LATE-STAGE FORMATION OF SHORT-LIVED RADIONUCLIDES BY SOLAR ENERGETIC PARTICLE IRRADIATION IN THE EARLY SOLAR SYSTEM.
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Introduction: The origin of short-lived ($\tau_{1/2}$ < 5 Myr) and now extinct radionuclides (^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe; hereafter SLRs) is fundamental to understanding the formation of the early solar system as they provide a unique source of information about the astrophysical environment in which the solar system formed, as well as a high-resolution chronology of early solar system events [1, 2]. The origin of SLRs in the early solar system, however, remains controversial [2] with two main classes of models proposed – injection of SLRs from a stellar source (e.g., supernova, asymptotic giant branch star or Wolf-Rayet star) and solar energetic particle (SEP) irradiation of dust and gas near the proto-Sun [2−7].

Excesses of ^{36}S correlated with ^{35}Cl/^{34}S ratios were previously reported in sodalite ($Na_8Al_6Si_6O_{24}Cl_2$), a secondary mineral in Ca-Al-rich Inclusions (CAIs) and chondrules from the Allende (CV) and Ningqiang (CV anomalous) carbonaceous chondrites [8−10]. The highest reported ^{36}Cl levels in sodalite ^{36}Cl/^{35}Cl ~ 5×10^{-6} [8, 9] are consistent with levels predicted for energetic particle irradiation of a reservoir with solar composition, but exceed by several orders of magnitude the values predicted for any stellar source [2]. Irradiation models predict that the production of ^{36}Cl by SEP irradiation cannot occur in isolation but would be coupled to the production of other SLRs such as ^{26}Al, ^{53}Mn, and ^{10}Be [5−7]. These data underscore the importance of ^{36}Cl and its relationship to other SLRs for understanding the origin of SLRs in the early solar system.

Timing of ^{36}Cl production: Recently, we reported extremely large ^{36}S excesses correlated with the respective ^{35}Cl/^{34}S ratios in wadalite ($Ca_6(Al,Si,Mg)_7O_{16}Cl_3$), a Cl-rich secondary mineral, in Allende CAI AJEF [11]. The inferred ^{36}Cl/^{35}Cl ratio of wadalite of $(1.81\pm0.13)\times10^{-5}$ (Fig. 1a) represents the highest initial abundance of ^{36}Cl reported in any meteorite; four times greater than the highest ^{36}Cl/^{35}Cl initial ratio observed in sodalite in CAIs and chondrules [8, 9]. The absence of radiogenic ^{26}Mg in secondary grossular (Fig. 1b) contrasts with the well-constrained primary mineral internal isochron in AJEF [12] yielding an initial ^{26}Al/^{27}Al ratio of ~5×10^{-5} and suggests that the wadalite-grossular paragenesis in AJEF formed >2.6 Myr after crystallization of the CAI. The well-defined ^{26}Al-^{26}Mg chronology, for both primary and secondary minerals within AJEF place important constraints on the origin of ^{36}Cl. If ^{36}Cl was produced together with ^{26}Al, the late formation of wadalite inferred from the low $(^{26}Al/^{27}Al)_0$ ratio in cogenetic grossular, would require an unrealistically high initial ^{36}Cl/^{35}Cl ratio of $>8.7\times10^{-3}$ at the time the primary CAI mineral assemblage crystallized. This value is more than sixty times the maximum level that can be produced by SEP irradiation of gas and/or dust of solar composition [5, 6]. This suggests that production of ^{36}Cl by SEP irradiation must have occurred late, >2 Myr after the formation of the first solar system solids and provides the first conclusive evidence that ^{36}Cl found in secondary, low temperature minerals in CAIs and chondrules was produced in processes unrelated to those responsible for the SLRs (^{26}Al, ^{41}Ca, ^{10}Be) observed in primary, high temperature minerals in the same objects.

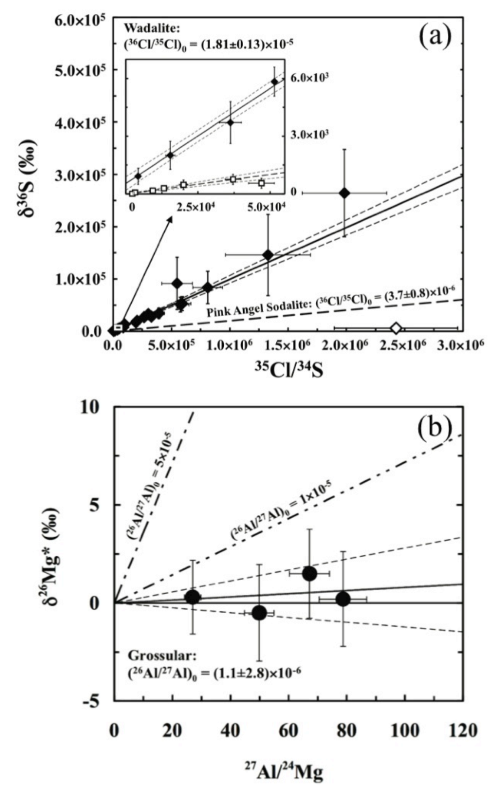

Fig. 1. (a) ^{36}Cl-^{36}S isochron diagram of wadalite from the Allende CAI AJEF (solid diamonds). The dashed line the inferred $(^{36}Cl/^{35}Cl)_0$ ratio for sodalite (open squares) from the Allende CAI Pink Angel [10]. Terrestrial wadalite is shown as open diamond. (b) ^{26}Al-^{26}Mg isochron diagram for grossular in the Allende CAI AJEF. The uncertainties in both panels (a) and (b) and inset are 2σ.

Production of SLRs during late-stage irradiation: Assuming *late-stage* irradiation of a reservoir with solar composition and a particle fluence sufficient to produce ^{36}Cl corresponding to the inferred $^{36}Cl/^{35}Cl$ ratio in wadalite ($\sim 2\times10^{-5}$), we use the approach of [5−7] to estimate relative abundances of co-produced ^{26}Al, ^{53}Mn and ^{10}Be. The range in predicted abundances reflects different assumptions among the models regarding production cross-sections, $^{3}He/H$ and $^{3}He/^{4}He$ ratios of SEP, hardness of the energy spectrum, and the relative importance of gradual to impulsive SEP events. The abundances of the three SLRs are compared against observed abundances in bulk meteorites [13, 14; Fig. 2]. In nearly all cases, the amounts of ^{26}Al and ^{53}Mn produced by SEP irradiation of a solar composition reservoir are significantly greater than the values observed in bulk meteorites, and an irradiation model accounting for ^{36}Cl, ^{26}Al and ^{53}Mn in a self-consistent manner is difficult to achieve. Only in the case of an extremely hard SEP spectra, $p \geq 5$, where p is the spectral exponent of the SEP power law [6], is a self-consistent solution achievable (Fig. 2). If the initial ^{36}Cl abundance, however, was any higher than the assumed value ($^{36}Cl/^{35}Cl > 2\times10^{-5}$), the problem will be exacerbated. The ^{36}Cl abundance assumed for the SLR abundance calculations is likely a lower limit for the amount produced by a late irradiation. Thus, ^{36}Cl production by late-stage SEP irradiation of a reservoir with solar composition would very likely overproduce both ^{26}Al and ^{53}Mn (Fig. 2) .

Late-stage irradiation of a volatile-rich reservoir: Overproduction of ^{26}Al and ^{53}Mn can be avoided if the reservoir irradiated to produce ^{36}Cl was depleted in refractory elements (enriched in volatile elements) relative to solar composition due to CAI and chondrule formation. In particular, irradiation of a reservoir enriched in chlorine – a primary target element for SEP production of ^{36}Cl – would significantly enhance the production of ^{36}Cl relative to ^{26}Al and ^{53}Mn. During the lifetime of the protoplanetary disk, chlorine is present mainly as HCl gas and will condense as solid HCl hydrates ($HCl\bullet 3H_2O$) when temperatures fall below ~160 K and may adhere to mineral grains and water ice particles [15]. Solar energetic particle irradiation of either an HCl-rich gas or dust particles mantled by HCl hydrates would significantly enhance the production of ^{36}Cl relative to ^{26}Al and ^{53}Mn.

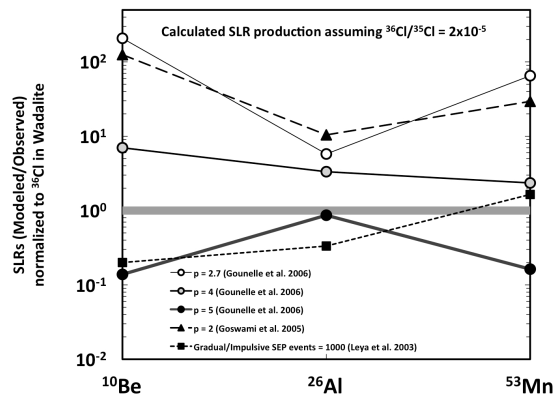

Fig. 2. Ratio of calculated to observed abundances of ^{10}Be, ^{26}Al, and ^{53}Mn assuming a particle fluence sufficient to produce ^{36}Cl corresponding to ($^{36}Cl/^{35}Cl$) = 2×10^{-5}. The calculated ^{26}Al and ^{53}Mn abundances are normalized to the inferred upper limits of ^{26}Al and ^{53}Mn abundances for bulk meteorite [13, 14]. As there are no constraints on the ^{10}Be abundance in bulk meteorites the calculated abundance for ^{10}Be is normalized to the inferred solar initial value.

Since oxygen is the primary target element, ^{10}Be will be co-produced with ^{36}Cl in any late SEP irradiation scenario. The most sensitive test for the late addition of ^{10}Be is determination of boron-isotope abundances in late-forming secondary phases in CAIs or chondrules (e.g., wadalite or grossular). On the basis of the model presented here, we predict $^{10}Be/^{9}Be$ ratios exceeding 10^{-4} will be found.

References: [1] McKeegan K. D. & Davis A. M. (2003) *in Treatise on Geochemistry, Vol. 1, ed. H. D. Holland, K. K. Turekian, & A. M. Davis (Amsterdam: Elsevier)*, 431. [2] Wasserburg G. J. et al. (2006) *Nuclear Phys. A.*, 777, 5–69. [3] Huss G. R. et al. (2009) *GCA*, 73, 4922–4945. [4] Shu F. H. et al. (2001) *ApJ*, 548, 1029–1050. [5] Leya I. et al. (2003) *ApJ*, 594, 605–616. [6] Gounelle M. et al. (2006) *ApJ*, 640, 1163–1170. [7] Goswami J. N. et al. (2001) *ApJ*, 549, 1151– 1159. [8] Lin Y. et al. (2005) *PNAS*, 102, 1306–1311. [9] Hsu W. et al. (2006) *ApJ*, 640, 525–529. [10] Ushikubo T. et al. (2007) *Meteoritics & Planet. Sci.*, 42, 1267 – 1279. [11] Jacobsen B. et al. (2011) *ApJ*, 731, L28. [12] Jacobsen B. et al. (2008) *EPSL*, 272, 353–364. [13] Thrane K. et al. (2006) *ApJ*, L159–L162. [14] Moynier F. et al. (2007) *ApJ*, 671, L181–L183. [15] Zolotov M. Y. & Mironenko M. V. (2007) *LPS XXXVIII*, # 2340.

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