{10}Be/^{9}Be ratio of 10^{-3} (the dashed-dot line). The upper limit abundances of ^{26}Al and ^{41}Ca in the hibonite showing presence of ^{10}Be are also shown. Softer spectra (γ>2) predicts higher yield of ^{41}Ca and ^{26}Al and is not compatible with the experimental observations (from Marhas et al., 2002).

4. Stellar origin of the short-lived nuclides: The question of the most plausible source.

The relatively short-lived nuclides (other than ^{10}Be) present in the early solar system may be considered to be of a stellar origin. Three stellar objects (SN, TP-AGB and W-R stars) are proposed as plausible sources of these nuclides (Wasserburg et al., 1994, 1995; Cameron et al., 1995; Arnould et al., 1997). The pertinent nucleosynthesis processes operating in these sources that can produce the various short-lived nuclides as well as the shortcomings in each case are summarized by Goswami and Vanhala (2000). All the three stellar objects could be the source of ^{41}Ca, ^{26}Al and ^{60}Fe. However ^{53}Mn is not a product of a TP-AGB or a W-R star and can be produced only in supernova. On the other hand, both TP-AGB and W-R stars can produce ^{107}Pd while its level of production in SN remains uncertain. Wasserburg et al. (1998) considered model yields of various nuclides in supernovae having different progenitor masses (see, e.g., Timmes et al., 1995) and concluded that it is not possible to explain the relative initial abundances of ^{26}Al and ^{60}Fe if one considers SN as the source of these nuclides. They argued that the data can be better explained by considering a TP-AGB star as the source of these nuclides. Since ^{53}Mn cannot be produced in a TP-AGB star, they suggested that it could be a product of continuous galactic nucleosynthesis (see, e.g., Wasserburg et al., 1996). The initial abundance of ^{60}Fe considered in this study was based on extrapolation of data obtained in a late forming differentiated meteorite (Shukolyukov and Lugmair, 1993). However, recent measurements in more primitive phases suggest a much higher value for initial ^{60}Fe/^{56}Fe (a few times 10^{-7} to ~10^{-6}; Tachibana and Huss, 2003; Mostefaoui et al., 2003; see Fig. 4) than previously inferred. These new values fall within the range predicted for SN with different progenitor masses (Timmes et al., 1995; Wasserburg et al., 1998) and are much higher than the predicted yield from low-mass TP-AGB star (Wasserburg et al., 1994, 1995).

Meyer et al. (2003 and pers. comm.) have also shown that SN yields (from a model for the explosion of a 25 solar mass star) can explain the initial solar system abundance of the shorter-lived nuclides, ^{41}Ca, ^{26}Al and ^{60}Fe as well as the longer-lived nuclides, ^{129}I and ^{182}Hf. They could match theoretical predictions and meteorite observations by considering a suitable mass cut for the expelled SN material, a mixing of ~0.01% of this material with the protosolar cloud and a time interval of ~0.9Ma between SN synthesis of the short-lived nuclides and their incorporation into early solar system objects. Thus, a SN appears to be the most probable source of the short-lived nuclides present in the early solar system (see, e.g, Zinner, 2003).

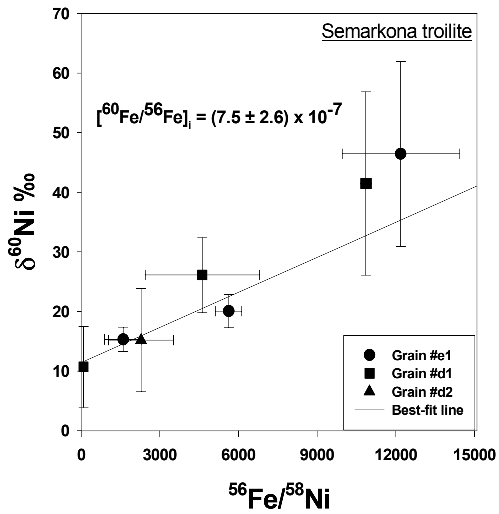

Fig. 4. Measured δ^{60}Ni (deviation in the ^{60}Ni/^{58}Ni ratio from normal expressed in permil unit) as a function of ^{56}Fe/^{58}Ni ratio in troilite grains from the Semarkona meteorite indicate presence of ^{60}Fe at the time of formation of these grains. The inferred initial ^{60}Fe/^{56}Fe ratio is also shown (from Mostefaoui et al., 2003).

5. A triggered origin of the solar system?

The presence of ^{41}Ca and ^{26}Al in early solar system solids suggests a very short time scale of less than a million year for the collapse of the protosolar cloud to form the Sun and some of the first solar system solids. This short time scale argues for an assisted or triggered origin of the solar system as it is much shorter than the time scale for unassisted collapse of a molecular cloud fragment in the standard scenario (Mouschovias, 1989; Shu, 1995). A proposal for a SN triggered origin of the solar system was made by Cameron and Truran (1977) soon after the discovery of ^{26}Al in early solar system objects (Lee et al., 1976). The dynamical viability of triggered collapse of a molecular cloud fragment was investigated in detail in a series of papers by the Harvard and DTM groups (see, e.g., Boss and Foster, 1997 ; Cameron et al., 1997;

Vanhala and Boss, 2002 and references therein). Numerical simulation studies were carried out following several approaches to find out the conditions under which an interstellar shock wave can induce collapse of a molecular cloud and to address the questions of whether radioactivities carried by the shock wave are injected into the collapsing cloud and if the time scale is short enough to be compatible with that inferred from meteorite records of now-extinct short-lived nuclides. The results obtained from these studies suggest that a low velocity (a few tens of km s^{-1}) isothermal shock can trigger collapse and also satisfy the other requirements.

If we consider a TP-AGB star as the source of the short-lived nuclides, we need a close association of such a star and the protosolar cloud. A survey of AGB stars during the present epoch revealed a very low probability of such an association (Kastner and Myers, 1994) although this does not rule it out. On the other hand if we consider a SN as the source, it is capable of inducing collapse of the protosolar cloud even if it is at a distance of more than 10 parsec from the cloud.

6. Observational evidence for triggered star formation

Formation of stars in O-B associations within large molecular cloud complexes is well documented. However, there are very few studies of low-mass star populations in such association. Studies of the properties of both high mass and low mass stars in several stellar populations in the Upper Scorpius OB association led to the suggestion that the star formation process in these populations was triggered by SN shock wave (Preibisch and Zinnecker, 1999; Preibisch et al., 2002). Plausible evidences for triggered origin of small groups of low mass stars have also been reported. The presence of six low-mass pre-main-sequence stars near the Allen's source [NGC 2264 IRS] has been attributed to their triggered formation induced by a strong outflow from this star (Thompson et al., 1998). The origin of the β-Pictoris moving group, that contains β-Pictoris, a young low mass star with an evolving protoplanetary disk, and 19 other young low mass stars, is also attributed to SN events taking place in two other star forming complexes located near the natal cloud of the β-Pictoris group ~12 Ma before present, the evolutionary age of this group (Ortega et al., 2002).

7. Conclusions

The presence of several now-extinct short-lived nuclides in the early solar system is well established from isotopic studies of meteorites. These nuclides may represent freshly synthesized stellar products or they could be products of energetic particle interactions. At least one of them, ^{10}Be, is not a product of stellar nucleosynthesis and must have been produced by energetic particle interactions. However, the exact setting (solar or presolar) of such interactions is yet to be ascertained. Presence of ^{10}Be in early solar system objects devoid of detectable records of the short-lived nuclides ^{26}Al and ^{41}Ca rules out energetic particle interactions as the primary source of ^{26}Al and ^{41}Ca and bolster the case for a stellar origin for these nuclides. Nucleosynthetic yields from a TP-AGB star appear to be compatible with the meteorite data for ^{41}Ca, ^{26}Al and ^{107}Pd. However, it is difficult to explain the recent results on the initial solar system abundance of ^{60}Fe if we consider such a source. On the other hand a supernova appears to be a viable source of ^{41}Ca, ^{26}Al, ^{60}Fe, ^{129}I and ^{182}Hf present in the early solar system. Continuous galactic nucleosynthesis may have contributed significantly to the inventory of ^{53}Mn present in the early solar system. A stellar origin for the short-lived nuclides ^{41}Ca, ^{26}Al and ^{60}Fe suggests a time scale of less than a million year for the collapse of the protosolar cloud leading to the formation of the Sun and some of the first solar system objects. This in turn argues for a triggered origin for the solar system. Numerical simulation studies suggest that a triggered origin within the time constraints placed by the isotopic data appears to be viable. Although rare, there are indirect evidences for triggered origin of low-mass stars and this could indeed be the case for our solar system.

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