Insights into Early Solar System Isotopic Reservoirs Inferred from Ryugu

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Introduction: Returned primitive Solar System material presents a unique opportunity to address multiple important planetary science questions. Recent work has demonstrated that material returned from the Japan Aerospace Exploration Agency's (JAXA) Hayabusa2 mission from Cb-type asteroid (162173) Ryugu is most closely related to Ivuna-type (CI) carbonaceous chondrites [*e.g.*, 1-2], which have a chemical composition similar to that of the Sun's photosphere. The pristine nature and CI-like chemical composition of Ryugu samples allows researchers to use bulk-rock nucleosynthetic isotope anomalies to establish genetic relationships to planetary bodies and to refine our knowledge of the isotopic evolution of the Solar System, as well as the accretion history of the terrestrial planets [*e.g.*, 1-6].

The initial isotopic study of four Ryugu particles found it has an indistinguishable Fe isotope composition from CI chondrites—which is itself different from all other carbonaceous chondrites [2]. This led to the conclusion that a third isotopic reservoir may have existed in the early Solar System for CI and CI-like bodies to form separate from the carbonaceous and non-carbonaceous reservoirs. However, the existence of a third isotopic reservoir has recently been challenged through two different models [7-8], and those studies have shown that the isotopic dichotomy between carbonaceous and non-carbonaceous meteorites extends to Fe isotopes. These authors suggest that the appearance of an apparent third isotopic reservoir in the meteorite record reflects a lack of Fe isotope data from carbonaceous achondrites [8]. Here we report Fe and Ti isotopic analyses with the addition of Ni isotope compositions on a bulk sample from Ryugu to shed new light on the isotopic reservoirs present in the early Solar System.

Methods: Ryugu particle A0208, provided by JAXA, was analyzed in this study. This particle was part of a surface sample that was collected in Chamber A during the first touchdown of the Hayabusa2 spacecraft. Approximately 8 mg of Ryugu particle A0208 was weighed and dissolved in a pre-cleaned PFA vial using a combination of concentrated $HF:HNO_3$, followed by aqua regia. Two procedural blanks as well as the geostandards BCR-2 and BHVO-2 were processed alongside our Ryugu sample for all procedures. Following dissolution, we obtained major and trace element concentrations using a Thermo Scientific Element XR ICP-MS at Lawrence Livermore National Laboratory (LLNL) following previously published methods [9].

All samples were processed through multiple chemical separations to purify the elements of interest using previously established procedures. The first separation was to isolate Fe from the sample matrix [10] followed by purification of Ti [*e.g.*, 11] and Ni [*e.g.*, 12]. Yields of our procedures were >80% and the blanks were negligible considering the total amount of material processed for Fe, Ti, and Ni. Iron and Ni isotopic analyses were performed on a Thermo Scientific Neptune *Plus* MC-ICPMS at LLNL while Ti isotopes were measured on a Thermo Scientific Neoma MC-ICPMS at LLNL [*e.g.*, 2, 11-12].

Results and Discussion: Whereas the previously analyzed Ryugu particles were all around 25 mg or less [1-2], our particle A0208 weighed only 8 mg. Despite this difference and the limited masses in general, we observe that our Ryugu particle exhibits elemental concentrations comparable to what has been reported in previous work (Fig. 1). Shown in figure 1 are major and trace element concentrations obtained for particle A0208 against the average concentration data from the initial Ryugu study [1], demonstrating overall excellent agreement. A few small differences exist between the two works (the most notable being Be), which are readily explained by heterogeneities at these small sample scales (< 25 mg).

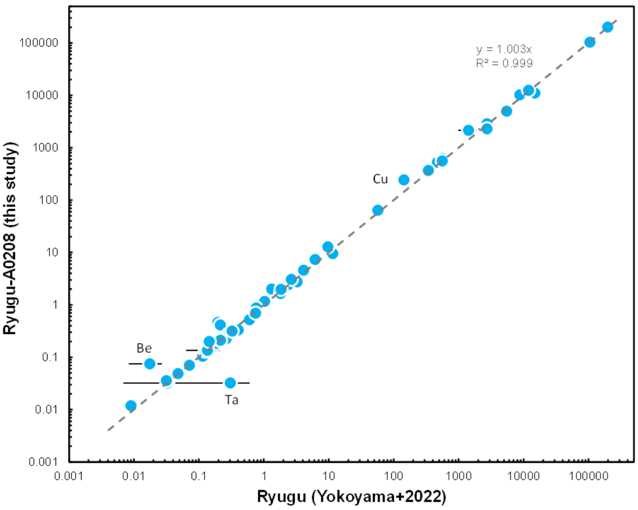

Figure 1. Major and trace element abundances of Ryugu A0208 particle of this work plotted against the average concentrations determined for Ryugu particles A0106, A0107, and C0108 from [1]. With a few exceptions, most elements are in good agreement between the two studies. Uncertainties for ICP-MS data from this study are estimated to be ±5%, whereas error bars shown for data from [1] are two standard deviations of the two ICP-MS measurements reported in that work.

Shown in Figure 2 are select Ti, Fe, and Ni isotope data commonly used for genetic comparison of meteoritic materials. Our measured Fe and Ti isotopic compositions are indistinguishable from other Ryugu particles as well as from CI chondrites [1-2]. The overlapping Fe and Ti isotopic compositions of our Ryugu particle with previous measurements indicate that sample heterogeneity is not a big concern for major elements analyzed here. Although specific values and uncertainties were not provided in [13], our Ni isotope data from Ryugu particle A0208 appear to be consistent with these previous Ni isotope measurements as well as CI chondrites (Fig. 2). This result offers further support to the interpretation that Ryugu is most closely related to CI chondrites [1-2, 13].

The new Ti, Fe, and Ni isotopic data obtained in this study demonstrate that Ryugu and CI chondrites may plot on a continuation of a trend defined by the carbonaceous chondrites. Previous studies have suggested that CI chondrites and Ryugu may have formed at greater heliocentric distances compared to other carbonaceous chondrites [*e.g.*, 2, 13-14] and our data are supportive of this interpretation given that Ryugu and CI chondrites are an endmember in the carbonaceous reservoir. While our data do not clearly provide evidence for the existence of a third isotopic reservoir in the early Solar System as previously suggested [2], this is not ruled out, either. Additional isotopic measurements are underway at LLNL for Cr and any finalized data and further interpretations will be reported at the meeting.

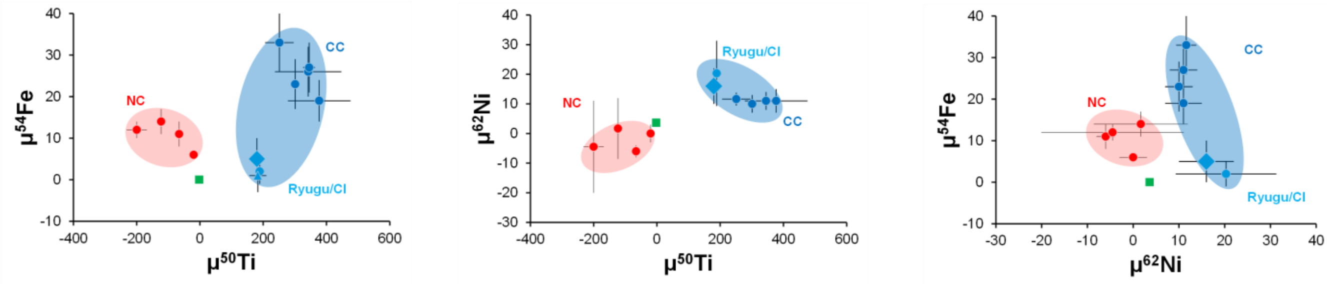

Figure 2. Plots of μ^{54}Fe vs. μ^{50}Ti, μ^{62}Ni vs. μ^{50}Ti, and μ^{54}Fe vs. μ^{62}Ni, where μ designates parts per million deviation from a terrestrial standard. Ryugu particle A0208 from this study is the large light blue diamond, previous Ryugu measurements are shown as a light blue triangle, average CI chondrite as a light blue circle, carbonaceous chondrites (CC) as dark blue circles, non-carbonaceous meteorites (NC) in red circles, and Earth as a green square. Iron and Ti isotopic data from [2]. Ni isotopic data compiled from [15-19].

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References

[1] Yokoyama T. et al. (2022) *Science* 10.1126/science.abn7850. [2] Hopp T. et al. (2022) *Science Advances* 8, eadd8141. [3] Fischer-Gödde M. & Kleine T. (2017) *Nature* 541, 525-527. [4] Burkhardt C. (2021) *Science advances* 7, eabj7601. [5] Schiller M. et al. (2020) *Science Advances* 6, eaay7604. [6] Burkhardt C. et al. (2019) *Geochimica et Cosmochimica Acta 261*, 145-170. [7] Marrocchi Y. et al. (2023) *The Astrophysical Journal Letters* 954, L27. [8] Yap T. & Tissot F.L.H. (2023) *Icarus* 405, 115680. [9] Wimpenny J. et al. (2022) *Earth & Planetary Science Letters* 578, 117318. [10] Rolison J. M. et al. (2019) *Applied Geochemistry* 103, 97-105. [11] Shollenberger Q. R. et al. (2022) *Geochimica et Cosmochimica Acta* 324, 44-65. [12] Render J. et al. (2018) *The Astrophysical Journal* 862, 26. [13] Spitzer F. et al. (2023) LPSC #2488. [14] Desch S.J. (2018) *The Astrophysical Journal* 238, 11. [15] Steele R.C.J. et al. (2012) *The Astrophysical Journal* 758,59. [16] Tang H. & Dauphas N. (2012) *Earth & Planetary Science Letters* 359-360, 248-263. [17] Tang H. & Dauphas N. (2014) *Earth & Planetary Science Letters* 390, 264-274. [18] Regelous M. et al. (2008) *Earth & Planetary Science Letters* 272, 330-338. [19] Burkhardt C. et al. (2017*) Meteoritics & Planetary Science* 52, 807-826.