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Low energy particle production of short-lived nuclides in the early solar system

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Abstract

Model calculations for the production of the short-lived nuclides ^{10}Be, ^{26}Al, ^{41}Ca and ^{53}Mn by solar energetic particles (SEP) in the asteroidal region during the early evolution of the solar system are presented. Based on the results of these calculations and the initial solar system abundances of the short-lived nuclides inferred from meteorite data, particularly for ^{10}Be that is a product of energetic particle interactions, we can infer the effective SEP irradiation dose received by the solar nebula material. The presence of ^{10}Be in early solar system objects that are devoid of ^{26}Al and ^{41}Ca at detectable levels rules out SEP irradiation as a common source of all the short-lived nuclides present in the early solar system and also allows us to characterize the energy spectrum of the SEP responsible for production of ^{10}Be. The results obtained in our study suggest that the contribution towards the inventory of the short-lived nuclides in the early solar system from SEP irradiation is negligible for ^{26}Al, while it may account for ~10-20% of ^{41}Ca and ^{53}Mn. Injection of freshly synthesized stellar material remains the most viable source of most of the short-lived nuclides (other than ^{10}Be) present in the early solar system

Keywords: meteorites, solar energetic particles, solar system

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1. Introduction

The source of the now-extinct short-lived nuclides such as ^{26}Al, ^{10}Be, ^{41}Ca, ^{60}Fe and ^{53}Mn present in the early solar system is an important issue that has been debated for the last three decades (see, e.g. Wasserburg, 1985; Cameron, 1993; Clayton, 1994; Meyer and Clayton, 2000; Goswami, 2003). Two different processes have been proposed for their production, stellar nucleosynthesis and energetic particle interactions. Stellar sources (e.g. thermally pulsing asymptotic giant branch stars, Wolf Rayet stars, novae and supernovae) have invariably contributed to the initial mix of the proto-solar molecular cloud and the possibility of injection of some or all of these short-lived nuclides from any one of these stellar sources into the early solar system is very likely (see, e.g. Wasserburg et al., 1994, 1995; Cameron et al., 1995; Arnould et al., 1997). On the other hand, interactions of energetic particles from an active early Sun with gas and dust in the solar nebula resulting in the production of these short-lived nuclides is an equally viable proposition (Heymann and Dziczkaniec, 1976, Wasserburg and Arnould, 1987; Goswami et al., 1997; Lee et al., 1998). A stellar source for the short-lived nuclides was widely accepted because of the difficulty in obtaining a self-consistent explanation for the initial abundances of the short-lived nuclides in the energetic particle interaction scenario unless some ad-hoc assumptions are made (see, e.g. Goswami and Vanhala, 2000). However, the discovery of ^{10}Be in early solar system objects (McKeegan et al., 2000) rejuvenated the energetic particle irradiation scenario because ^{10}Be gets destroyed in high temperature stellar environment and cannot be a product of stellar nucleosynthesis (Reeves, 1994).

Presence of ^{10}Be in early solar system solids shows that energetic particle interactions did occur during the early evolution of the solar system and it is important to address the question whether this irradiation may also produce some of the other short-lived nuclides such as, ^{26}Al, ^{41}Ca and ^{53}Mn. Studies of early solar system objects looking for correlated presence of ^{10}Be with the other short lived nuclides coupled with model calculations of energetic particle production of these nuclides can provide answer to this question. In this paper we present results of such model calculations in light of new experimental results obtained by us and also reported in literature and discuss their implications for the source and origin of the short-lived nuclides present in the early solar system.

2. Experimental results

About two-dozen refractory early solar system objects from different primitive meteorites have been analyzed so far to look for correlated presence of ^{10}Be and ^{26}Al; in a few cases ^{41}Ca was also analyzed (McKeegan et al., 2000, 2001; Sugiura et al., 2001; Srinivasan, 2001; MacPherson et al., 2003; Marhas et al., 2002, Marhas and Goswami, 2003). The analyzed samples include Calcium-Aluminium-rich Inclusions (CAIs), FUN inclusions (characterized by Fractionated and Unknown Nuclear effects) and refractory hibonite ($CaAl_{12}O_{19}$) grains from several primitive carbonaceous chondrites. The results obtained in these studies show that the initial ^{26}Al/^{27}Al values in the analyzed objects range over a wide range, from a very low value of $\sim 5\times 0^{-8}$ to the canonical value of 5×10^{-5}. Even though ^{41}Ca was not studied in all the samples, the available data show that inclusions devoid of detectable ^{26}Al or with very low initial ^{26}Al/^{27}Al are also devoid of detectable ^{41}Ca, while samples with canonical ^{26}Al/^{27}Al ratio also have canonical abundance of ^{41}Ca /^{40}Ca. The presence of ^{26}Al and ^{41}Ca is thus very strongly correlated and suggests a common source of these two nuclides. On the other hand all the analyzed samples host ^{10}Be at detectable level with initial ^{10}Be/^{9}Be clustering within a narrow range of a few times 10^{-4} to $\sim 10^{-3}$, irrespective of the three orders of magnitude differences in the initial values of ^{26}Al/^{27}Al in these objects (Fig. 1). These data clearly suggest that ^{26}Al and ^{10}Be are decoupled and they are not cogenetic (Marhas et al. 2002, 2003). The same is true when we consider the data for ^{10}Be and ^{41}Ca.

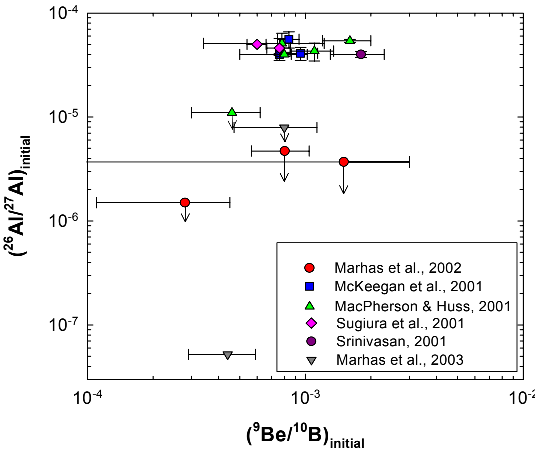

Fig 1. Initial ^{26}Al/^{27}Al vs initial ^{10}Be/^{9}Be in refractory inclusions from primitive meteorites.

3. Irradiation scenarios, input parameters and results

Several low energy particle irradiation scenarios have been proposed for the production of ^{10}Be present in the early solar system. These include:

(a) spallation reactions within the proto solar molecular cloud (Ramaty et al., 1996; Bloemen et al., 1999),

(b) spallation reactions in the expanding supernova envelope (Cameron, 2001),

(c) solar energetic particle interaction taking place in the solar nebula. Two variants of this scenario have been proposed: (1) irradiation very close to Sun (the X-wind model, Shu et al., 1997; Lee et al., 1998; Gounelle et al., 2001, Leya et al., 2003) and (2) irradiation of nebular material at meteorite forming zone (asteroidal region, Goswami et al., 1997; 2001).

We would like to note here Desch et al (2003) have recently suggested that ^{10}Be present in the early solar system could simply represent ^{10}Be in ambient galactic cosmic rays that were trapped by the collapsing protosolar cloud and contribution from any energetic particle irradiation is insignificant.

In the present study we consider production of ^{10}Be in the early solar system, along with ^{26}Al, ^{41}Ca and ^{53}Mn due to SEP interaction with nebular material at asteroidal distances following the approach outlined in Goswami et al. (2001). We consider both short irradiation duration typical of X-wind irradiation (a few tens of years) and much longer irradiation expected to be typical of irradiation in the asteroidal region. Calculations were carried out by expressing SEP flux both in terms of kinetic energy E, [$dN/dE \propto E^{-\gamma}$] and rigidity (momentum per charge) R, [$dN/dR \propto e^{(-R/R_0)}$], where γ and R_0 define the spectral shape. A range of values for γ (2-5) and R_0 (50-400) was used to encompass the broad range seen in contemporary solar flares. A flux normalization of $N_{E>10\ \mathrm{MeV}} = 100$ cm^{-2} sec^{-1} was considered in these calculations; this value represents the long-term (million year) averaged flux of SEP based on lunar sample data (Reedy, 1998). Both proton-induced and alpha particle induced reactions were taken into account assuming an alpha particle to proton ratio of 0.1. We consider irradiation of nebular solids of CI chondritic (=solar) composition representing precursors of early solar system objects such as the CAIs. Calculations were also carried out for target composition representative of the refractory early solar system objects (CAIs and hibonite) that contain fossil records of the now-extinct short-lived nuclides. The targets were assumed to be spherical, with sizes varying from 10 μm to 1 cm and characterized by a power law size distribution of the type $dn/dr \propto r^{-\beta}$, with β values of 3 to 5.

Radionuclides	**Major Target Elements**
^{26}Al	Na, Al, Si, Mg
^{41}Ca	Ar, K, Ca
^{53}Mn	Cr, Fe, Mn
^{10}Be	O

Table 1. Target elements in nebular solids considered for SEP production of short-lived nuclides.

The relevant cross sections for the production of ^{26}Al, ^{41}Ca and ^{53}Mn were taken from Ramaty et al. (1996). Cross section for the production of ^{10}Be from oxygen was taken from Sisterson et al. (1997). The major target elements considered for production of the different nuclides are shown in Table 1. Self-shielding of SEP by nebular gas and dust was ignored to maximize production and obtain a limit on the effective dose of SEP needed to match the observed initial ^{10}Be abundance in early solar system objects.

In Fig. 2 we show the production of the short-lived nuclides ^{26}Al and ^{41}Ca, relative to ^{10}Be and their initial solar system abundances [(^{26}Al/^{27}Al)$_i$ =5×10^{-5}, (^{41}Ca/^{40}Ca)$_i$=1.4×10^{-8}], for both a power-law in kinetic energy [fig. (a)] and exponential in rigidity [fig. (b)] representation of the SEP spectrum. The SEP flux is adjusted to match the observed initial ^{10}Be/^{9}Be ratio of 10^{-3} for all the irradiation durations. Also plotted are the upper limits of abundances of ^{26}Al and ^{41}Ca (^{26}Al/^{27}Al <2×10^{-6}; ^{41}Ca/^{40}Ca<4×10^{-9}) in hibonites with ^{10}Be/^{9}Be ratio close to the canonical value of 10^{-3} (see also Fig. 1).

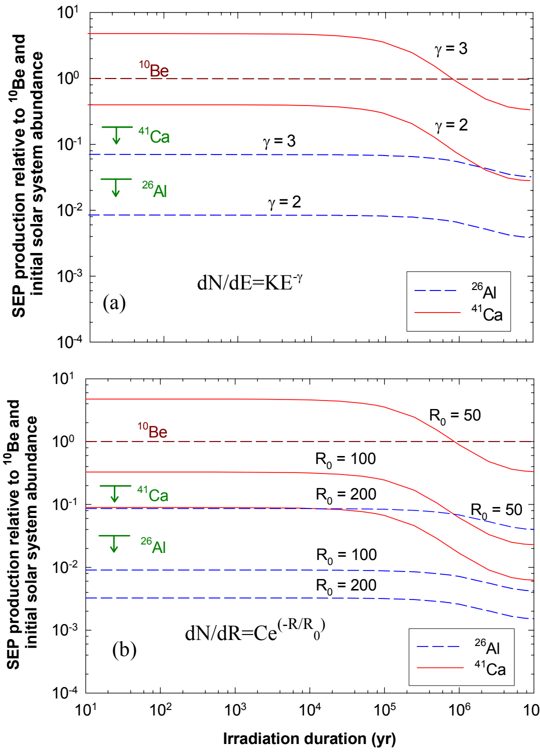

Fig. 2 SEP production of short-lived nuclides, ^{26}Al and ^{41}Ca, relative to ^{10}Be and their canonical abundances, for different SEP spectral types [energy spectrum (Fig. a) and rigidity spectrum (Fig. b)] and spectral parameters γ and

R_0. The targets (nebular solids) were assumed to be chondritic (=solar) in composition characterized by a grain size distribution, $dn/dr \propto r^{-4}$. Also plotted are the upper limits of initial ^{26}Al and ^{41}Ca in hibonites devoid of these nuclides at detectable level but hosting ^{10}Be with near canonical abundance.

It is clear from Fig. 2a that a steeper energy spectrum ($\gamma \geq 3$) will lead to over production of ^{41}Ca relative to its canonical value. Similar conclusion may be drawn from the results obtained for an exponential in rigidity representation of SEP spectrum (Fig 2b). Excess production of ^{41}Ca relative to its canonical value can be avoided only for R_0 values exceeding 100 MV. However, the most stringent constraint on the spectral parameter is placed by the data for early solar system objects (primarily FUN inclusions and CM hibonites) that are devoid of detectable ^{41}Ca and ^{26}Al (the upper limits in Fig. 2) but show presence of ^{10}Be with near canonical value. This would require that the SEP interacting with the nebular material were characterized by harder spectrum with $\gamma \leq 2$ or $R_0 > 150$ MV.

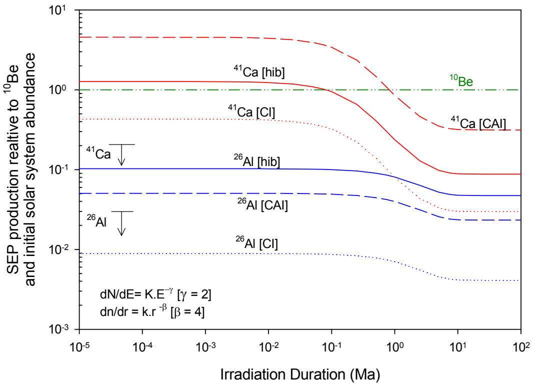

Fig. 3 Solar energetic particle production of the short-lived nuclides ^{26}Al and ^{41}Ca relative to ^{10}Be and their canonical abundances for three different target compositions; CI (=solar), hib (hibonite) and CAI (calcium-aluminum-rich inclusion). See Fig 2. for additional details.

There are suggestions that the precursor of the analyzed early solar system objects may have composition similar to the objects themselves rather than CI (=solar) composition considered by us. We have therefore carried out production calculations by using target compositions similar to the two types of objects, Ca-Al-rich refractory inclusion (CAIs) and hibonite, analyzed for short-lived nuclide records. The results of these calculations are shown in Fig. 3 for a particular spectral parameter and grain size distribution (γ=2, β=4) for all the three compositions. It is obvious that the basic nature of the results do not depend critically on target composition.

4. Discussion

Model calculations of SEP production of short-lived nuclides, ^{26}Al, ^{41}Ca and ^{10}Be in early solar system objects coupled with observed presence of ^{10}Be in early solar system objects devoid of detectable ^{41}Ca and ^{26}Al suggest that the energetic particles from the early Sun irradiating the solar nebula material was characterized by a harder energy spectrum than contemporary as well as long-term averaged SEP spectrum based on satellite and lunar sample data, respectively. The suppression of production of ^{41}Ca and ^{26}Al relative to ^{10}Be for harder spectrum can be attributed to the differences in the excitation function of the relevant nuclear reactions with production of ^{41}Ca and ^{26}Al taking place primarily at lower energies ($E < 30$ MeV) and that of ^{10}Be at relatively higher energies. We estimate the effective SEP irradiation dose received by the nebular material has to be $\sim 2\times10^{18}$ protons cm^{-2} with energy $\geq$10 MeV/amu to explain the initial abundance of ^{10}Be in early solar system objects if we assume a CI (=solar) composition of the targets representing the precursor solids of these refractory objects. The dose may be somewhat lower if the target composition is considered to be similar to the analyzed early solar system objects themselves (see Fig. 3). Although we have assumed a solar system initial ^{10}Be/^{9}Be ratio of 10^{-3} in our calculations, the experimental data suggest a spread in this ratio from $\sim 4\times10^{-4}$ to $\sim 1.5\times10^{-3}$ (see Fig. 1). It is plausible that this spread is caused by variation in the effective SEP irradiation dose received by different parcels of nebular material and/or irradiation geometry and shielding during irradiation.

Another short-lived nuclide that can be produced effectively during SEP irradiation is ^{53}Mn. Even though the presence of this nuclide in the early solar system is well established, its initial abundance is not very well defined due to experimental difficulties. However, data obtained from analysis of late forming chondrules and differentiated meteorites suggest a plausible solar system initial ^{53}Mn/^{55}Mn value of ~10^{-5} **(**Lugmair and Shukolyukov, 2001**)**. We have evaluated SEP production of ^{53}Mn using the same parameters as above and the results of these calculations are shown in Fig. 4. Our results suggest that even though SEP production of ^{53}Mn did take place it cannot explain the inferred initial ^{53}Mn/^{55}Mn ratio of ~10^{-5}. As in the case of ^{41}Ca and ^{26}Al, the main contribution towards the inventory of ^{53}Mn in early solar system has to come from stellar nucleosynthesis. However, unlike ^{41}Ca and ^{26}Al, whose short half-lives suggest injection of freshly synthesized nuclides into the protosolar cloud prior to or during its collapse, it is difficult to rule out the possibility of contribution from continuous galactic nucleosynthesis in the case of ^{53}Mn (see, e.g. Wasserburg et al., 1996).

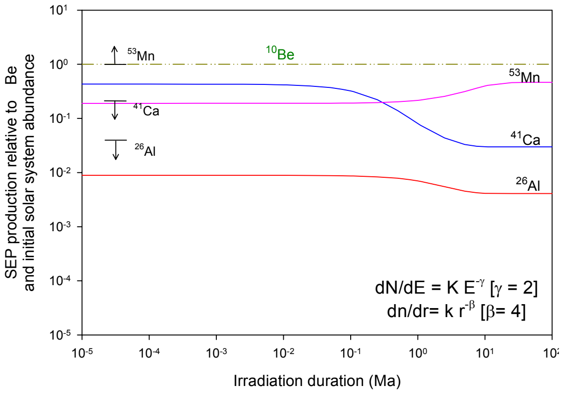

Fig 4. SEP production of ^{53}Mn, ^{26}Al and ^{41}Ca relative to ^{10}Be and their initial solar system abundances. The initial ^{53}Mn/^{55}Mn ratio was taken as 10^{-5}. (See Fig 2. for additional details).

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