PROLONGED IRRADIATION AS A POSSIBLE SOLUTION FOR THE DECOUPLING OF ^{10}Be and ^{41}Ca IN METEORITIC REFRACTORY INCLUSIONS.

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Introduction: Irradiation by energetic charged particles from an active young Sun has been proposed as a source for a suite of short-lived radionuclides (SLRs) [e.g., 1]. Among the SLRs that could potentially be produced by irradiation, ^{10}Be ($t_{1/2}$ = 1.3 Myr) appears to be decoupled from ^{26}Al ($t_{1/2}$ = 0.7 Myr) and ^{41}Ca ($t_{1/2}$ = 0.1 Myr) in terms of the abundances in meteoritic Ca-Al-rich Inclusions (CAIs). Isotope measurements of CAIs have shown that the ^{10}Be/^{9}Be ratios in CAIs span from 3×10^{-4} to $\sim10^{-2}$, regardless of the ^{26}Al content, which could range from ^{26}Al/^{27}Al ~ 0 to ^{26}Al/^{27}Al ~ 5.2×10^{-5} (the canonical value) [2−8]. Given that ^{10}Be exclusively requires an irradiation origin and that the high but variable ^{10}Be/^{9}Be ratios are most likely derived from the fluence fluctuations in the solar energetic particles [7−9], the decoupling between ^{10}Be and ^{26}Al implies that the majority of ^{26}Al was not derived from irradiation but instead of a stellar source [4]. Compared to ^{10}Be and ^{26}Al, the initial abundance and distribution of ^{41}Ca in the Solar System is poorly understood due to analytically challenging mass spectrometry. Literature data showed that ^{41}Ca existed in the solar nebula at the level of ^{41}Ca/^{40}Ca = 4.2×10^{-9}, and its presence or absence in CAIs is qualitatively correlated with ^{26}Al [10,11]. The latter observation can be understood in the context that ^{26}Al and ^{41}Ca were co-delivered from a stellar source after some of the oldest solids have formed in the solar nebula, and early Solar System irradiation that produced ^{10}Be did not account for the presence of ^{26}Al and ^{41}Ca [4,11].

The production of ^{10}Be by irradiation processes involving nuclear reactions between energetic particles (protons and alphas) and oxygen-rich targets (e.g., oxides, silicates) has been reasonably well studied [e.g., 1,12]. With a favorable target chemistry, for example, CAI-like composition, the aforementioned nuclear reactions would also be conducive to the production of ^{41}Ca, but not of ^{26}Al [e.g., 12]. Earlier calculations have shown that assuming a short irradiation duration (~20 years), proton irradiation with fluence ($\sim10^{19}$ cm^{-2}) capable of producing ^{10}Be at the observed levels in CAIs would yield a ^{41}Ca/^{40}Ca ratio close to 10^{-7}, a factor of ~25 higher than the inferred initial ratio in CAIs, while ^{26}Al/^{27}Al was produced at the level of 10^{-6}, more than one order of magnitude lower than 5.2×10^{-5} [e.g., 12] The results suggested that a stellar source was required for ^{26}Al. However, irradiation contributions to the ^{41}Ca inventory have never been well understood. This is because not only has ^{41}Ca never been observed at such high abundances in any ^{10}Be-bearing refractory inclusions, but it is also absent in some of the ^{10}Be-bearing CAIs, e.g., platy hibonite crystals (PLACs) from CM chondrites [10, 11]. Given that some of the ^{41}Ca-free inclusions cannot have formed late [13], such a decoupling between the two radionuclides cannot be attributed to formation of these objects after ^{41}Ca has completely decayed away. The low abundance or absence of ^{41}Ca, albeit based on very limited data, poses a challenge to early Solar System irradiation models. To understand this ^{10}Be−^{41}Ca conundrum, we evaluated the outcomes of prolonged energetic charged particle irradiation. Preliminary results of calculations are reported here.

Prolonged energetic charged particle irradiation: Earlier calculations of irradiation production of ^{10}Be in the early Solar System were based on the assumption of enhanced proton flux ($\sim10^{10}$ cm^{-2}s^{-1}) and short irradiation time [e.g., 1]. Such irradiation settings resulted in gross overproduction of ^{41}Ca compared to the observed abundance when ^{10}Be was produced at the right amounts. One potential solution to this problem is a prolonged irradiation time because of the large difference in half-lives of the two radionuclides. To understand the ^{41}Ca abundances produced by prolonged irradiation, we performed calculations involving proton and α-particle spallation of CAI-like targets. The flux of projectiles was expressed in the form of a differential spectrum $dN/dE \propto E^{-\gamma}$, where $\gamma = 2.7$ characterizing a gradual flare (i.e., ^{3}He-free) environment was chosen. The main nuclear reactions producing ^{41}Ca were ^{42}Ca(p,pn)^{41}Ca, ^{44}Ca(p,x)^{41}Ca and ^{40}Ca(α,^{3}He)^{41}Ca, and ^{10}Be was produced through the ^{16}O(p,x)^{10}Be reaction. The cross sections of relevant nuclear reactions were either taken from the nuclear databases (e.g., ENDF/B-VII) or estimated by using the TALYS code [14]. The target composition was assumed to be CAI-like, and no energy loss or neutron irradiation was considered as we assumed irradiation of small CAIs or their precursors in the solar nebula. The length of irradiation time was kept as a free parameter, but was considerably longer than 20−30 years used in earlier work [e.g., 1]. The total proton fluence was constrained by setting irradiation-produced ^{10}Be/^{9}Be = 9×10^{-4}.

Results: Some calculation results are listed in Table 1. As can be seen, ^{41}Ca/^{40}Ca decreases with increasing irradiation time. When the irradiation time is much shorter than the half-life of ^{41}Ca (e.g., ~10^4 years), the resulting ^{41}Ca/^{40}Ca ratio (~10^{-7}) is too high compared to 4.2×10^{-9}. An extremely long irradiation time of >1 Myr is required to produce ^{41}Ca/^{40}Ca at the level of ~10^{-8}, only 2−3 times higher than the observed ratio in meteorites. Such a factor of 2−3 difference could be reconciled by involving the uncertainties associated with the calculations (e.g., uncertainties of cross section measurements and estimates). The flux of projectiles inferred from the calculations implies that irradiation of solids should have occurred in a less energetic environment compared to, for example, the X-point in the X-wind model [1]. That CAIs were steadily irradiated for more than 1 Myr requires some mechanisms retaining them against gas-drag drift into the Sun, for example, outward diffusion due to nebula turbulence [15].

The above scenario, although plausible for CAIs, does not solve the problem of the absence of ^{41}Ca (and ^{26}Al) in ^{10}Be-bearing CAIs (e.g., PLACs). The ^{10}Be/^{9}Be ratios inferred in PLACs are at a relatively uniform level of ~5×10^{-4}, compared to a factor 3−4 variation seen in other CV CAIs bearing ^{26}Al (and ^{41}Ca) [2−8]. Prolonged irradiation (> 1 Myr) producing ^{10}Be/^{9}Be = 5×10^{-4} would still yield ^{41}Ca/^{40}Ca ~ 10^{-8}, because the production of ^{41}Ca has reached a saturation level. Trapping of galactic cosmic ray (GCR) ^{10}Be by the molecular cloud core could potentially be a solution for this decoupling [16]. If true, this mechanism should only account for ^{10}Be in ^{26}Al-^{41}Ca-free refractory inclusions, as the observed variation in ^{10}Be/^{9}Be in ^{26}Al-bearing CAIs appeared to be too large to be explained by the trapping model.

It should be noted that ^{41}Ca/^{40}Ca = 4.2×10^{-9} was inferred based on the measurements of only three CAIs. It is not yet clear if ^{41}Ca/^{40}Ca = 4.2×10^{-9} really characterized the initial abundance in the Solar System. If there existed higher ^{41}Ca/^{40}Ca in ^{10}Be-bearing CAIs (with or without ^{26}Al), irradiation as a source for ^{41}Ca would certainly be more favorable. Otherwise, one has to invoke a long irradiation time to marginally explain the low ^{41}Ca/^{40}Ca ratio. More high quality data on ^{41}Ca/^{40}Ca are certainly key to understanding the origin of this radionuclide.

Fluence	Flux	Time (yr)	^{41}Ca/^{40}Ca
2.60×10^{19}	9.0×10^{7}	9.16×10^{3}	1.10×10^{-7}
2.75×10^{19}	9.0×10^{6}	9.70×10^{4}	9.20×10^{-8}
2.79×10^{19}	5.0×10^{6}	1.77×10^{5}	7.44×10^{-8}
3.06×10^{19}	1.9×10^{6}	5.11×10^{5}	3.90×10^{-8}
3.52×10^{19}	1.0×10^{6}	1.12×10^{6}	2.10×10^{-8}
6.89×10^{19}	5.0×10^{5}	4.37×10^{6}	1.07×10^{-8}

Table 1. ^{41}Ca/^{40}Ca produced by prolonged irradiation

References: [1] Gounelle et al. (2006). ApJ, 640, 1163 [2] McKeegan et al. (2000). Science, 289, 1334 [3] Sugiura et al. (2001). MAPS, 36, 1397 [4] Marhas et al. (2002). Science, 298, 2182 [5] MacPherson et al. (2003). GCA, 67, 3165 [6] Chaussidon et al. (2006). GCA, 70, 224 [7] Liu et al. (2010). ApJ, 719, L99 [8] Gounelle et al. (2013) ApJ, 763, 33 [9] Srinivasan and Chaussidon (2013) EPSL, 374, 11 [10] Liu (2012) ApJ, 761, 137 [11] Sahijpal et al. (1998) Nature, 391, 559 [12] Herzog et al. (2011) MAPS, 46, 1427 [13] Liu et al. (2009). GCA, 73, 5051 [14] Koning et al. (2005) AIP conf. 769, 1154 [15] Cuzzi et al. (2003) Icarus, 166, 385 [16] Desch et al. (2004). ApJ, 602, 528