

IRON ISOTOPE AND THE ORIGIN OF NANOPHASE IRON IN LUNAR REGOLITH Kun Wang¹, Frédéric Moynier¹, Frank A. Podosek¹, and Julien Foriel¹, ¹Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis MO (wangkun@wustl.edu)

Introduction: The Moon and many other airless planetary bodies have been under continuous bombardment by cosmic ray radiation, solar wind sputtering/implantation, and micro-meteorite impacts [1-2]. The cumulative alteration effects are called space weathering and have changed the surface optical features of these airless bodies [3-4]. Nanophase metallic iron (npFe⁰; or submicroscopic metallic iron, SMFe) is widely observed on the surface of lunar regolith minerals or inside agglutinates and has been recognized as the cause of these optical alterations [5-6]. Two competing theories were proposed to explain its origin: (a) the reduction of silicates/oxide in lunar regolith saturated with solar-wind-implanted hydrogen during impact melting [7]; (b) the deposition of the solar wind sputtering/micrometeorite impact generated vapors [5].

These two competing formation mechanisms should have caused different effects on the iron isotope composition of npFe⁰. In “solar wind hydrogen reduction” scenario (a), the main possible source of Fe isotopic fractionation is during the reduction of Fe(II) to Fe(0). However, since this process would have happened at high temperatures [7], no detectable isotopic fractionation is expected [8-9]. The iron isotopic compositions of this npFe⁰ formed by this mechanism would be same as the host lunar regolith. In the “solar-wind-sputtering/micrometeorite-generated vapor deposit” scenario (b), iron in the hot vapor might preferentially lost light isotopes to space by kinetic effect. In this way, npFe⁰ should have enriched in heavy isotopes of iron relatively to host lunar regolith. Therefore, examining the iron isotope composition of npFe⁰ would help clearly distinguish between these two mechanisms.

Bulk lunar regolith shows enrichment in the heavy isotopes of Fe when compared to lunar igneous rocks by an average of 0.10 permil/a.m.u. and the mature and fine regolith samples have enriched most, up to 0.15 permil/a.m.u. [10]. Since the mature and fine lunar regolith have large surface-to-volume ratio and long time to accumulate more npFe⁰, it suggested npFe⁰ might more enrich in heavy isotopes of Fe than bulk regolith [10]. However, no direct isotopic investigation of the npFe⁰ in the lunar regolith has been reported.

Apollo 16 lunar regolith plagioclases are ideal samples to search for the iron isotopic composition of npFe⁰, because (a) Plagioclase is a stoichiometric Fe-free mineral, so little intrinsic iron could contaminate the npFe⁰ on the surface; (b) Apollo 16 regolith is very

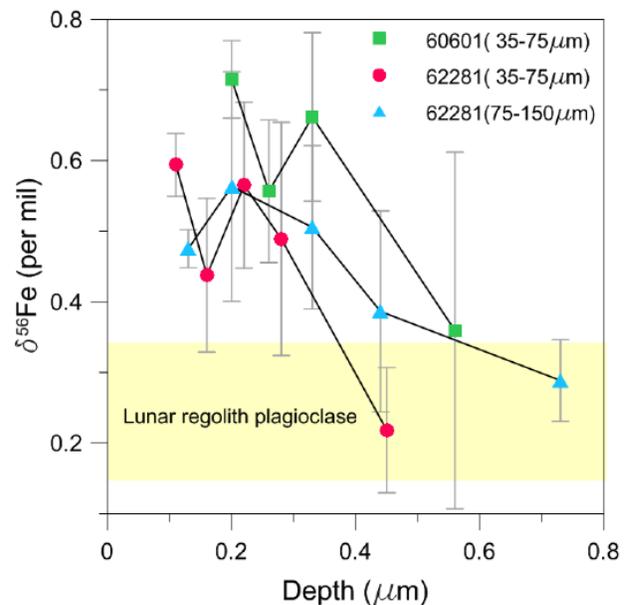


Fig. 1 Iron isotopic compositions ($\delta^{56}\text{Fe}$) of the surface etchings of lunar regolith plagioclases. Yellow shaded area represents the bulk plagioclase separated from lunar igneous rocks [14].

mature [11], hence in favor of accumulating more npFe⁰. Through step-by-step etching technique the surface (~ 0.1 to 0.8 μm) of hand picked pure lunar regolith plagioclase has been dissolved in order to study the iron isotopic composition of npFe⁰ on the surface. Further, we will discuss the origin of the npFe⁰ in lunar regolith from the perspective of iron isotopic fractionation.

Samples and Method: We use the same sample solutions previously treated for Cr isotopes [12]. Pure plagioclases were separated from 50 grams of Apollo 16 regolith 62281 and 60601 by a Frantz magnetic separator and then by hand. The cleaned grains were then progressively etched by using 0.1 N HCl in room temperature for 1 hour each step. The final step continued for 20 hours to consume as much as possible the inner part. The acid solution in every etch step was pipetted out to run through Fe purification following procedures described previously [13]. The isotopic measurements were performed by standard-sample-bracketing method on a Thermo Scientific Neptune Plus MC-ICP-MS at Washington University in St. Louis. The results are reported as delta notation relative to isotopic reference IRMM-014, $\delta^{56}\text{Fe} = \left[\frac{(^{56}\text{Fe}/^{54}\text{Fe})_{\text{sample}}}{(^{56}\text{Fe}/^{54}\text{Fe})_{\text{IRMM-014}}} - 1 \right] \times 10^3$.

Results and Discussion: For three independent experiments (60601 or 62281, 35-75 μm or 75-150 μm), the first three-four one-hour etching solutions all have significantly higher $\delta^{56}\text{Fe}$ values ($\delta^{56}\text{Fe} = 0.39\text{-}0.71\text{‰}$) than the last twenty-hour etching solutions ($\delta^{56}\text{Fe} = 0.22\text{-}0.36\text{‰}$). Fig. 1 shows a clear $\delta^{56}\text{Fe}$ decreasing-trend from the surface to the core of plagioclase grains for the three independent experiments. The $\delta^{56}\text{Fe}$ values in the last etching solution fall into normal lunar plagioclase values ($\delta^{56}\text{Fe} = 0.15\text{-}0.34\text{‰}$; shown as yellow shaded area in Fig. 1) measured in separated lunar igneous rocks plagioclases [14].

This surface-related iron isotopic composition could be contributed to three possible sources [12,15]: (a) contamination by meteoritic components; (b) solar wind iron implantation; (c) vapor-deposit iron coating. Meteoritic components could contribute from 0.7 to 1.7% mass in a typical regolith from Apollo 16 [16]. However, no types of meteorites could provide such high iron isotopic composition measured here ($\delta^{56}\text{Fe}$ up to 0.71‰). For example, the average $\delta^{56}\text{Fe}$ for chondrites is $0.01\pm 0.01\text{‰}$ [17] and for iron meteorites it is $\sim 0.1\text{‰}$ [18-20]. Solar wind implanted iron is not a plausible source for this highly fractionated iron isotope composition either. Inefficient coulomb drag theory predicts heavier isotopes are depleted in solar wind relative to the outer convective zone of the Sun [21]. Consistently, spacecrafts WIND and SOHO both have reported very negative iron isotopic compositions for solar wind iron [22-23], which are very different with the iron composition measured here.

Therefore, the iron of the surface ($< 0.4\mu\text{m}$) etching solutions of lunar Apollo 16 regolith plagioclases represent the iron of the npFe^0 instead of meteorites components or solar wind implanted iron. Abundant npFe^0 has been observed by transmission electron microscope [15], where the appearance depth is comparable with the etching depth here. The highly fractionated iron isotopic composition of npFe^0 ($\delta^{56}\text{Fe}$ up to 0.71‰) can be best explained as the preferential loss of light iron isotopes to space during hot vaporization stage according to the classical thermal escape model [24-25]. Due to the high temperature of the vapor, a small but significant amount of Fe atoms in the high-velocity-tail of the Maxwell-Boltzmann distribution might reach the escape velocity of the Moon (2.38 km/s). As shown in Fig. 2, the thermal escape model [26] sufficiently explained the highly fractionated iron isotopic composition of npFe^0 observed in this study. The vapor temperatures can be evaluated as ~ 2500 to 2750K , if the fractionation starts from an average lunar regolith iron isotope composition ($\sim 0.3\text{‰}$) [10]. It is worth to note that the average lunar regolith $\delta^{56}\text{Fe}$ already include the influence of the high $\delta^{56}\text{Fe}$ caused by

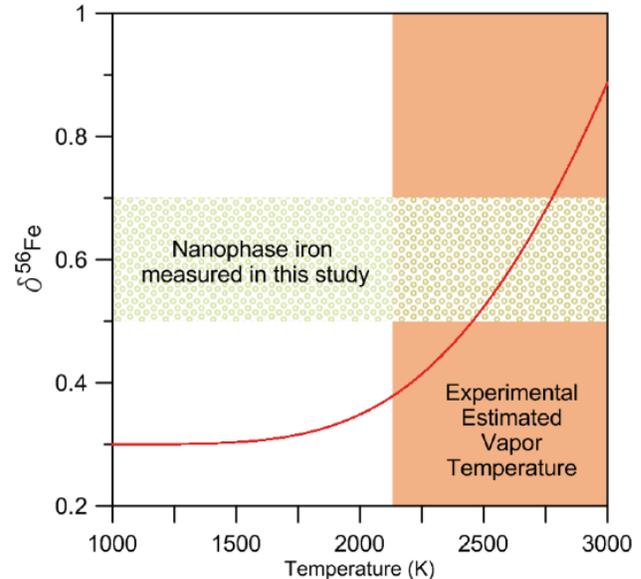


Fig. 2 The iron isotopic compositions ($\delta^{56}\text{Fe}$) of nanophase iron measured in this study could be explained by fractionation during preferential thermal escape (red line) starting from an average lunar regolith value [10]. Experimental estimated vapor temperature range is from [5,30-32].

the formation of npFe^0 . So if we start the fractionation from $\delta^{56}\text{Fe}$ of a typical lunar igneous rock values (0.1-0.2‰) [10, 27-29], a higher ($\sim 3000\text{K}$ or upper) temperature of the vapor is needed. All these temperatures are compatible with the theoretical and experimental evaluations of the vapor temperature [5, 30-32]. Therefore our results: i) provide an unambiguously support to the “vapor deposit” origin of npFe^0 , ii) explain the origin of the heavy Fe isotopic composition of the lunar regolith and iii) provide a range of temperature for the micro-meteorite impact events at the origin of the npFe^0 .

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