NICKEL ISOTOPIC COMPOSITION OF RYUGU SAMPLES RETURNED BY THE HAYABUSA2 MISSION. F. Spitzer[1], C. Burkhardt[1], T. Kleine[1], the Hayabusa2-initial-analysis chemistry team, and the Hayabusa2-initial-analysis core, [1]Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany (spitzer@mps.mpg.de).

Introduction: The initial analyses of samples returned from Cb-type asteroid 162173 Ryugu by JAXA's Hayabusa2 mission provided isotopic, mineralogical, and chemical evidence for a close link of Ryugu to CI chondrites [1,2]. A subsequent study has shown that Ryugu and CI chondrites share the same nucleosynthetic Fe isotope signatures, which are distinct from those of other carbonaceous chondrites [3]. This not only demonstrates that Ryugu and CI chondrites are genetically linked, but also that they derive from another reservoir than all other carbonaceous chondrites [3].

Nickel isotopes hold considerable promise to further investigate the genetic link between Ryugu and CI chondrites. When normalized to $^{61}Ni/^{58}Ni$, CI chondrites display the largest $\mu^{62}Ni$ and $\mu^{64}Ni$ anomalies among carbonaceous chondrites (where $\mu^{i}Ni$ is the parts per 10^6 deviation from terrestrial standard values) and are characterized by distinct $\mu^{60}Ni$ values compared to all other carbonaceous chondrite-like materials. This makes Ni a key element to test whether Ryugu and CI chondrites are genetically linked and isotopically distinct from other carbonaceous chondrites.

Methods: We obtained four Ryugu samples (A0106 and A0106–A0107 from the first touchdown site, C0107 and C0108 from the second touchdown site) along with six carbonaceous chondrites including the CI chondrites Orgueil and Alais, which have been chemically processed alongside the Ryugu samples [2]. In addition, we also measured several grouped and ungrouped carbonaceous chondrites. Chemical purification of Ni involved a 3-step ion-exchange chromatographic procedure that achieves sufficiently low $^{58}Fe/^{58}Ni$ and $^{64}Zn/^{64}Ni$ ratios in the final purified Ni cuts to allow for accurate and precise correction of isobaric interferences [4,5]. The total yield of the chemical procedure typically is ~80–90 %. Total procedural blanks for the Ni separation and purification were <10 ng Ni and, hence, negligible given the amount of Ni analyzed. All isotope measurements were performed on the Thermo Scientific NeptunePlus MC-ICP-MS at the Institut für Planetologie, University of Münster. Instrumental mass bias is corrected by internal normalization to either $^{61}Ni/^{58}Ni$ or $^{62}Ni/^{61}Ni$ using the exponential law. All data are reported in $\mu^{i}Ni$ values.

Results: Our new Ni isotopic data for CM, CO, CV, and CR chondrites agree well with those reported in previous studies and reveal that these chondrites are characterized by negative $\mu^{60}Ni$ and positive $\mu^{62}Ni$ and $\mu^{64}Ni$ values (Fig. 1). The two ungrouped carbonaceous chondrites Tagish Lake (TL) and Tarda, for which no Ni isotopic data have been reported previously, have Ni isotope anomalies similar to those of carbonaceous

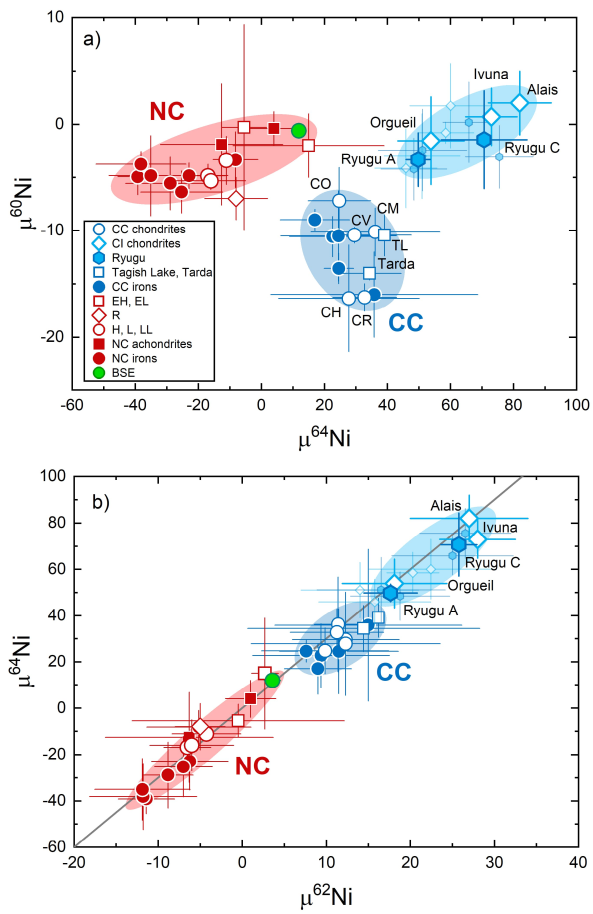

Figure 1: Diagrams of (a) $\mu^{60}Ni$ vs. $\mu^{64}Ni$ and (b) $\mu^{64}Ni$ vs. $\mu^{62}Ni$. Ni isotopic data normalized to $^{61}Ni/^{58}Ni$. CI chondrites and Ryugu have the largest ^{62}Ni and ^{64}Ni anomalies among carbonaceous chondrites, but unlike other carbonaceous chondrites show no resolved anomaly in $\mu^{60}Ni$. As a result, Ryugu/CI chondrites define a distinct compositional cluster in Ni isotope space. Small shaded diamonds and hexagons are different samples of Orgueil (N=4) and Ryugu A (N=2) and Ryugu C (N=2), respectively. The grey solid line in b) is the slope of ~3 defined by bulk meteorites [6]. Data are from this study and compiled from the literature [5–13].

chondrites. By contrast, CI chondrites have larger μ^{60}Ni, μ^{62}Ni, and μ^{64}Ni values compared to the other carbonaceous chondrites (Fig. 1). The Ni isotopic compositions of all four Ryugu samples overlap with those of the CI chondrites, where the two Ryugu A samples plot closely to Orgueil, whereas the two Ryugu C samples are more similar to Alais and Ivuna (Fig. 1).

Discussion: *Link between Ryugu and CI chondrites.* The new Ni isotopic data reveal that CI chondrites and Ryugu share the same Ni isotopic composition, which is distinct from all other carbonaceous chondrites (Fig. 1). In a plot of μ^{60}Ni versus μ^{64}Ni, Ryugu/CI chondrites define a distinct cluster that neither overlaps with any other CC chondrites nor with NC meteorites (Fig. 1). Thus, the Ni isotopic composition of Ryugu/CI chondrites is different from all other known meteoritic materials, indicating a distinct nucleosynthetic heritage of CI compared to other CC chondrites. This is consistent with the nucleosynthetic Fe isotope variations [3] as well as mass-dependent Cu and Zn isotope variations [14] among carbonaceous chondrites, which also reveal a uniquely distinct composition for CI chondrites and Ryugu. Together, these results indicate a distinct formation region of Ryugu/CI chondrites in the solar protoplanetary disk, likely at a larger heliocentric distance than those of other carbonaceous chondrites.

There are small Ni isotopic variations among different CI chondrites and Ryugu samples, where Orgueil and the Ryugu A samples exhibit smaller anomalies than Alais, Ivuna, and the two Ryugu C samples (Fig. 1). Since the Ryugu A and C samples are from two different touchdown sites, this suggests that these Ni isotope variations reflect heterogeneities at the sampling scale, which might be related to each sample's mineralogy.

Origin of isotope diversity among carbonaceous chondrites. Isotopic variations among carbonaceous chondrites are thought to reflect variable proportions of three main components having distinct isotopic compositions: refractory inclusions (e.g., CAI), chondrules/chondrule precursors, and CI chondrite-like matrix [15]. The incorporation of CI chondrite-like matrix in other groups of carbonaceous chondrites is consistent with systematic variations of (*i*) volatile element contents [15], (*ii*) mass-dependent isotope fractionations of moderately volatile elements [16,17], and (*iii*) nucleosynthetic ^{54}Cr anomalies [16] correlated with the fraction of matrix in each chondrite. However, in Ni isotope space, CI chondrites (and Ryugu) are offset from the composition of other carbonaceous chondrites, indicating that CI chondrites are not fully representative of the matrix in other groups of carbonaceous chondrites. Instead, this matrix appears to have formed from different precursor material than CI chondrites, either because it formed in a different area of the disk or because it was modified by processes in the disk prior to its incorporation in carbonaceous chondrites.

References: [1] Yada T. et al. 2022. Nat. Astron. 6:214–220. [2] Yokoyama T. et al. 2022. Science abn7850. [3] Hopp T. et al. 2022. Science Adv. 8:8141. [4] Render J. et al. 2018. Astrophys. J. 862:26. [5] Nanne J. A. M. et al. 2019. Earth Planet. Sci. Lett. 511:44–54. [6] Steele R. C. J. et al. 2012. Astrophys. J. 59:758. [7] Makhatadze G. V. et al. 2023. Geochim. Cosmochim. Acta 343:17–32. [8] H. Tang and N. Dauphas 2012. Earth Planet. Sci. Lett. 359–360:248–263. [9] H. Tang and N. Dauphas 2014. Earth Planet. Sci. Lett. 390:264–274. [10] C. Burkhardt et al. 2017. Meteorit. Planet. Sci. 52:807–826. [11] Steele R. C. J. et al. 2011. Geochim. Cosmochim. Acta 75:7906–7925. [12] Cook D. L. et al. 2020. Meteorit. Planet. Sci. 55:2758–2771. [13] Cook D. L. et al. 2021. Astrophys. J. 917:59. [14] Paquet M. et al. 2022. Nat Astron. doi: 10.1038/s41550-022-01846-1. [15] Alexander C. M. O'D. 2019. Geochim. Cosmochim. Acta 254:277–309. [16] J. L. Hellmann et al. 2020. Earth Planet. Sci. Lett. 549:116508. [17] Pringle E. A. et al. 2017. Earth Planet. Sci. Lett. 468:62–71.

The Hayabusa2 Initial Analysis Chemistry Team: Y. Abe, J. Aléon, C. M. O'D. Alexander, S. Amari, Y. Amelin, K. Bajo, M. Bizzarro, A. Bouvier, R. W. Carlson, M. Chaussidon, B.-G. Choi, N. Dauphas, A. M. Davis, T. Di Rocco, W. Fujiya, R. Fukai, I. Gautam, M. K., Haba, Y. Hibiya, H. Hidaka, H. Homma, P. Hoppe, G. R. Huss, K. Ichida, T. Iizuka, T. R. Ireland, A. Ishikawa, S. Itoh, N. Kawasaki, N. T. Kita, K. Kitajima, S. Komatani, A. N. Krot, M.-C. Liu, Y. Masuda, K. D. McKeegan, M. Morita, K. Motomura, F. Moynier, I. Nakai, K. Nagashima, D. Nesvorný, A. N. Nguyen, L. Nittler, M. Onose, A. Pack, C. Park, L. Piani, L. Qin, S. S. Russell, N. Sakamoto, M. Schönbächler, L. Tafla, H. Tang, K. Terada, Y. Terada, T. Usui, S. Wada, M. Wadhwa, R. J. Walker, K. Yamashita, Q.-Z Yin, T. Yokoyama, S. Yoneda, E. D. Young, H. Yui, H. Yurimoto, A.-C.

The Hayabusa2 Initial Analysis core: S. Tachibana, T. Nakamura, H. Naraoka, T. Noguchi, R. Okazaki, K. Sakamoto, H. Yabuta, H. Yurimoto, Y. Tsuda, S. Watanabe.