Mercury and the Moon both have tenuous atmospheres that contain atomic sodium and potassium. These chemicals must be continuously resupplied, as neither body can retain the atoms for more than a few hours (refs 1–6). The mechanisms proposed to explain the resupply include sputtering of the surface by the solar wind6–8, micrometeorite impacts5, thermal desorption6–8 and photon-stimulated desorption11,12. But there are few data and no general agreement about which processes dominate13,14. Here we report laboratory studies of photon-stimulated desorption of sodium from surfaces that simulate lunar silicates. We find that bombardment of such surfaces at temperatures of ~250 K by ultraviolet photons (wavelength $\lambda < 300$ nm) causes very efficient desorption of sodium atoms, induced by electronic excitations rather than by thermal processes or momentum transfer. The flux at the lunar surface of ultraviolet photons from the Sun is sufficient to ensure that photon-stimulated desorption of sodium contributes substantially to the Moon’s atmosphere. On Mercury, solar heating of the surface implies that thermal desorption2 will also be an important source of atmospheric sodium.

We made measurements in an ultrahigh-vacuum apparatus, with base pressures $< 1 \times 10^{-10}$ torr (ref. 15), and used X-ray photoelectron spectroscopy, temperature-programmed desorption and low-energy ion scattering for surface characterization. Amorphous, stoichiometric SiO$_2$ films ~10 nm thick were prepared by thermal evaporation of silicon in an oxygen atmosphere ($1 \times 10^{-5}$ torr), onto the surface of a Re(0001) single crystal16. These films simulate lunar silicates (SiO$_2$ is the dominant component of the lunar surface). Sodium was deposited from an evaporation source, and coverages were measured by X-ray photoelectron spectroscopy and temperature-programmed desorption (ref. 7, and B.V.Y., V.N. Ageev and T.E.M., manuscript in preparation). The measurement scheme for photon-stimulated desorption (PSD) of Na atoms includes a mechanically chopped photon source (500-W Hg arc lamp with filters), a highly sensitive detector of Na based on surface ionization, and the use of a time-of-flight technique. For companion studies of electron-stimulated desorption (ESD), an efficient pulsed low-energy electron source was used together with the Na detector.

There are intimate connections between ESD and PSD15; in general, similar electronic processes cause desorption of atoms via electron or photon excitation. The electronic excitations accessible using photons can also be excited by electrons of comparable energy, and a tunable electron gun (0–200 eV) has a much wider energy range than a laboratory photon source (Hg arc lamp, $E_{\text{max}} \approx 5$ eV). Thus, we measure low-energy desorption thresholds and cross-sections using PSD, and probe cross-sections and mechanisms over a wider energy range using ESD.

Figure 1a shows the cross-section (cm$^2$) for Na atom desorption via PSD as a function of photon energy $h\nu$. Visible and near-ultraviolet photons ($\lambda > 300$ nm, $h\nu < 4$ eV) cause little or no detectable desorption of Na. For ultraviolet photons with $h\nu > 4$ eV, the cross-section rises; at $h\nu = 5$ eV, the PSD cross-section is $\sim (3 \pm 1) \times 10^{-20}$ cm$^2$. The ESD cross-section for atomic Na as a function of electron energy $E_e$ is shown in Fig. 1b. We find that (1) the initial threshold is at $-4$ eV, the same as the PSD threshold, (2) the desorption cross-sections at $\sim 5$ eV have similar magnitudes for ESD and PSD and (3) there is a resonance-like feature at $\sim 11$ eV in ESD of Na. Similar features are seen for all Na coverages less than 1 monolayer (ML) at a substrate temperature of ~250 K for both PSD and ESD. The yields and thresholds are also substantially the same for a Na/SiO$_2$ surface that has been heavily bombarded by ions (1-keV He$^+$), which simulates damage by the solar wind. The threshold for desorption of ionic Na$^+$ via ESD is $\sim 25$ eV, significantly higher than for neutral Na.

The velocity distribution for ESD of neutral Na is shown in Figure 2. The peak in the distributions is at 1,000 m s$^{-1}$; the peak in the corresponding kinetic-energy distribution is at $\sim 0.1$ eV. The velocities (energies) are clearly non-thermal (substrate at 250 K), and have values consistent with the ‘hot’ components of the lunar and mercurian atmospheres11,18–20.

We interpret the PSD and ESD data of Fig. 1a, b on the basis of charge-transfer excitations21,22 from SiO$_2$ to the unoccupied Na $3s$ orbital (Fig. 3), so that adsorbed Na$^+$ is neutralized and desorbs. Na is adsorbed in ionic form on SiO$_2$ for coverages <1 ML (B.V.Y., V.N. Ageev and T.E.M., manuscript in preparation). The radius of ionic Na$^+$ (~1.0 Å) is smaller than that of neutral Na$^0$ (~1.9 Å). When an electron is attached to Na$^+$ to make Na$^0$, the neutral adsorbed atom is at a smaller atom–surface separation than the equilibrium value; this is a repulsive configuration which can lead to desorption of a non-thermal Na atom. Desorption of Na involves a competition

![Figure 1](https://example.com/figure1.png)
between electron-excited or photon-excited electron transfer to form Na\(^{+}\), and the lifetime of Na\(^{+}\) in a repulsive configuration. On SiO\(_2\), because the Na 3s level is in the bandgap region between the Fermi level and the conduction-band minimum, the lifetime of the neutral atom is long enough for efficient desorption. In contrast, the ESD Na yields from oxidized surfaces of tungsten and molybdenum are negligible for \(E_e < 25\) eV (refs 23, 24): the Fermi level is near the conduction-band minimum, and the lifetime of the neutral is too short for efficient desorption.

The sodium source rate needed to maintain the observed column density of \(\sim 10^7\) atoms cm\(^{-2}\) above the lunar surface (that is, the desorption rate of Na from the lunar surface) is variously estimated\(^{14,25}\) to be in the range \(\sim 5 \times 10^4\) to \(\sim 2 \times 10^6\) atoms cm\(^{-2}\) s\(^{-1}\). The different values are mainly based on different assumptions about the escape dynamics of Na. We can estimate the PSD flux \(\Phi_{Na}^{PSD}\) of Na from the lunar surface induced by ultraviolet photons, based on our measurements and some assumptions. The PSD cross-section \(Q\) is \(\sim (3 \pm 1) \times 10^{-7}\) cm\(^2\) at \(h\nu = 5\) eV. The solar photon flux \(F_{ph}\) (ref. 26) at the lunar surface is \(\sim 2 \times 10^{10}\) photons cm\(^{-2}\) s\(^{-1}\) at \(h\nu \approx 5\) eV, and decreases very quickly with increasing energy; the flux is \(\sim 10^{9}\) photons cm\(^{-2}\) s\(^{-1}\) at \(h\nu > 8\) eV, above the bandgap energy. If we assume the Na surface coverage \(\sigma\) to be \(\sim 3 \times 10^{13}\) cm\(^{-2}\), consistent with the lunar average bulk concentration of Na (ref. 5), we find

\[
\Phi_{Na}^{PSD} = \frac{1}{4} F_{ph} Q \sigma \approx 4 \times 10^4 \text{ atoms cm}^{-2} \text{ s}^{-1}
\]

where the factor of 1/4 gives a surface-averaged value. Considering the uncertainties and variations in the lunar surface composition and the concentration of Na, the computed value is in good agreement with the upper limit of Na source rates indicated above.

For comparison, we estimate the possible role of ESD in the production of Na, due to bombardment of the lunar surface by electrons from the solar plasma. Based on the average electron flux of \(\sim 4 \times 10^{10}\) cm\(^{-2}\) s\(^{-1}\) with a mean temperature of \(\sim 1.4 \times 10^4\) K (ref. 27), the ESD cross-section versus electron energy \(E_e\) in Fig. 1b, and the same Na surface coverage as above, the ESD flux \(\Phi_{Na}^{ESD}\) is \(\sim 100\) atoms cm\(^{-2}\) s\(^{-1}\). Although there are considerable uncertainties in the parameters as applied to the lunar surface, \(\Phi_{Na}^{ESD}\) is considerably less than both \(\Phi_{Na}^{PSD}\) and the range of Na source rates from the lunar surface.

We now consider how the charge-transfer process occurs in PSD and ESD of Na. In PSD by ultraviolet photons, desorption can proceed via a direct excitation (that is, by photo-excitation of an electron from a surface state to neutralize surface Na\(^{+}\)), or via an indirect process\(^{25}\). In the latter case, the photons excite ‘hot’ electrons to the conduction band from defect states in amorphous SiO\(_2\), or across the bandgap from the valence band; these electrons can propagate to the surface and neutralize surface Na\(^{+}\), which then desorbs with a non-thermal velocity distribution. Thus, the PSD/ESD electronic excitation processes are similar, and the cross-sections for Na desorption near threshold are of the same order of magnitude. In the present case, the direct electron flux from the solar wind is clearly too small to cause significant desorption of ‘hot’ Na, but the solar photon flux appears to be more than sufficient.

These measurements provide strong scientific support and a rationale for the arguments\(^{6-10}\), discussed recently by Mendillo et al.\(^{25}\), that a PSD process is important in production of the lunar Na atmosphere. Other processes\(^{3-5,25}\) also contribute; for example, a micrometeor source may be significant when associated with a meteor shower\(^{29}\). As micrometeor impacts can change the local surface concentration of Na, some of the observed temporal and spatial variations in atmospheric Na concentrations may be partly due to surface-coverge-dependent PSD fluxes (as well as being affected by rates of impact vaporization of Na). In the case of Mercury, thermal desorption of Na is believed to contribute to the Na atmosphere because of the high day temperatures (\(\sim 700\) K at the sub-solar point\(^{11}\)), but PSD is also likely to be important, especially at other latitudes.

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The systematic enumeration of all possible networks of atoms in inorganic structures is of considerable interest. Of particular importance are the 4-connected networks (those in which each atom is connected to exactly four neighbours), which are relevant to a wide range of systems—crystalline elements, hydrates, covalently bonded crystals, silicates and many synthetic compounds. Systematic enumeration is especially desirable in the study of zeolites and related materials, of which there are now 121 recognized structural types, with several new types being identified every year. But as the number of possible 4-connected three-dimensional networks is infinite, and as there exists no systematic procedure for their derivation, the prediction of new structural types has hitherto relied on empirical methods (see, for example, refs 2–4). Here we report a partial solution to this problem, based on recent advances in mathematical tiling theory5–8. We establish that there are at least 145 distinct unidimensional networks based on a complex tiling unit. Of the total number of networks that we have derived, only two contain neither three- nor four-membered rings, and most of the binodal and trinodal networks are new.

We define a tiling as a periodic subdivision of space into bounded, connected regions without holes, which we call tiles. If two tiles meet along a surface, we call the surface a face. If three or more faces meet along a curve, we call the curve an edge. Finally, if at least three edges meet at a point, we call that point a vertex. Vertices and edges together form a network. A network can be derived from a tiling whenever it is possible to choose a collection of simple cycles (closed circuits) such that each edge occurs in at least three of them, and the cycles can be spanned by non-intersecting faces such that the union of all faces separates space into tiles. We note the distinction between faces and rings (usually defined as cycles without short cuts).

We have earlier solved the much simpler problem of classifying all periodic tilings of the euclidean plane, the sphere and the hyperbolic plane6,10. Our algorithms5 enumerate, and permit the visualization of, all possible topological types of tilings for each two-dimensional symmetry group with 1, 2, 3 (and so on) kinds of inequivalent vertices. We shall call these unidonal, binodal, trinodal (and so on) tilings. This approach has been applied to the enumeration of polyomaxalate cages11. We can now address the three-dimensional case, which has direct applications to structural chemistry.

The starting point is to associate with each type of periodic tiling...