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Magnesium and ^{54}Cr isotope compositions of carbonaceous chondrite chondrules – Insights into early disk processes

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Abstract

We report on the petrology, magnesium isotopes and mass-independent $^{54}Cr/^{52}Cr$ compositions ($\mu^{54}Cr$) of 42 chondrules from CV (Vigarano and NWA 3118) and CR (NWA 6043, NWA 801 and LAP 02342) chondrites. All sampled chondrules are classified as type IA or type IAB, have low $^{27}Al/^{24}Mg$ ratios (0.04–0.27) and display little or no evidence for secondary alteration processes. The CV and CR chondrules show variable $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg$ values corresponding to a range of mass-dependent fractionation of ~500 ppm (parts per million) per atomic mass unit. This mass-dependent Mg isotope fractionation is interpreted as reflecting Mg isotope heterogeneity of the chondrule precursors and not the result of secondary alteration or volatility-controlled processes during chondrule formation. The CV and CR chondrule populations studied here are characterized by systematic deficits in the mass-independent component of ^{26}Mg ($\mu^{26}Mg^*$) relative to the solar value defined by CI chondrites, which we interpret as reflecting formation from precursor material with a reduced initial abundance of ^{26}Al compared to the canonical $^{26}Al/^{27}Al$ of $\sim 5 \times 10^{-5}$. Model initial $^{26}Al/^{27}Al$ values of CV and CR chondrules vary from $(1.5 \pm 4.0) \times 10^{-6}$ to $(2.2 \pm 0.4) \times 10^{-5}$. The CV chondrules display significant $\mu^{54}Cr$ variability, defining a range of compositions that is comparable to that observed for inner Solar System primitive and differentiated meteorites. In contrast, CR chondrites are characterized by a narrower range of $\mu^{54}Cr$ values restricted to compositions typically observed for bulk carbonaceous chondrites. Collectively, these observations suggest that the CV chondrules formed from precursors that originated in various regions of the protoplanetary disk and were then transported to the accretion region of the CV parent asteroid whereas CR chondrule predominantly formed from precursor with carbonaceous chondrite-like $\mu^{54}Cr$ signatures. The observed $\mu^{54}Cr$ variability in chondrules from CV and CR chondrites suggest that the matrix and chondrules did not necessarily formed from the same reservoir. The coupled $\mu^{26}Mg^*$ and $\mu^{54}Cr$ systematics of CR chondrules establishes that these objects formed from a thermally unprocessed and ^{26}Al-poor source reservoir distinct from most inner Solar System asteroids and planetary bodies, possibly located beyond the orbits of the gas giants. In contrast, a large fraction of the CV chondrules plot on the inner Solar System correlation line, indicating that these objects predominantly formed from thermally-processed, ^{26}Al-bearing precursor material akin to that of inner Solar System solids, asteroids and planets.

Keywords: Carbonaceous chondrites; Chondrules; Magnesium; Chromium; Isotopes; Protoplanetary disk; Mass transport

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1. INTRODUCTION

Chondritic meteorites are sedimentary rocks that represent fragments of undifferentiated asteroids that accreted during the first few million years of Solar System formation and are chemically similar to the non-volatile composition of the Sun (Wood, 1988). Thus, these primitive asteroidal bodies provide direct information on the formation and earliest evolution of the Sun and its protoplanetary disk. The major constituent of most chondrites are chondrules, millimeter-sized inclusions that were once molten in the protoplanetary disk and accumulated in the disk mid-plane together with several other kinds of particles, including low temperature components. Chondrules are mainly composed of olivine and pyroxene minerals, which crystallized within minutes to days between ~1300 and ~1800 K (Scott, 2007). These silicate minerals are also the main constituents of the fine-grained matrix that mantles chondrules and other chondritic inclusions and fills the space between them in chondrites (Scott and Krot, 2005). Chondrite meteorites and, by extension, their chondrules and matrix are believed to represent the building blocks of rocky planets. Therefore, the collisional growth of submicron dust particles into macroscopic chondrules represents the first step of planet formation in protoplanetary disks.

Judging by their sheer abundance in chondrite meteorites, chondrules must reflect one of the most energetic processes that operated in the early Solar System. Several heat sources have been proposed for the thermal processing of chondrule precursors, including shock waves (Boss and Graham, 1993; Connolly and Love, 1998; Hood, 1998; Connolly et al., 2006), current sheets (Joung et al., 2004), x-winds (Shu et al., 1997), magnetized disk winds (Salmeron and Ireland, 2012) and colliding planetesimals (Asphaug et al., 2011; Sanders and Scott, 2012). Based on the short-lived ^{26}Al-^{26}Mg chronometer (half-life of 730,000 years), it has long been accepted that chondrule formation began ~2 Myr after condensation of the Solar Systems first solids, calcium-aluminum-rich inclusions, CAIs (MacPherson et al., 1995; Kurahashi et al., 2008; Villeneuve et al., 2009; Kita and Ushikubo, 2012). However, a recent absolute chronology of chondrules based on U-corrected Pb–Pb dating, indicates formation ages ranging from 4567.32 ± 0.42 to 4564.71 ± 0.30 Myr (Connelly et al., 2012) for chondrules from Allende and NWA 5697 chondrites. These data refute the long-held view of an age gap between CAIs and chondrules and, instead, establish that chondrule formation started contemporaneously with CAIs and lasted ~3 Myr. Therefore, chondrules represent time sequenced samples that allow us to probe the nature and isotopic evolution of the material that accreted to form asteroids and, ultimately, planetary bodies.

Large-scale nucleosynthetic isotopic heterogeneity exists among inner Solar System solids, planets, and asteroids, most noticeably for neutron-rich isotopes of the iron-group elements such as, for example, ^{48}Ca, ^{50}Ti, ^{54}Cr and ^{62}Ni (Papanastassiou and Brigham, 1989; Thrane et al., 2008; Holst et al., 2013; Trinquier et al., 2007, 2009; Larsen et al., 2011; Regelous et al., 2008; Schiller et al., 2015a). This variability is interpreted as reflecting un-mixing of nucleosynthetic components during the earliest stages of Solar System formation (Trinquier et al., 2009; Schiller et al., 2015a). Thus, variations in the abundance of stable nuclides such as ^{54}Cr within the inner Solar System can be used to track genetic relationships between early-formed solids and their respective reservoirs. Based on a limited dataset, Trinquier et al. (2009) identified correlated ^{46}Ti and ^{50}Ti nucleosynthetic variability in chondrules from the Allende CV3 chondrite, defining both excesses and deficits compared to the terrestrial composition. Similarly, Connelly et al. (2012) documented ^{54}Cr variability in individual Allende chondrules as well as chondrules from the NWA 5697 ordinary chondrite. At face value, these results indicate that chondrules formed from isotopically heterogeneous precursor material. Chondrule formation thus occurred in different regions of the protoplanetary disk prior to the transport of these objects to the accretion regions of their respective parent bodies. As such, unraveling the extent of nucleosynthetic isotope heterogeneity within chondrule populations is critical to understand whether these objects regulate the level of isotope heterogeneity observed among the inner Solar System asteroidal and planetary bodies.

Recent high-precision Mg isotope measurements of inner Solar System materials demonstrate the existence of variability in the mass-independent ^{26}Mg composition (μ^{26}Mg*) of bulk Solar System reservoirs with solar or near-solar Al/Mg ratios, which has been interpreted as reflecting heterogeneity in the initial abundance of ^{26}Al (^{26}Al decays to ^{26}Mg with a half life of ~730,000 years) across the solar protoplanetary disk at the time of CAI formation (Larsen et al., 2011). This interpretation has been challenged in some recent studies (Kita and Ushikubo, 2012; Wasserburg et al., 2012; Kita et al., 2013), arguing that the μ^{26}Mg* variability predominately reflects Mg isotope heterogeneity. In spite of this debate, an important observation is that the μ^{26}Mg* variability identified by Larsen et al. (2011) resonate with excesses and deficits in ^{54}Cr for the same samples or reservoirs. Correlated variability for nuclides of distinct nucleosynthetic origins has been interpreted as reflecting selective thermal processing of diverse presolar components (Trinquier et al., 2009; Paton et al., 2013). Thus, linking the μ^{26}Mg* and μ^{54}Cr compositions of individual chondrules may allow us to probe the scale of the correlated variability defined by bulk Solar System reservoirs. Moreover, the ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg ratios can be fractionated in a predictable manner during condensation and evaporation processes in the solar protoplanetary disk. As such, coupled magnesium isotope and μ^{54}Cr measurements of individual chondrules can be used to identify genetic relationships between early formed solids and asteroidal bodies as well as track the formation history of chondrule precursors.

In this paper, we report the petrology and mineral chemistry as well as the Mg and Cr isotope compositions of 42 chondrules from various CR2 and CV3 chondrites. CR chondrites are considered as one of the most primitive classes of meteorites, having experienced only mild aqueous alteration and no evidence for significant effects of thermal metamorphism (Briani et al., 2013). Our samples of CR