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Presolar Grains as Probes of Type II Supernova Nucleosynthesis

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Presolar grains, submicron- to micron-sized meteoritic particles, originate from stellar winds and the ejecta of stellar explosions, providing direct samples of stellar material. Among these, silicon carbide (SiC) grains are particularly well-studied. Multielement isotope analyses of presolar SiC grains have firmly linked their origins to asymptotic giant branch (AGB) stars and core-collapse Type II supernovae (CCSNe) [1]. While AGB stars account for the majority of presolar SiC grains (>90%), CCSNe contribute a smaller fraction, including X, C, and D grains [1,2]. Additionally, all presolar silicon nitride (Si_3N_4) grains exhibit isotopic similarities to X SiC grains, indicating a shared origin in CCSN ejecta [2].

In this study, we conducted a comprehensive survey of isotope ratios (C, N, Si, Mg, S, Ca, Ti, Fe, and Ni) in presolar CCSN SiC and Si_3N_4 grains extracted from the Murchison meteorite using secondary ion mass spectrometry. High spatial resolution (~100–200 nm) imaging enabled the suppression of contamination and the extraction of intrinsic isotopic signatures [3,4]. Our dataset includes: (i) C, N, Si isotope and initial 26Al/27Al data from 39 X and one C SiC grain, as well as four Si_3N_4 grains [4]; (ii) initial 32Si/28Si ratios from two X grains and the C grain [5]; (iii) Ca isotope data from all four Si_3N_4 grains and the C grain [6]; (iv) Ti isotope data from 25 X grains [7]; and (v) Fe and Ni isotope data from 19 X grains and the C grain. The initial 26Al/27Al and 32Si/28Si ratios assume that 26Mg and 32S excesses, relative to terrestrial Mg and S isotope ratios, are the result of in situ 26Al (t1/2 = 0.72 Ma) and 32Si (t1/2 = 150 a) decay, respectively.
These data reveal several key findings: (i) anti-correlated 26Al/27Al and 30Si/28Si ratios in X and Si_3N_4 grains [4]; (ii) significant 46Ca excesses in the C and Si_3N_4 grains; (iii) the initial presence of 63Ni (t1/2 = 100 a) in C and X grains; and (iv) contrasting Ni isotopic patterns between C and X grains. The Ti isotope data for X grains align with previous findings and suggest that 49V (t1/2 = 330 d) fully decayed to 49Ti before grain condensation [8], thus supporting their late formation in CCSN remnants post-explosion.

We compared our results with CCSN model predictions [9,10], as well as with an analytic model for neutron bursts in the He/C zone [11] that allows for rapid testing of uncertainties in (n,γ) cross sections and stellar parameters. Our data-model comparisons indicate that X and C SiC and Si_3N_4 grains sampled material from at least the He/C, Si/S, and Fe/Ni zones of their parent CCSNe, reflecting nucleosynthesis products from large-scale, selective mixing across CCSN shells [2]. The multielement data require higher-than-solar Ti/Si, Ca/Si, and Ni/Si ratios in the 28Si-rich Fe/Ni zone, challenging the proposal of local mixing across the He shell in [12]; the model of [12] predicts the presence of a 28Si-rich C/Si zone at the bottom of the He shell that is produced by alpha captures at an unusually high density and temperature. Furthermore, the contrasting Ni isotopic patterns between C and X grains require that C grains originated from more energetic CCSNe, ruling out the hypothesis that C and X grains came from the same or similar CCSNe but C grains sampled lower proportions of material from the Si/S and Fe/Ni zones than X grains.

In conclusion, our multielement isotope dataset provided stringent constraints on the nucleosynthetic processes produced by neutron bursts, nuclear statistical equilibrium, and alpha-rich freezeouts in CCSNe. However, due to significant uncertainties in the (n,γ) cross sections of 32Si, 41Ca, and 45Ca, new nuclear experiments are needed to refine model predictions and further elucidate the large-scale mixing processes in the parent CCSNe of these grains.

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Author: LIU, Nan (Boston University)

Co-authors: Ms JAIN, Ananya (Boston University); Dr MEYER, Bradley (Clemson University); Dr ALEXANDER, Conel (Carnegie Institution for Science); Dr WANG, Jianhua (Carnegie Institution for Science); Mr WALLS, Lucas (Clemson University)

Presenter: LIU, Nan (Boston University)

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