29th International Cosmic Ray Conference Pune (2005) **1**, 79-82

Limits on the Spectral shape and Flux of Energetic charged particles from the Proto-Sun

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Evidence for the presence of ^{10}Be (half-life = 1.5 Ma) in the early solar system has been found from studies of primitive meteorites. Interaction of solar energetic particles from the active early Sun with gas and dust present in the solar nebula is considered to be the most plausible source of this nuclide. The presence of ^{10}Be in meteorite samples is often accompanied by other short-lived nuclides (e.g., ^{26}Al) for which a stellar origin is generally favoured. Our studies show that ^{10}Be is also present in samples in which ^{26}Al is below detection level and suggest that the primary source of these two nuclides cannot be the same. This observation places limits on the spectral shape and flux of energetic particles from the proto-Sun such that production of ^{10}Be is not accompanied by significant production of ^{26}Al. Our data suggest that the energetic particles from the early Sun were characterized by a hard spectrum and the particle flux was more than 10,000 times the average flux from the contemporary Sun.

1. Introduction

Isotopic studies of early solar system objects in primitive meteorites have revealed the presence of about a dozen 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., 1, 2]. The former presence of these now-extinct nuclides is based on the observation of excess abundances of their decay products in the analyzed samples. The nuclides with relatively short half-life (Table 1) such as ^{41}Ca (0.1 Ma), ^{26}Al (0.7 Ma), ^{60}Fe (1.5 Ma) and ^{10}Be (1.5 Ma) must have been produced shortly before the formation of the solar system or during the very early stages of the formation of the solar system. Two plausible sources are proposed for these nuclides; 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. Although there was a general consensus for a stellar source for the short-lived nuclides present in the early solar system [1], the discovery of ^{10}Be in early solar system objects [2] revived the energetic particle production model because ^{10}Be is not a product of stellar nucleosynthesis.

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

Radionuclide	Half-life(Ma)	Daughter Nuclide	Reference Nuclide	Initial Ratio *
^{41}Ca	0.10	^{41}K	^{40}Ca	1.5×10^{-8} [3]
^{26}Al	0.74	^{26}Mg	^{27}Al	5×10^{-5} [4]
^{10}Be	1.5	^{10}B	^{9}Be	$(5\text{-}10)\times10^{-4}$ [2]
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$(2\text{-}10)\times10^{-7}$ [5,6]

* (w.r.t. reference nuclide; e.g. ^{41}Ca/^{40}Ca)

2. Energetic particle production of ^{10}Be

^{10}Be present in the early solar system could have been produced by energetic particle interactions in various settings where copious flux of low to intermediate energy particles (tens to hundreds of MeV) is present.

These include interaction of solar energetic particles (SEP) with infalling disk material very close to the proto-Sun (in the X-wind model [7]) or with solar nebula material at asteroidal distances [8, 9], interaction of galactic cosmic rays with protosolar cloud material prior to or during its collapse [7, 10, 11] and spallation reactions induced by passage of r-process jets through expanding SN envelope [12]. The observational evidence for an extremely enhanced activity of solar type stars during their very early evolutionary stage, the so-called T-Tauri phase, with emission in UV and X-rays ranging from a few thousands to a hundred thousand time higher than that of contemporary Sun [13, 14] suggests the possibility that the active early Sun could also be a source of an extremely enhanced flux of energetic particles compared to contemporary Sun. This makes SEP production the most plausible source of ^{10}Be present in the early solar system. We have carried out analytical studies to investigate whether SEP production of ^{10}Be can also lead to production of some of the other short-lived nuclides such as ^{41}Ca, ^{36}Cl, ^{26}Al, and ^{53}Mn. We considered interactions of energetic solar protons and alpha particles with nebular gas and dust of solar composition assuming various spectral representation for the SEP [8]. This study showed that production of ^{10}Be in the required amount will not match the inferred initial abundances of the other nuclides (Table 1). Even though there are suggestions for specific target configuration and composition [7] to avoid this problem, they are ad-hoc in nature. We also noted that production of ^{10}Be relative to other nuclides is sensitive to the choice of the spectral parameters because of the significantly higher threshold for the reactions leading to production of ^{10}Be than for those producing ^{41}Ca, ^{36}Cl, ^{26}Al, and ^{53}Mn.

3. Source(s) of ^{10}Be and other short-lived nuclides in the early solar system

Although the possibility of energetic particle production of short-lived nuclides other than ^{10}Be appears unlikely, it is necessary to demonstrate it experimentally because ^{10}Be is found to be present in many early solar system solids that also host the short-lived nuclide ^{26}Al [2, 15, 16]. We have accomplished this by analyzing a special set of refractory objects (hibonite [a Ca-Al-oxide] from primitive 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. The data obtained by us [17; this work] showed presence of ^{10}Be in all the analyzed hibonite [see, e.g. Fig. 1]. This result conclusively demonstrated that the source responsible for the production of ^{10}Be did

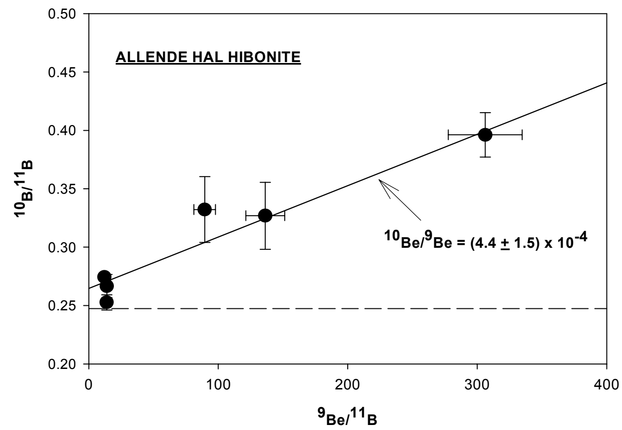

Figure 1. Measured $^{10}B/^{11}B$ ratio in a hibonite (HAL) from the Allende meteorite plotted against measured $^{9}Be/^{11}B$ ratio. The dashed line represents the normal $^{10}B/^{11}B$ ratio. The data show clear evidence for excess ^{10}B indicating the presence of ^{10}Be at the time of formation of HAL hibonite. The initial $^{26}Al/^{27}Al$ in this object is $\sim 5\times10^{-8}$ [18], three orders of magnitude below the canonical early solar system value (Table –1).

not produce ^{26}Al and ^{41}Ca at a detectable level. Thus, even though SEP interaction is the primary source of ^{10}Be, it did not contribute significantly to the inventory of the short-lived nuclides ^{26}Al and ^{41}Ca present in the early solar system and a stellar source for these nuclides appears to be more plausible [1, 19].

4. Constraints on the Spectral shape and Flux of SEP from the early Sun

We have followed the approach used in [8] for the calculation of SEP production of short lived nuclides such as ^{26}Al, ^{41}Ca and ^{10}Be 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. Calculations were carried out by expressing SEP flux both in terms of kinetic energy E, [$dN/dE=K.E^{-\gamma}$] and rigidity R, [$dN/dE=C \exp(-R/R_0)$], where γ and R_0 defines the spectral shape. The value of γ was varied from 2 to 5 and R_0 from 50 to 400 to encompass the broad range seen in contemporary solar flares. A flux normalization of $N_{E>10\ MeV} = 100\ cm^{-2}\ sec^{-1}$ was used in these calculations, which is represents the long-term averaged value [20]. Both proton-induced and α-induced reactions were taken into account assuming a α/p ratio of 0.1. The targets were nebular solids of solar (=CI chondrite) composition that are considered as precursors of the refractory early solar system solids such as the hibonites. We assume the targets to be

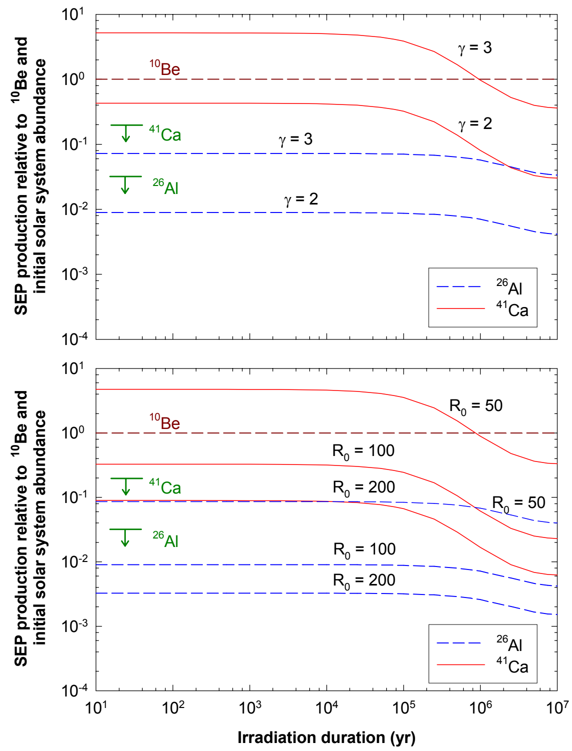

Figure 2. Production of short-lived nuclides, ^{26}Al and ^{41}Ca relative to ^{10}Be and their canonical abundances [$^{26}Al/^{27}Al \sim 5 \times 10^{-5}$, $^{41}Ca/^{40}Ca \sim 1.4 \times 10^{-8}$], by SEP for different kinetic energy and rigidity spectra. The SEP flux is adjusted to match ^{10}Be production with an initial $^{10}Be/^{9}Be = 10^{-3}$ for all irradiation times. Targets are considered to be solar in composition (see text). Also plotted is the upper limit of initial values of ^{26}Al, ^{41}Ca found in CM hibonites relative to their canonical initial abundances.

spherical, with sizes varying from 10 μm to 1 cm and characterized by a power law size distribution of the type dn/dr α $r^{-\beta}$, with β values ranging from 3 to 5. The primary target elements of interest are oxygen (for ^{10}Be), Na, Al, Si and Mg (for ^{26}Al) and Ar, K and Ca (for ^{41}Ca). Reaction cross sections for O (p,x) ^{10}Be were taken from [21], cross sections for production of ^{26}Al and ^{41}Ca are those adopted in [8]. Self-shielding of SEP by nebular gas and dust was ignored to maximize production. The calculations were carried out for different sets of SEP spectral parameters, β values and irradiation time. We show in Fig. 2 some of the results obtained from these calculations. It is clear from these results that a softer energy spectra (γ=3) will lead to over production of ^{41}Ca relative to its canonical value, whereas, for a harder spectra ($\gamma \leq 2$) production of both ^{26}Al and ^{41}Ca will be much below their canonical values. Similar results are also seen if we consider various rigidity spectra. Significant production of ^{26}Al and ^{41}Ca can be avoided for relatively harder spectra with R_0 exceeding 150 MV. Production of the short-lived nuclides ^{26}Al and ^{41}Ca is more efficient for softer SEP spectra, while harder spectra favour production of ^{10}Be. This is a reflection of the fact that higher energy (>50MeV) protons are required for effective production of ^{10}Be, while low-energy protons (< 30MeV) are primarily responsible for the production of ^{26}Al and ^{41}Ca.

We estimate the effective SEP fluence received by the nebular material to be ~2 × 10^{18} protons/cm^2 with energy ≥10 MeV.amu^{-1}. There is a spread in the initial value of ^{10}Be/^{9}Be from ~4 × 10^{-4} to about 1.5×10^{-3} in samples with initial ^{26}Al/^{27}Al ratio both close to the canonical value of 5 × 10^{-5} as well as in samples with extremely low initial ^{26}Al/^{27}Al or devoid of detectable ^{26}Al. In the SEP irradiation scenario this spread can be attributed to variations in the SEP irradiation dose or irradiation geometry of the nebular material. If we consider an effective irradiation duration of ≤1 Ma, the SEP flux from the proto-Sun was higher by a factor of ≥10,000 than the long-term averaged value for the contemporary Sun.

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