

SOLAR XE, KR, AND AR IN LUNAR SAMPLES; DO THEY GET FRACTIONATED IN THE SUN OR ON THE MOON?

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Element abundances in solar energetic particles differ from bulk solar or photospheric values as a function of the **first ionisation potential (FIP)** or a related parameter, elements with $FIP \leq 10\text{eV}$ being 4-5 times overabundant [1-3]. Elements close to the 10eV step are particularly important to learn more about this separation. We concluded [4, 5] that lunar samples retain solar Xe (FIP=12.1eV), Kr (14.0eV) and Ar (15.8eV) unaltered relative to the abundances in the solar corpuscular radiation, a conclusion based mainly on ilmenites analysed by the closed system etch technique. We deduced that Xe in the solar corpuscular radiation is enhanced relative to Kr and Ar and that the Xe-Kr fractionation varied with time. Here we present additional experiments confirming the ilmenite results and discuss other studies in the light of our new data. Geiss and coworkers [6, 7] showed that the Xe overabundance deduced here is expected, if the **first ionisation time** governs the fractionation at the source.

Fig. 1 shows **Ne/Ar and Kr/Xe release patterns** of samples from two recently irradiated soils (71501 ilmenite, 67601 bulk; antiquities $\leq 100\text{Ma}$) and two early irradiated soil breccias (79035 ilmenite, antiquity $\sim 1\text{Ga}$; 14301 pyroxene, $\geq 3\text{Ga}$). Like in the ilmenites, Ne/Ar (and He/Ar, not shown) in 14301 start considerably below present-day solar wind ratios (SWC, ref. 8) but later approach these reference values. Thus, ilmenite and pyroxene lost part of the He and Ne from the very shallowly sited SW, but retained (nearly) unfractionated He, Ne, and Ar in the more deeply implanted SEP component (cf. 4, 5). The plagioclase-rich bulk sample 67601 does not show SWC-like Ne/Ar (or He/Ar) ratios at any depth. In contrast to Ne/Ar, Kr/Xe ratios (as well as Ar/Kr) are nearly constant, in the pyroxene separate and - particularly remarkably - the bulk sample as well as the ilmenites discussed previously. These flat patterns, together with the conclusion that the relatively mobile light noble gases are unfractionated relative to SWC in later steps, indicate that Ar/Kr/Xe ratios reflect the true relative abundances of the heavy noble gases in both SW and SEP. We conclude that lunar samples allow us to rule on possible fractionations of Ar, Kr, and Xe in the SW source region. We use solar abundances by Anders and Grevesse [2], which are based on the most recent values for neighbouring elements.

Kr/Xe ratios are all considerably below the solar value, and the two soils have nearly twice as high mean ratios than the two soil breccias. We conclude a) that **Kr-Xe fractionate in the SW source region** and b) that the fractionation factor today is only about half as large as 1-3 Ga ago. Ar/Kr in all samples is also about 30-40% below the Anders and Grevesse value. Relative to Ar, Xe in SW and SEP is thus enhanced similarly to low-FIP ($<10\text{eV}$) elements, despite that the FIP of Xe is 12.1eV. It has been argued [6, 7] that the fractionation in the chromosphere should be governed by the time it takes to ionize an atom rather than the **FIP**. Fig. 2 shows on the abscissa this first ionisation time (**FIT**) [7]. The Xe:Kr:Ar fractionation in the solar wind source region deduced here is in very good agreement with the FIT-hypothesis. The secular variation of the Kr/Xe ratio may suggest that FIT increased in the past few Ga.

We now **review work by others**, discussing in particular reservations expressed about whether the lunar regolith does preserve the abundances of the heavy solar noble gases. One in-vacuo etch run of a mineral separate that includes Kr and Xe data has been published (pyroxene of low-antiquity soil 75081, [9]). Kr/Xe ratios in the major etch and

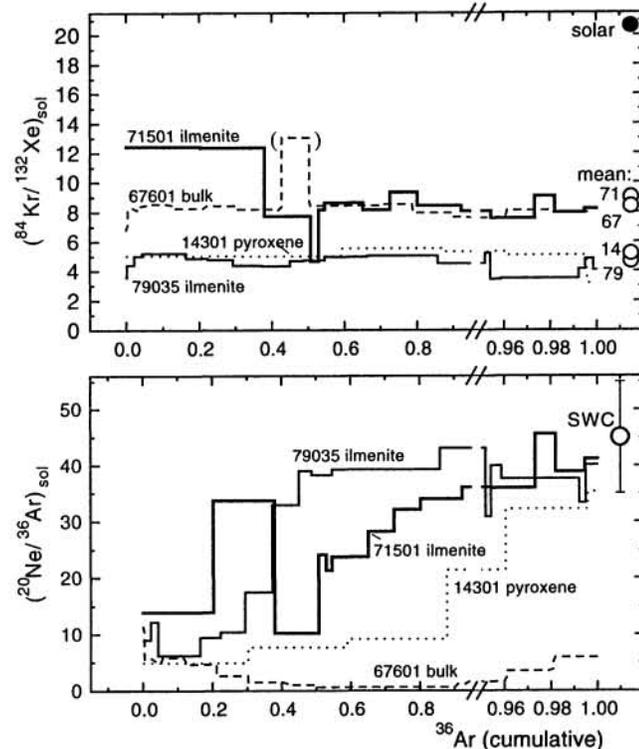


Fig. 1: Ne/Ar ratios are variable, but approach solar wind values (SWC, ref. 8) in the last etch steps of the 3 mineral separates. In contrast, Kr/Xe is essentially constant in all 4 runs and the average values are grouped according to antiquity. The figure shows that SEP-He-Ne-Ar - and thus solar Kr and Xe - is not fractionated on the Moon. The Kr/Xe ratios are lower than the solar value [2], indicating fractionation in the SW source region.

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pyrolysis steps are close to those of ilmenite 71501. Similar Kr/Xe ratios are observed in low temperature combustion steps ($\leq 400^\circ\text{C}$) of metal from recently irradiated soil 68501 [10]. These steps should have released noble gases by oxidizing the carrier rather than by diffusion and should thus show little fractionation upon analysis. In early studies, it was observed that Kr/Xe ratios in lunar bulk samples vary more than twofold. These variations were thought to reflect fractionation on the Moon [11, 12]. However, Kerridge [13] showed that they correlate with the antiquity of the samples and concluded - as we do here - that lunar samples preserve a record of a secular decrease of the Xe abundance in the SW. Pepin and coworkers [14, 15] measured noble gases and nitrogen in ilmenites from 71501 and 79035 by stepwise combustion/pyrolysis. They made two remarkable observations that challenge the conclusions of this work. First, the average N/Xe ratio in both samples was several times above the solar value, suggesting to them that the ilmenites had lost Xe, since they assumed the N to be predominantly solar. Second, He-Xe amounts summed up to a certain step displayed approximately solar relative abundances. The authors postulated a low temperature (LT) reservoir containing noble gases unfractionated relative to solar values. We doubt that such a LT reservoir exists, since Kr/Xe ratios in the initial combustion steps of both ilmenites ($300\text{-}400^\circ\text{C}$) are close to the values in the respective etch runs and (for 71501) also near those of the first combustion steps of 68501 metal [10]. In summary, we conclude that the noble gas data by others are well in agreement with our etch results and, hence, the view that lunar samples correctly reflect the relative abundances of Ar, Kr, and Xe in the solar corpuscular radiation.

Remains the **nitrogen** problem. No consensus has been reached on whether or not nitrogen in lunar soils is mostly solar in origin [16, 17]. The constancy of the N/Ar ratio and the lack of a dependence of $\delta^{15}\text{N}$ on the N concentration argue for the former view [17]. A main argument for a major non-solar N component is the difficulty to explain the large intra- and inter-sample spread in $\delta^{15}\text{N}$. A secular change of $\sim 30\%$ in the SW seems not possible [16] and the idea that light N might correspond to SEP noble gases, implanted with higher energy than the SW, faces the difficulty that the isotopic differences between SW and SEP would have opposite signs for N and noble gases. It has been noted that this difficulty should perhaps not be overemphasized, as long as the reason for the difference between SW- and SEP-noble gases is not understood [17]. A comprehensive discussion is beyond the scope of this contribution, but it seems that lunar N can hardly be predominantly solar if our interpretation of the noble gas data is correct. Otherwise, the three heavy noble gases would be depleted relative to N all by the same factor, which seems difficult to accomplish, or the solar wind N flux would be enhanced relative to Ar by roughly an order of magnitude [10], more than any other element. This seems improbable for an element with a FIP in between those of Kr and Xe and a FIT slightly higher than Ar.

Acknowledgments: Work supported by the Swiss National Science Foundation

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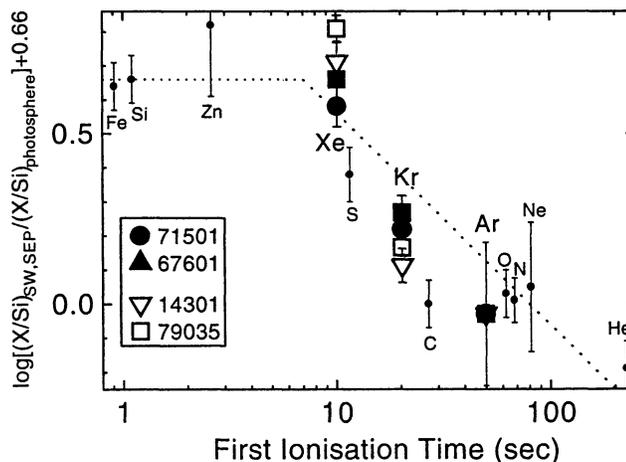


Fig. 2: Abundances of several elements in the solar corpuscular radiation relative to photospheric or solar system values (ref. [2]; ordinate shifted by 0.66 units, to account for new evidence that high-FIP elements in SEP have photospheric abundances relative to hydrogen [3]). Ar, Kr, Xe data from this work, other elements from [2]; Kr and Xe anchored to Ar from [2]. First ionisation time from ref. [7]. The Kr, and Xe overabundance in the SW deduced here is expected, if - as suggested by [6, 7] - FIT governs the fractionation in the SW source region.