INSIGHTS INTO EARLY SOLAR SYSTEM MIXING DYNAMICS FROM CHROMIUM AND TITANIUM ISOTOPE ANOMALIES IN INDIVIDUAL CHONDRULES. J.M. Schneider[1*], C. Burkhardt[1], G.A. Brennecka[1] and T. Kleine[1], [1]Institut für Planetologie, University of Münster, 48149 Münster, Germany, (j.m.schneider@uni-muenster.de)

Introduction: Nucleosynthetic isotope anomalies in meteorites and their components are powerful tracers of genetic relationships among planetary materials and provide key constraints on dynamic processes in the solar nebula [1]. For instance, the Cr and Ti isotopic compositions of bulk meteorites define two distinct clusters [2], distinguishing between non-carbonaceous (NC) and carbonaceous (CC) meteorites, which likely represent material that initially formed inside and outside Jupiter's orbit [3,4].

Whereas the isotopic variability among bulk meteorites is well documented for several elements, little is known about isotope anomalies among components of primitive meteorites, and how they relate to the anomalies in bulk meteorites. Of the meteorite components, chondrules are arguably the most important, as they represent up to 90% of the material in bulk chondrites and may have been the most abundant solids in the early solar nebula [5]. Determining the extent and origin of isotope anomalies in chondrules is therefore key for understanding the origin of the anomalies in bulk meteorites and for constraining mixing and transport processes in the early Solar System.

As of now, isotope anomaly data for individual chondrules are sparse, and usually restricted to a single element. For instance, prior studies reported ^{54}Cr [6] and ^{50}Ti [7] variations among individual chondrules, but until now no study reported combined Cr-Ti isotopic data obtained on the very same samples. However, such combined isotopic data are critical for understanding the origin of the isotope anomalies, because different elements reflect the heterogeneous distribution of distinct carriers that may have affected chondrule precursors differently.

We present ^{54}Cr data for individual chondrules from enstatite, ordinary, and carbonaceous (CV, CR) chondrites. The exact same chondrules were previously investigated for Ti isotopes [7]. The combined Cr-Ti isotopic data are used to address the spatial distribution and cause of Ti and Cr isotope anomalies in meteoritic and planetary materials, with the ultimate goal to constrain global features of nebular dynamics during the earliest stages of Solar System formation.

Methods: Chromium was separated and purified using a three-stage ion exchange chromatography procedure modified from [8]. The Cr isotopic measurements were performed using a ThermoFisher Triton *Plus* at the Institut für Planetologie in Münster. Samples were loaded on 1-3 filaments and each filament was measured multiple times if possible. Instrumental mass fractionation was corrected assuming a terrestrial ^{50}Cr/^{52}Cr = 0.051859 and using the exponential law [9,10]. The data are reported in ε^{54}Cr values as the parts-per-10,000 deviation from the value measured for the terrestrial NIST SRM3112a Cr standard.

Results: The Cr isotopic data of the analyzed bulk meteorites and terrestrial rock standards are indistinguishable from literature values [11,12], attesting to the accuracy of our analytical procedure. The ε^{54}Cr values of chondrules from ordinary and enstatite chondrites exhibit only limited variations and are indistinguishable from the values measured for their respective host meteorites. By contrast, and consistent with [6], chondrules from CV and CR chondrites display variable ε^{54}Cr with values ranging from ~0 up to ~1.5 (Fig. 1). In contrast to ε^{50}Ti and Ti concentrations reported in [7], the CV and CR chondrules show no correlation between ε^{54}Cr and Cr concentration.

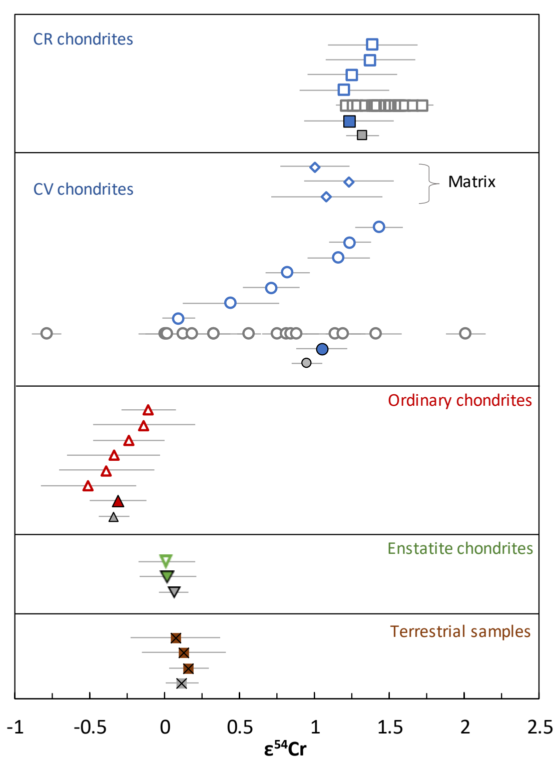

Fig. 1. ε^{54}Cr data for individual chondrules (open symbols) and bulk samples (filled symbols). Literature data are shown in grey for comparison [6,11,12].

Discussion: The combined Cr-Ti isotopic data confirm the fundamental dichotomy between the NC and CC reservoirs in the sense that NC and CC chondrules show disparate isotope systematics. Whereas NC chondrules display very limited isotopic variability and plot within the field of bulk NC meteorites, CC chondrules cover a much wider range of compositions and plot above and below the field of bulk CC meteorites (Fig.2). In the following, we explore how these observations can be used to obtain information on small-scale and large-scale mixing in the early solar nebula.

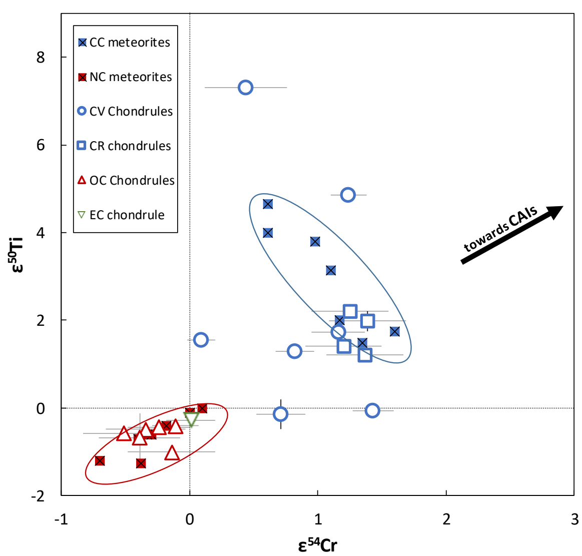

Fig. 2. ε^{54}Cr versus ε^{50}Ti for individual chondrules (open symbols) and bulk meteorites (filled symbols). The ε^{50}Ti data are from [7]; bulk meteorite data from [2]. The isotopic composition of CAIs clusters at~6.5 [13] in ε^{54}Cr and ranges from ~4 to ~9 in ε^{50}Ti [7].

An important observation from Fig. 2 is that the ^{50}Ti and ^{54}Cr variations among CC chondrules are decoupled (Fig. 2). Whereas the Ti isotopic variations among CC chondrules are attributable to the heterogeneous admixture of CAIs or CAI-like refractory material to the chondrules [7], their Cr isotopic composition is not affected by this process. This is because Cr is not refractory and is depleted in CAIs relative to chondrules. As such, even though CAIs have ε^{54}Cr anomalies of ~6.5 [13], their admixture to chondrules does not markedly change the chondrule's ε^{54}Cr. Consequently, the ε^{54}Cr variations among chondrules reflect the heterogeneous distribution of another carrier than the variations in ε^{50}Ti.

Presolar ^{54}Cr-rich nanospinels identified in primitive meteorites are a potential carrier of the ε^{54}Cr variations in meteoritic materials [14,15]. However, mass balance considerations show that to account for the observed ε^{54}Cr variation among CC chondrules, the number of these grains in individual chondrules would have to vary by tens of thousands of grains. This is highly unrealistic in terms of nebular dynamics and the overall rarity of such grains in meteorites.

A key observation from the ε^{54}Cr versus ε^{50}Ti plot is that the CC field is intermediate between the NC field and CAIs (Fig. 2). Thus, addition of bulk material with an isotopic composition similar to that measured for CAIs readily accounts for the isotopic composition of the CC reservoir [3,7], and by extension also for the ε^{54}Cr and ε^{50}Ti variations among CC chondrules. In this view, CAIs represent the high-T refractory component of an isotopically anomalous reservoir, whereas non-refractory elements (*e.g.*, Cr) reside in other phases, which nevertheless have the same isotopic composition than CAIs (*i.e.*, ε^{54}Cr ~6.5). The ε^{54}Cr variability among CC chondrules is then caused by the heterogeneous distribution (at the chondrule precursor scale) of non-refractory material with a CAI-like isotopic composition, whereas the ε^{50}Ti variations reflect the heterogeneous distribution of CAIs themselves. In other words, the ε^{54}Cr and ε^{50}Ti variations among chondrules trace heterogeneities within the same dust reservoir, where ε^{50}Ti traces the refractory part of this material, while ε^{54}Cr traces its non-refractory part. Because Ti and Cr are hosted in different carriers of this dust reservoir, the ε^{54}Cr and ε^{50}Ti variations among the chondrules are decoupled, reflecting different proportions of the Ti and Cr carriers in the precursors of each chondrule.

Overall our findings demonstrate that, compared to NC chondrites, CC chondrites contain a higher proportion of nebular material with a CAI-like isotopic composition. Mixing between this material and material with an NC-like isotopic composition ultimately led to formation of the CC reservoir [3,7]. As such, CC chondrules provide a record of this mixing, by preserving isotopic signatures of the dust components that have been mixed to produce the isotopic dichotomy observed among bulk meteorites.

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