THE INITIAL ABUNDANCE OF NIOBIUM-92 IN THE OUTER SOLAR SYSTEM. Y. Hibiya[1] T. Iizuka[1], and H. Enomoto[1], [1] Department of Earth and Planetary Science, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan (yuki-hibiya@eps.s.u-tokyo.ac.jp).

Introduction: The *p*-process radionuclide niobium-92 (^{92}Nb) decays to zirconium-92 (^{92}Zr) by electron capture with a half-life of 37 million years. The system is a promising chronometer for addressing the early solar system evolution and planetary differentiation [1, 2]. Thus, the initial abundance of ^{92}Nb and its distribution in the early solar system provide valuable constraints on the time-scale of our solar system evolution, and on the origin of *p*-process nucleosynthesis.

The initial ^{92}Nb abundance at the solar system formation was previously determined to be $(^{92}Nb/^{93}Nb)_0 = (1.7 \pm 0.6) \times 10^{-5}$, applying the internal isochron approach to NWA 4590 angrite (U–Pb age: 4557.93 ± 0.36 Ma) [2]. This value is consistent with those obtained using other meteorites (eucrites, ordinary chondrites, and mesosiderites [1, 3]). Recently, [4] obtained the highly precise initial ^{92}Nb abundance of $(^{92}Nb/^{93}Nb)_0 = (1.6 \pm 0.1) \times 10^{-5}$ using rutiles and zircons separated from several mesosiderites with a known absolute age. Although this is not the internal isochron from a single meteorite, the result is also consistent with the current canonical value of $(1.7 \pm 0.6) \times 10^{-5}$, indicating that ^{92}Nb was homogeneously distributed in the solar system. However, all samples previously studied for ^{92}Nb are thought to have originated from the inner solar system.

Here we report internal Nb-Zr isochron dating of the NWA 6704 achondrite that is considered to have originated from the outer solar system. Our results reveal that the initial abundance of ^{92}Nb in the outer solar system was distinctly higher than the value in the inner solar system. We discuss the implications of the finding for the early solar system chronology and the nucleosynthetic origin of ^{92}Nb.

Sample: Northwest Africa (NWA) 6704 is an achondrite having a fresh igneous texture and a broadly chondritic bulk composition [5]. The absolute crystallization age was determined by U–Pb dating to be 4562.76 ± 0.30 Ma [6]. This meteorite underwent melting above liquidus temperature and subsequent rapid enough cooling (> 10^{-1} °C/yr; [5]) to enable multiple isotopic systems to be closed within their time resolution. Δ^{17}O, ε^{50}Ti, ε^{54}Cr and ε^{84}Sr of NWA 6704 are consistent with those of carbonaceous chondrites [5-7], indicating that this meteorite samples the same reservoirs in the solar nebula as the carbonaceous chondrite parent bodies (i.e., the outer solar system). Thus, NWA 6704 is of vital importance in that it enables us to evaluate the distribution of ^{92}Nb between the inner and outer solar system.

Methods: We prepared mineral and whole rock fractions from five fragments of NWA 6704. All non-magnetic mineral fractions were hand-picked under a stereoscopic microscope, and metal fraction was separated using neodymium hand magnet from a disaggregated specimens of NWA 6704.

Nb/Zr analysis. The Nb/Zr ratios were obtained using a *Thermo Fisher Scientific*™ *iCAP Q*™ ICP–MS at the University of Tokyo without chemical separation.

Zirconium isotope analysis. Zr was separated and purified from samples using a protocol modified from [2]. The Zr isotopic compositions were measured using a *Thermo Fisher Scientific Neptune Plus* MC-ICP-MS interfaced to a *Cetac Aridus II* desolvating nebulizer at the University of Tokyo.

Results and Discussion: The Zr isotope data including four orthopyroxene fractions and one metal fraction and the two whole rock data for NWA 6704 are all identical with the value obtained for a standard solution of NIST-SRM 3169 Zr within analytical uncertainty. In contrast, six chromite fractions with high ^{93}Nb/^{90}Zr show distinctly higher ε^{92}Zr up to +1.52 ± 0.40. These define good correlation with low MSWD (Fig. 1). The y-intercept defines an initial ε^{92}Zr of –0.17 ± 0.09. The slope of the regression line defines an initial $^{92}Nb/^{93}Nb$ of $(2.8 \pm 0.3) \times 10^{-5}$ at the time of NWA 6704 formation. By combining this value with the U–Pb age of NWA 6704 (4562.76 ± 0.30 Ma; [6]), an initial $^{92}Nb/^{93}Nb$ of $(3.0 \pm 0.3) \times 10^{-5}$ at the time of solar system formation is derived (Fig. 1).

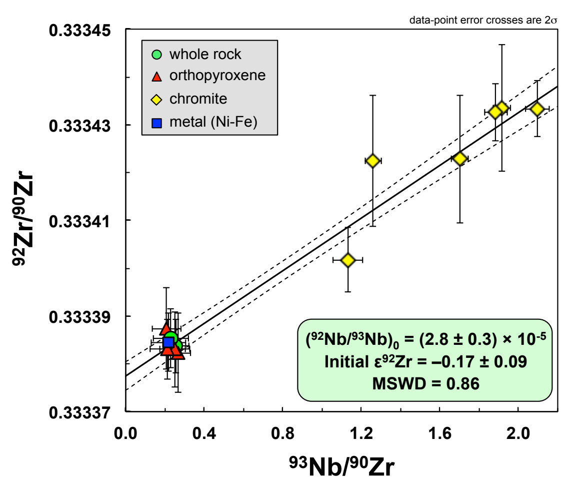

Figure 1. Nb-Zr isochron diagram for NWA 6704.

The initial abundance of ^{92}Nb in the outer solar system. The obtained value of an initial ^{92}Nb/^{93}Nb = (3.0 ± 0.3) × 10^{-5} at the time of solar system formation is distinctly higher than the initial value in the inner solar system of (1.7 ± 0.6) × 10^{-5} [2] (Fig. 2). Thus, our results reveal that ^{92}Nb was heterogeneously distributed in the protoplanetary disk before the formation of NWA 6704 (4562.76 ± 0.30 Ma; [6]), and was relatively enriched in the outer solar system. The difference between these two values of (1.7 ± 0.6) × 10^{-5} and (3.0 ± 0.3) × 10^{-5} corresponds to the age of up to 30 million years (My), calculated using the half-life of ^{92}Nb (37 My; [8]). Thus, our results limit the application of the current canonical value of (^{92}Nb/^{93}Nb)$_0$ = (1.7 ± 0.6) × 10^{-5} in the Nb–Zr dating of the planetary materials from the outer solar system.

The nucleosynthetic origin of ^{92}Nb. The obtained initial high abundance of ^{92}Nb provides clues on the origin of the proton-rich "*p*-process" nucleosynthesis. There have been several processes proposed to account for the current initial ^{92}Nb/^{93}Nb in the early solar system, that is, the initial abundance of (^{92}Nb/^{93}Nb) = (1.7 ± 0.6) × 10^{-5} obtained in the inner solar system. These include photodisintegration reactions (so called *γ*-process) in Type Ia supernova (SNIa) [9], and the α-rich freezeout [10] or neutrino-induced reactions (so called *ν*-process) [11] in core-collapse Type II supernovae (SNII). The α-rich freezeout model in SNII [10], however, has a difficulty in reconciling the initial ^{92}Nb abundance with the overproduction of other nuclides. Recently, [12] extended the study of [9] to investigate if the initial abundances of ^{92}Nb and radionuclide ^{53}Mn can be reconciled by one process in SNIa. [12] concluded that the initial abundances of ^{92}Nb and ^{53}Mn can be consistently explained if the initial abundance of ^{92}Nb/^{92}Mo ratio in the early solar system was at least 50% lower than the current nominal value of ^{92}Nb/^{92}Mo = (3.4 ± 0.6) × 10^{-5}. Recently, the initial ^{53}Mn abundance (^{53}Mn/^{55}Mn) at the solar system formation determined from NWA 6704 turned out to be identical to the initial abundance of ^{53}Mn in the inner solar system within uncertainties [13], ensuring the homogeneous distribution of ^{53}Mn in the early solar system. On the contrary, our study defines the initial abundance of ^{92}Nb/^{92}Mo = 6.3 × 10^{-5} using the solar Mo/Nb of 3.27 [14], which is distinctly higher than the current nominal value. Being compared with the estimates from astrophysical calculations [12], the results of our study cannot be consistently explained by the SNIa model. Thus, our results exclude the possibility of SNIa as the nucleosynthetic site of ^{92}Nb, and require another production site to be invoked for selectively producing ^{92}Nb. At the moment, only the *ν*-process in SNII [11] satisfies such a requirement for selectively producing ^{92}Nb. Considering that ^{92}Nb is a short-lived radionuclide, the time-scale from the last SNII explosion to the solar system formation should not be so long (at most 10^8 yr; [15]). In other words, if the time-scale was so long as to decrease ^{92}Nb under the detection limit, the heterogeneity of ^{92}Nb between inner and outer solar system would not be formed.

Summary: The internal Nb-Zr isochron dating of NWA 6704 reveals that the initial abundance of ^{92}Nb in the outer solar system was distinctly higher than that in the inner solar system. Using the obtained value, we further investigated the nucleosynthetic origin of ^{92}Nb. The results suggest that the *ν*-process in SNII is the probable origin for ^{92}Nb at the moment. Consequently, our study hints at the existence of SNII within 10^8 years before the formation of our solar system.

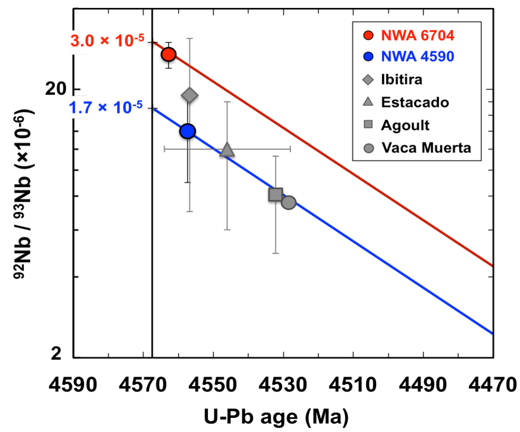

Figure 2. The comparison of the initial ^{92}Nb value obtained in this study, ^{92}Nb/^{93}Nb = (3.0 ± 0.3) × 10^{-5}, with the value of ^{92}Nb/^{93}Nb = (1.7 ± 0.6) × 10^{-5} in the inner solar system [2], All ^{92}Zr/^{90}Zr ratios are normalized to the reference value ^{92}Zr/^{90}Zr = 0.333383 for the standard solutions [16].

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