KRYPTON AND XENON FROM SOLAR ENERGETIC PARTICLES IN A LUNAR ILMENITE
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Studies of solar He, Ne, and Ar in the lunar regolith by closed system stepped etching (CSSE) allow us to much better define the isotopic composition of noble gases implanted by solar energetic particles (SEP, ref. 1) than has been possible by stepwise pyrolysis (2). SEP He, Ne, and Ar are all isotopically heavier than the corresponding solar wind components (1,3). CSSE has the major advantage that it leads to much less diffusive element fractionation than gas release methods involving high temperatures. Here we report the first CSSE study of solar noble gases including Kr and Xe. We analyzed an ilmenite separate from lunar soil 71501 (42-64µm, *100mg), obtained as sinks in Clerici's solution. In addition, we studied a bulk sample from plagioclase-rich soil 67601 (25-42µm, *170mg).

He, Ne, Ar isotopes: The Ne isotopic pattern (Fig. 1) of the ilmenite is very similar to those of other ilmenite and pyroxene separates: 20-Ne/22-Ne in step 1 is identical to modern solar wind (SWC, 4). Later data-points plot on a straight line towards the SEP-Ne point. 20-Ne/22-Ne displays a transient minimum of 13.0 in step 3, before rising again to the SWC value in step 6. This indicates that a phase relatively easily attacked by HF accounts for roughly the first 50% of the solar noble gases in this sample. The SEP-point is reached in step 13. The following 3 steps release cosmogenic Ne together with a mixture of SEP-Ne and SW-Ne, the latter presumably from a minor, highly HF-resistant phase. He and Ar isotopes also closely match patterns of earlier CSSE runs (3,5), with 4-He/3-He = 2250 (SW) and =4350 (SEP), and 36-Ar/38-Ar = 5.46 (SW) and =4.8 (SEP).

Element ratios: The 4-He/36-Ar and 20-Ne/36-Ar patterns (Fig. 2) are again similar to those of earlier CSSE runs on ilmenites: they start below solar ratios but closely approach the SEP values in those steps which release (nearly) pure SEP-Ne. These patterns have been interpreted to show loss of some SW-He, Ne, but essentially quantitative retention of SEP-He, Ne, Ar in lunar ilmenites (5).

84-Kr/132-Xe decreases in the first 4 steps by about a factor of 3. This possibly indicates some element fractionation during the release of the least acid-resistant phase. The second half of the gas release displays virtually constant Kr/Xe. This, together with the fact that already the light gases He and Ne are kept well in the most acid resistant reservoirs, strongly suggests that solar Kr-Xe are quantitatively retained - at least in the more HF-resistant phase and possibly in the whole ilmenite. This is reinforced by the fact that the 67601 bulk sample - which clearly lost a large part of its solar He and Ne - yet displays throughout the whole run constant Kr/Xe ratios (data not shown) very similar to those of the ilmenite. The small variation of 36-Ar/132-Xe suggests that solar Ar as well is retained in the ilmenite quite qualitatively.

Solar Ar/Kr/Xe ratios inferred here do not agree with tabulated "solar system" values (e. g. 6, *SS* in Fig. 2), for which Kr and Xe abundances are interpolated between neighbouring species. This may suggest noble gas fractionation in the solar corpuscular radiation depending on first ionisation potential or a related parameter (6). The close coincidence of 4-He/36-Ar and 20-Ne/36-Ar with the SWC values in the last etching fractions makes it unlikely that the "non-solar-system" Ar/Kr/Xe abundances in lunar or meteoritic samples indicate substantial diffusive losses of implanted solar Ar, Kr, or even Xe. Our data speak against Frick et al. (7), who claim that the low temperature fractions of their combustion/pyrolysis analysis of a 71501 ilmenite indicate "solar-system" like abundances for the surface-sited and thus presumably most recently implanted noble gases. Strong element fractionation in the combustion/pyrolysis experiment (Fig. 2) seems to preclude inferences about elemental abundances. Note that if solar Xe is quantitatively retained, it would seem difficult to explain observed N/Xe above solar system ratios (e. g. 7) by a predominantly solar source for lunar nitrogen.

Kr, Xe isotopes: The steps releasing nearly pure SW-Ne or SEP-Ne may be expected to show also pure, unfractinated SW- or SEP-Kr-Xe, apart from possible cosmogenic contributions. The two steps with pure SW-Ne contain Kr just very slightly lighter than atmospheric Kr (Fig. 3). Steps with (isotopically heavier) SEP-Ne also release isotopically heavier Kr. The last steps contain large amounts of cosmogenic Kr. By analogy to Ne, we interpret the heavy trapped component as SEP-Kr. Xe behaves similar to Kr. A lighter Xe component (SW) is released first, followed by heavier (SEP-)Xe (data not presented).

Fig. 1: Ne in steps 1 and 6 identical to the solar wind value (SWC, ref. 4); step 13 identical to SEP-Ne in lunar plagioclase and pyroxene (1,3,5).
Fig. 2: 4-He/36-Ar and 20-Ne/36-Ar in the last few steps approach SWC values (4), indicating that SEP-He-Ne-Ar are quantitatively retained in lunar ilmenite, and suggesting also qualitative retention of solar Kr-Xe. 36-Ar/84-Kr and 84-Kr/132-Xe are 2-3 times below “solar system” values (6, “SS”), suggesting fractionated noble gas abundances in the solar corpuscular radiation. Dotted line gives 20-Ne/36-Ar in a stepped combustion/pyrolysis of 71501 ilmenite (7). Strong element fractionation compromises deduction of SW element abundances from such data.

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<th>128Xe</th>
<th>129Xe</th>
<th>130Xe</th>
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<td>36.73</td>
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<td>(99.4)</td>
<td>(16.0)</td>
<td>(91.2)</td>
<td>100</td>
<td>(37.9)</td>
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Table 1: Preliminary composition of Kr and Xe in the solar wind and in solar energetic particles deduced from 71501 ilmenite CSSE data. Parentheses indicate values deduced by assuming SEP and SW related by mass-fractionation.

shown). Due to cosmogenic gases, not all isotope ratios of SEP-Kr-Xe can be deduced independently. In Table 1, values in parentheses are derived by assuming SEP and SW components to be related by mass-fractionation, as is the case for Ne. Particularly the Xe data support this assumption. Kr and Xe data-points from bulk sample 67601 cluster around values isotopically slightly heavier than the SW composition observed in the 71501 ilmenite. This is not surprising, since in this sample neither SW-Ne nor SEP-Ne did reveal themselves in pure form, as is common for bulk soils.

Summary: The first closed system stepped etching (CSSE) study on lunar soil samples including Kr and Xe strongly indicates that solar Ar-Kr-Xe are quantitatively retained in lunar ilmenite and that this mineral also retains SEP-He-Ne well. Preliminary abundance ratios 36-Ar/84-Kr/132-Xe derived from these data are 15600 : 8.4 : 1. These values differ from tabulated "solar system" abundances (e.g. 68400 : 20.6 : 1, ref. 6). One possible explanation is a fractionation of the solar corpuscular radiation depending on the first ionisation potential. Trapped Kr and Xe become isotopically heavier with progressive etching. In analogy to the light noble gases, in particular Ne, we postulate this to show the presence of SEP-Kr-Xe which are isotopically heavier than the more shallowly implanted SW-Kr-Xe.

Acknowledgments: We thank W. Wittwer for sample preparation. Work supported by the Swiss National Science Foundation.