Electronic Annex:

The relationship between CM and CO chondrites: Insights from combined analyses of titanium, chromium, and oxygen isotopes in CM, CO, and ungrouped chondrites

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Supplementary Table EA1. The ε^{46}Ti, ε^{48}Ti, and ε^{50}Ti isotope compositions of the meteorite samples studied here, as well as of the BCR-2 terrestrial rock standard run during the same analytical sessions. The reported error is either the internal error (2SE) based on the number of analyses (n) of each sample solution or the external reproducibility (2SD), whichever is larger.

Meteorite	Classification	ε^{46}Ti	ε^{48}Ti	ε^{50}Ti	n
EET 83226	C2-ung	0.41 ± 0.17	–0.01 ± 0.07	4.25 ± 0.15	6
EET 83355	C2-ung	0.50 ± 0.17	0.00 ± 0.07	3.11 ± 0.15	3
MAC 87300	C2-ung	0.53 ± 0.17	–0.03 ± 0.08	4.67 ± 0.15	3
NWA 5958	C2-ung	0.37 ± 0.09	–0.01 ± 0.07	3.34 ± 0.15	5
LEW 85332	C3-ung	0.33 ± 0.17	–0.05 ± 0.07	2.42 ± 0.15	3
MAC 88107	C3-ung	0.32 ± 0.17	0.04 ± 0.07	3.03 ± 0.15	6
MAC 87301	C3-ung	0.59 ± 0.17	0.07 ± 0.07	4.12 ± 0.15	3
Coolidge	C4-ung	0.33 ± 0.17	–0.04 ± 0.07	2.67 ± 0.15	6
LAP 04757	Chondrite-ung	–0.13 ± 0.17	0.00 ± 0.07	–0.19 ± 0.15	1
LAP 04773	Chondrite-ung	–0.28 ± 0.17	–0.03 ± 0.07	–0.54 ± 0.15	3
GRO 95566	CM-an	0.47 ± 0.17	–0.02 ± 0.07	3.50 ± 0.15	3
Aguas Zarcas A[1]	CM2	0.30 ± 0.17	–0.15 ± 0.07	2.21 ± 0.18	6
Aguas Zarcas B[1]	CM2	0.25 ± 0.17	–0.06 ± 0.07	2.86 ± 0.23	6
Murchison	CM2	0.17 ± 0.17	–0.07 ± 0.07	2.81 ± 0.15	5
Murray	CM2	0.23 ± 0.17	0.00 ± 0.07	2.67 ± 0.15	6
Isna	CO3.8	0.33 ± 0.17	0.00 ± 0.08	2.83 ± 0.15	6
BCR-2	Ter. Std.	–0.13 ± 0.17	0.02 ± 0.07	–0.04 ± 0.15	5
BCR-2	Ter. Std.	–0.09 ± 0.17	0.03 ± 0.07	–0.03 ± 0.17	6

[1] Aguas Zarcas A is from the less altered lithology and Aguas Zarcas B is from the more altered lithology.

Supplementary Table EA2. The ε^{53}Cr and ε^{54}Cr isotope compositions of the meteorite samples studied here, as well as of the DTS-1 terrestrial rock standard and the Smithsonian Allende CV chondrite reference powder run during the same analytical sessions. The reported error is either the internal error (2SE) based on the number of analyses (n) of each sample solution or the external reproducibility (2SD), whichever is larger.

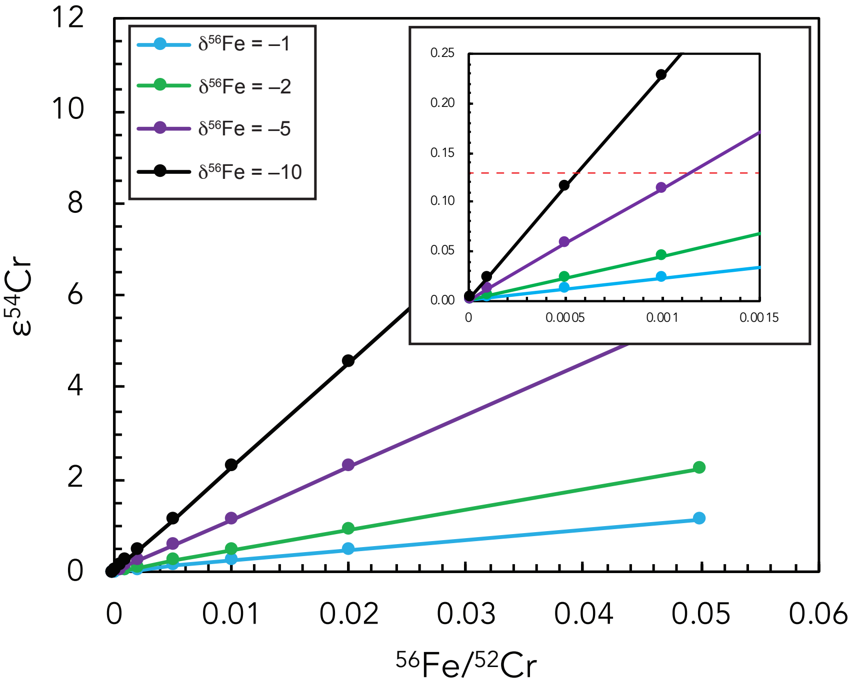
Meteorite	Classification	ε^{53}Cr	ε^{54}Cr	n
EET 83226	C2-ung	0.13 ± 0.07	0.93 ± 0.13	6
EET 83355	C2-ung	0.11 ± 0.07	0.76 ± 0.13	6
MAC 87300	C2-ung	0.04 ± 0.11	0.71 ± 0.14	6
NWA 5958	C2-ung	0.26 ± 0.07	1.18 ± 0.16	6
LEW 85332	C3-ung	0.18 ± 0.07	1.23 ± 0.13	6
MAC 88107	C3-ung	0.20 ± 0.07	1.11 ± 0.15	6
MAC 87301	C3-ung	0.09 ± 0.07	0.83 ± 0.14	6
Coolidge	C4-ung	0.01 ± 0.07	0.59 ± 0.13	6
LAP 04757	Chondrite-ung	0.17 ± 0.09	–0.33 ± 0.13	6
LAP 04773	Chondrite-ung	0.08 ± 0.09	–0.46 ± 0.16	6
GRO 95566	CM-an	0.13 ± 0.08	0.92 ± 0.13	3
Aguas Zarcas A[1]	CM2	0.22 ± 0.07	0.98 ± 0.13	6
Aguas Zarcas B[1]	CM2	0.20 ± 0.09	0.88 ± 0.13	6
Murchison	CM2	0.21 ± 0.07	1.10 ± 0.15	6
Murray	CM2	0.13 ± 0.07	0.84 ± 0.13	6
Isna	CO3.8	0.11 ± 0.08	0.66 ± 0.14	6
Allende	CV3	0.08 ± 0.07	0.87 ± 0.13	6
Allende	CV3	0.11 ± 0.07	0.94 ± 0.13	11
DTS-1	Ter. Std.	0.08 ± 0.07	0.06 ± 0.13	6

[1] Aguas Zarcas A is from the less altered lithology and Aguas Zarcas B is from the more altered lithology.

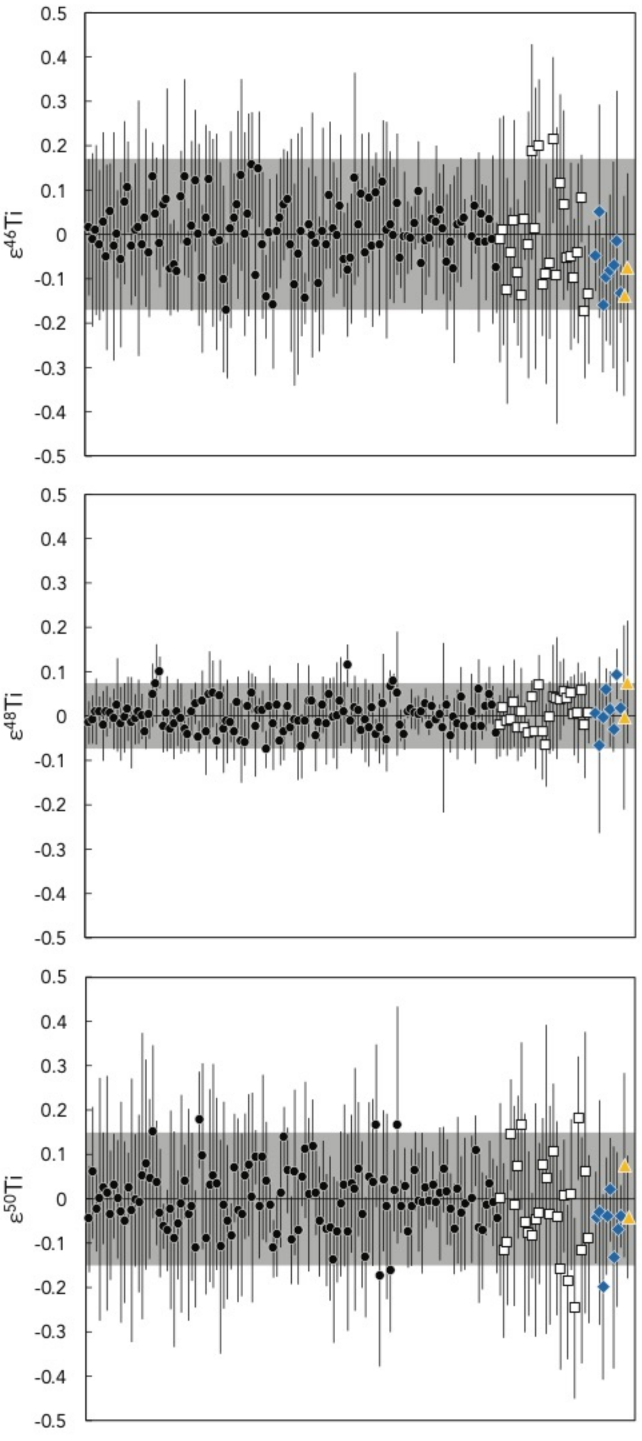
EA.1. Additional Cr Purification to Prevent Isobaric Interference Effects

In Fig. S1, we have shown the theoretical effect of isotopically mass-fractionated residual Fe (for δ^{56}Fe = –1, –2, –5, and –10 ‰) on measured ε^{54}Cr values following a typical Fe interference correction assuming unfractionated ^{56}Fe/^{54}Fe (i.e. δ^{56}Fe = 0 ‰) and an identical isotopic instrumental mass bias for Cr and Fe. Because the δ^{56}Fe of any residual Fe remaining in the sample after column chemistry is not directly measured, these theoretical calculations are for illustrative purposes only. It is therefore necessary to measure the Fe/Cr and ε^{54}Cr of rock standards of known isotopic composition to confirm the accuracy and precision of our methodology utilized here (including the chemical separation procedures and mass spectrometric methods) for Cr isotopic analyses.

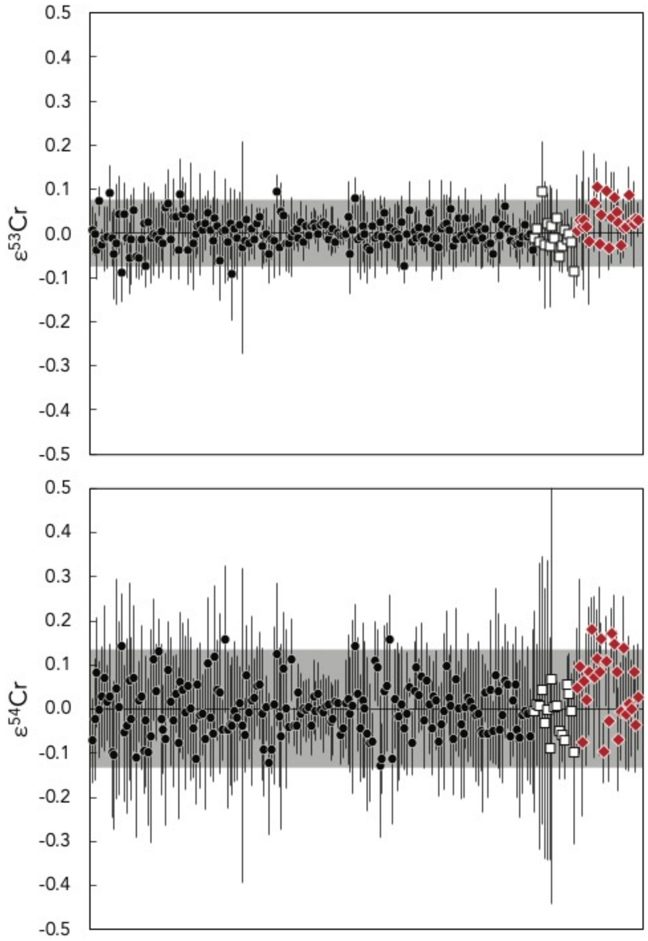
In order to verify that there was no effect on ε^{54}Cr because of isotopically mass-fractionated residual Fe, we measured the bulk unprocessed Fe/Cr ratios, post-chemistry Fe/Cr ratios, and ε^{54}Cr of the terrestrial rock standard DTS-1 and the Allende CV3 chondrite reference powder alongside the sample measurements. The bulk unprocessed Fe/Cr ratio was ~70 for the Allende reference powder and ~15 for DTS-1; the Fe/Cr was ~55-75 for the meteorite samples studied here. Using the theoretical calculations illustrated in Fig. 4 as a guide, we measured the Cr isotopic composition of the rock standards only when ^{56}Fe/^{52}Cr $< 5\times10^{-4}$ (measured via MC-ICPMS) was attained in the post-chemistry purified Cr solution. The average ε^{54}Cr value of DTS-1 measured in this study was 0.06 ± 0.13 (2SD), which is within error of zero. The ε^{54}Cr value for two separately processed aliquots of the Allende reference powder measured in this study were 0.87 ± 0.13 (2SD) and 0.94 ± 0.13 (2SD), which are in agreement with the average value of 0.89 ± 0.11 (2SD) from previous measurements in other laboratories (Shukolyukov and Lugmair, 2006; Trinquier et al., 2007; Qin et al., 2010; Williams et al., 2020). These data demonstrate that accurate ε^{54}Cr values are obtained for standards with bulk Fe/Cr ratios similar to those of the meteorite samples studied here and confirm that there is no effect on the measured ε^{54}Cr outside of the analytical uncertainty as a result of residual Fe when post-chemistry ^{56}Fe/^{52}Cr $< 5\times10^{-4}$ was achieved in these samples.



Supplementary Fig. EA1. Theoretical calculations of ε^{54}Cr versus ^{56}Fe/^{52}Cr show the potential effects of residual Fe on isotopic measurements of Cr via MC-ICPMS for varying degrees of isotopic fractionation of the residual Fe due to column chemistry procedures. Inset shows a magnification of the lower-left corner of the plot with red dashed line indicating the external reproducibility (2SD) of the ε^{54}Cr measurements.



Supplementary Fig. EA2. The external reproducibility (2SD) for ε^{46}Ti (± 0.17), ε^{48}Ti (± 0.07), and ε^{50}Ti (± 0.15), shown as gray bands, based on repeat analyses of NIST 3162a (black circles) and SPEX (white squares) Ti standard solutions and the geological reference materials BCR-2 (blue diamonds) and AGV-1 (orange triangles) analyzed in this study and by Torrano et al. (2019). All measurements shown here were acquired at the same intensities.



Supplementary Fig. EA3. The external reproducibility (2SD) for ε^{53}Cr (± 0.07) and ε^{54}Cr (± 0.13), shown as gray bands, based on repeat runs of NIST SRM 979 (black circles) and SPEX (white squares) Cr standard solutions and geological reference material DTS-1 (red diamonds). All measurements shown here were acquired at the same intensities.