THE DEPTH DISTRIBUTION OF HYDROGEN IN LUNAR MATERIALS*  D.A. Leich, T.A. Tombrello, and D.S. Burnett, California Institute of Technology, Pasadena, California 91109.

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We have used the resonant nuclear reaction \(^1\text{H} + \text{^19F,} \gamma \text{^16O}\) to directly measure the hydrogen distribution as a function of depth in lunar soil particles. Chemical etching experiments have shown that solar wind rare gases are trapped near the surfaces of lunar soil grains; however, the implied gas layer thicknesses are surprisingly larger than the range of ions of typical solar wind energy (~100 Å corresponding to ~1 keV/nucleon)\(^1\). Our technique can provide more detailed information on the distribution of solar wind implanted ions.

When a sample is irradiated with a \(\text{^19F}\) beam of energy \(E_0\), slightly above the resonance energy \(E_R\) (16.45 MeV), the \(\text{^19F}\) ions slow down due to electronic collisions until the resonance energy is reached at a depth \(X_R\). The reaction proceeds at a rate proportional to the hydrogen concentration in a thin layer at \(X_R\). At greater depths, the \(\text{^19F}\) energy is below the resonant energy. The non-resonant cross section to either side of the resonance energy is negligible compared to the cross section at resonance, so hydrogen outside the layer at \(X_R\) contributes only a negligible amount. Since the stopping power, \(\text{dE/dx}\), is nearly independent of energy, the depth \(X_R\) can be related to the beam energy \(E_0\) by the relation \(E_0 - X_R \text{(dE/dx)} = E_R\). Measuring the \(\gamma\)-ray production rate as the \(\text{^19F}\) beam energy \(E_0\) is varied gives a direct indication of hydrogen concentration as a function of depth in the sample. The depth resolution (~200 Å) is determined by the ratio of the resonance width to the stopping power. A second resonance at 17.65 MeV limits the useful range of the 16.45 MeV resonance for depth distribution measurements to about 4000 Å.

We have studied a variety of Apollo 11 and 15 coarse fine samples, primarily glasses. Figure 1 shows the profile for a 10085 brown glass fragment which contains a relatively large amount of hydrogen. The peak density corresponds to about \(3 \times 10^{21}\) atoms per cm\(^3\) at a depth of 1000 Å (~2000 ppm of H by weight). The density drops sharply between 1400 Å and 2200 Å followed by a more gradual decrease with increasing depth. The residual density at 4000 Å was about \(8 \times 10^{20}\) atoms per cm\(^3\); however, the distribution had not yet begun to level off.

The measurement of the entire distribution was repeated twice on this sample. Each repetition showed a reduction in the hydrogen content of roughly 20% in the outer 2000 Å and 5% between 2000 Å and 4000 Å deep as compared to the previous run. Data from the third run are plotted in Fig. 1 (error bars omitted for clarity) to illustrate this gradual reduction in hydrogen content observed in each of the coarse fine fragments. The hydrogen content in the region 0-500 Å deep usually increases following a few days of atmospheric exposure, but is rapidly depleted during the first ten minutes (~10\(^{14}\) ions/cm\(^2\)) of remeasurement with the \(\text{^19F}\) beam. It is likely that this extremely mobile surface layer is a very superficial H\(_2\)O contamination.

Surface glass samples from the lunar top and bottom of breccia 15059 and from the lunar bottom of 15015 were analyzed. From lunar surface photography
and microimpact pit densities, these rocks appear to have been irradiated in only one orientation. These samples were handled by us without atmospheric exposure; however, they had previously been exposed to the LM cabin atmosphere and to the terrestrial atmosphere prior to processing in the LRL. The data points on Fig. 2 show two consecutive measurements of 15059,32 the lunar top sample of 15059, and, for comparison, the solid curve indicates the profile observed for 15015. These profiles differ from that of the 10085 sample (Fig. 1) in that they are more sharply peaked toward the surface with no strong suggestion of a "deep" component. The profile for 15059,28, the lunar bottom sample of 15059, was essentially identical to that for the top sample, shown in Fig. 2, except for a slightly lower concentration between depths of about 500 Å and 2500 Å.

Although we have shown that H exists in lunar soil samples at depths much greater than the range of solar wind protons, interpretation of the distributions is hampered by both the mobility and the ambiguity of the origin of the observed hydrogen. Heavy radiation damage has been observed in the outer 1000 Å of micron-sized soil particles by high voltage electron microscopy (2), and this may partially account for the high hydrogen mobility we have observed. Also, terrestrial water exists in returned lunar soil samples in amounts comparable to the hydrogen content from solar wind implantation (3). Unless carefully cleaned, laboratory test samples exhibit a contamination hydrogen peak at zero depth but show no penetration of the surface within the resolution of the measurement. It is tempting to speculate that the relatively large amounts of tightly-bound hydrogen below about 2000 Å in the 10085 sample is true H₂, whereas the mobile hydrogen in the surface region can be interpreted as a mixture of lunar H₂ and terrestrial H₂O. However, exposure to liquid H₂O showed that the H₂O may have penetrated to these depths; consequently, we are unable to strongly support this interpretation at present.

The two 15059 samples permit the strongest conclusions because the total history of terrestrial exposure and handling was exactly the same for 15059,28 and 15059,32. Consequently, the similarities in both the H contents and profiles of these two samples imply that the hydrogen measured in 15059,32 is primarily terrestrial in origin, undoubtedly as H₂O, or has been inherited from the parent material, perhaps lunar soil, from which the glass was formed. The small excess of H in 15059,32 above 15059,28 would require less than one year of surface exposure to accumulate! It appears that either the surface residence of 15059 has been extremely brief or, more reasonably, that the solar wind hydrogen has been essentially totally lost, at least from the depth region which we were able to measure.

The somewhat greater penetration of the hydrogen into 15059,32 as compared to the three bottom-surface samples suggests a number of possible interpretations. The excess of H at 500-2500 Å deep may represent an inward diffusion of implanted solar wind hydrogen or, perhaps, a deeply implanted higher energy (~ 10 keV) solar particle component. Alternatively, the heavy radiation damage associated with solar wind exposure may facilitate the migration of both solar wind hydrogen and terrestrial H₂O to these depths. It may also be that physical differences, uncorrelated with solar wind exposure, can account for variations in the ability of a particular sample to absorb and
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retain terrestrial H₂O and for variations in the deep penetration of the H₂O.

The high degree of similarity of the distributions obtained from the top and bottom surface chips is best interpreted as indicating that these samples absorb H₂O from exposure to atmospheric humidity. Exposure to normal laboratory atmosphere did not significantly increase the observed hydrogen content of the rock chip surfaces, however the initial exposure to the LM cabin atmosphere may have saturated an active surface with H₂O so that further exposure could produce little additional adsorption.

A sample of Al-coated Pt foil from the Apollo 16 Cosmic Ray Experiment was shown to contain <10¹⁵ H atoms/cm² in the depth range corresponding to 10⁻⁴⁻⁰ keV protons from the April 16, 1972 solar flare. This suggests that the energy spectrum diverts from the E⁻³ dependence observed at higher energies. However, implantation experiments have shown that retention of the implanted solar flare protons at depths corresponding to 10⁻⁴⁻⁰ keV proton ranges is poor; hence we are unable to strongly defend this conclusion.

REFERENCES