since the signals cut off early in the afterglow. At low CO_2 pressures, a value $\sim 4 \times 10^{-7}$ cm^3/sec is noted at $\simeq 210$°K.

The CO_2^+ ions in the present study should be in the same ground electronic state ($\tilde{X}\,^2\Pi_g$) as those encountered in the photoionized Martian ionosphere, considering the energetics of their production from neon metastable atoms via the Penning reaction. Less can be said of the vibrational state of the ions, although available information on quenching of CO_2 vibration by noble gases[10] suggests that the ions may have been reduced to their ground vibration state within $\lesssim 10^{-4}$ sec. For these ions, the value of $\alpha(CO_2^+)$ at $T_e = T_+ = T_{gas} = 300$°K is found to be $(3.8 \pm 0.5) \times 10^{-7}$ cm^3/sec, while at ~ 210°K it appears to be of the same order. Since it is doubtful that the room-temperature value is in error by more than the stated amount, and no remarkable increase in the coefficient seems to occur at 200°K, the present results suggest strongly the need for modification of the Martian ionospheric models to conform to values of $\alpha(CO_2^+)$ substantially less than 10^{-6} cm^3/sec.

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RUTHERFORD SCATTERING OF PROTONS IN THE SURFACE LAYERS OF A TUNGSTEN SINGLE CRYSTAL

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Measurements of Rutherford scattering yields in single crystals have, during the last two years, been used to obtain information about the motion of fast charged particles through single crystals.[1] In the experiments, a very marked decrease in scattering yield is found whenever the particle beam is aligned within a certain critical angle ψ_c of a major crystal axis. The observed critical angles have been in good agreement with the theoretical estimate of Lindhard,[2] $\psi_c = (2Z_1 Z_2 e^2/dE)^{1/2}$. Z_1 and Z_2 are the atomic numbers of the particle and the crystal atoms, respectively; e is the electronic charge; E is the particle energy; and d is the repetition distance of the atoms in the crystal axis parallel to which the particles entered the crystal. ψ_c is typically of the order of 1°.

The minimum yields observed hitherto, have, with few exceptions, been higher than the theoretical estimate for a perfect crystal by a factor of 2-10 depending on the target material. The theoretical estimate is based on the assumption that only those particles in the exterior beam which hit the crystal surface within $\sim a$ [the screening distance in the Thomas-Fermi atomic potential, $a = 0.46(Z_1^{2/3} + Z_2^{2/3})^{-1/2}$

Å] of the center of a row of atoms are able to hit the nuclei of the crystal atoms. The rest of the particles will never come closer than a to the nuclei. This assumption leads to a minimum yield $Y_{min} = 100\pi a^2 Nd\,\%$ of the normal yield, i.e., the yield obtained from an amorphous target. N is the number of crystal atoms per cm^3. Y_{min} is typically 1-2%.

The deviation of the experimentally observed minimum yields from the theoretical estimate may be reasonably explained as being the effect of thermal lattice vibrations[2-4] and amorphous surface layers (e.g., oxide) on the crystal.[1,5]

It is of interest to have an accurate experimental confirmation of the assumption that, for the particles not contributing to the yield, the minimum impact parameter with crystal atoms is ~a. Also, it is of importance to obtain a knowledge of the behavior of the particles in the region immediately below the crystal surface where the beam splits up into the two parts: the one being able to hit crystal atoms, the other not being able to do so. The Rutherford-scattering technique described earlier[1] has therefore been improved by the introduction of a magnetic spectrograph for the energy analysis of the scattered protons. This leads to a depth resolution of ~50 Å compared with ~500 Å obtainable with the solid-state detector used earlier. Furthermore the measurements have been done using tungsten single crystals. Tungsten is known to have only ~1 atomic layer of surface oxide under the vacuum conditions of the present experiment (~10^{-6} mm Hg)[6] and the mean thermal vibrational amplitude at room temperature is 0.08 Å,[7] which is smaller than in most other metals and may be compared with $a = 0.11$ Å.

The measurements were performed in the 600-kV heavy-ion accelerator in Aarhus. A preliminary description of the apparatus is given in Ref. 5. In the measurements presented here, a 400-keV proton beam was used. The current was ~10^{-8} A, the beam cross section 0.8 mm^2, and the angular spread of the beam less than 0.1°. The scattering angle was 90°. The over-all energy resolution, including the instability of the accelerator energy, is shown inserted in Fig. 1 as the spectrum of the primary 400-keV protons measured with the magnetic analyzer.

Figure 1, Curve a, shows the energy spectrum of protons scattered in a tungsten crystal. The crystal surface was parallel to the (100) plane

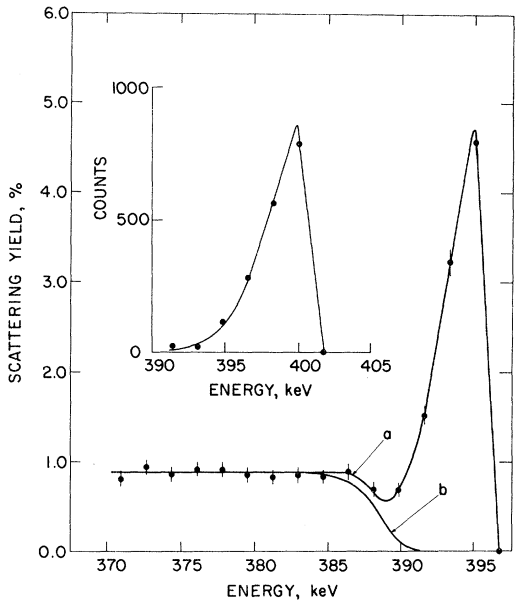

FIG. 1. Energy spectrum of protons scattered 90° in a tungsten single crystal. Energy of incident protons = 400 keV. Curve a: Spectrum measured with proton beam aligned with ⟨111⟩ axis. Curve b: As a, but spectrum corrected for the shape of the resolution curve. Insert: Resolution curve of accelerator and magnetic analyzer.

and the primary beam was incident along the ⟨111⟩ direction. The yield is given relative to the yield from a polycrystalline target.

In the interpretation of the yield curve, it must be pointed out that surface atoms can be hit by the protons even in the case of a perfect crystal, and thus give the normal scattering yield. The underlying atoms are effectively shielded by the surface atoms; they can be hit only by protons which have already been deflected through an angle $\psi \geq \psi_c$ by another row of atoms and which have moved at least a distance $X_1 = c_1/\sin\psi$, where c_1 is the distance between nearest-neighboring atomic rows. During the deflection and along the path length X_1 the protons lose an energy $\Delta E(\psi, c_1)$. Scattering cross sections for fast charged particles are dominated by small-angle scattering, i.e., most of the protons are deflected a small angle $\psi \sim \psi_c$ and have to travel at least a distance $X_1 \approx c_1/\psi_c$ before they can hit an atomic nucleus.

For 400-keV protons incident along the ⟨111⟩ in tungsten, $\Delta E(\psi_c, c_1)$ may be calculated by integrating the electronic stopping along the path of the proton using the electron density corresponding to Lindhard's string potential.[2]

The result turns out to be $\Delta E(\psi_c, c_1) \sim 4$ keV. To this energy loss must be added the energy loss along the path out of the crystal after the scattering event. This loss amounts to ~1.5 keV in the present case. Thus, as a rough estimate, the yield curve is expected to rise from practically zero yield just behind the surface to $\sim 100\pi a^2 Nd\,\%$ of normal yield at ~6 keV below the energy at which the surface yield appears.

The protons scattered from the surface atoms show up in Fig. 1, Curve *a*, as the peak at $E \sim 395$ keV (= 400 keV – the energy lost in the elastic scattering). The shape of this peak fits closely to the inserted resolution curve. The area of the peak is ~1.8 times the area expected from a perfect crystal, where only the first atomic layer (1.03×10^{15} atoms per cm^2) contributes. This indicates either that the density of the first atomic layer is higher than normal or, more likely, that surface disorder or excessive thermal vibrational amplitudes near the surface causes some of the atoms in the underlying layers to be exposed to the proton beam.

To get the yield from the atoms behind the surface, the measured-yield curve must be corrected for the resolution curve, in particular for the tail from the surface peak. The corrected curve is shown in Fig. 1, curve *b*. The shielding effect of the surface atoms is clearly seen. The yield becomes constant at ~10 keV behind the surface peak on the corrected curve (8 keV on the uncorrected) which is in fair agreement with the estimate of 6 keV given above. For $E < 385$ keV the yield is $(0.9 \pm 0.1)\%$ of normal yield. The atoms near the surface not being on lattice sites (0.8×10^{15} per cm^2) scatter ~0.1 % of the original well-aligned beam through an angle $> \psi_c$. This increases the yield behind the surface by ~0.1 % of the normal yield, and for $E < 385$ keV the corrected yield thus becomes $(0.8 \pm 0.1)\%$ of the normal yield. The theoretical value for a perfect crystal without lattice vibrations is $Y_{\min} = 100\pi a^2 Nd\,\% = 0.66\,\%$. Taking into account the lattice vibrations, then according to Lindhard,[2] $Y_{\min} = 100\pi(a^2 + \rho_p^2)Nd\,\%$, where ρ_p is the component of the mean vibrational amplitude perpendicular to the row of atoms. The value of ρ_p given by Lonsdale[7] is $\rho_p = (\frac{2}{3})^{1/2} \times 0.08$ Å, which leads to $Y_{\min} = 0.94\,\%$.

From the good agreement between the theory and the observed minimum yield, it may be concluded that the minimum impact parameter is not greater than ~*a*. Further, the number of atoms obtained from the yield peak area on Fig. 1 is only ~1.8 times the number contributing in the case of a perfect crystal. Therefore the correction due to the surface disorder is small and well defined, i.e., the measured-yield curve is a good approximation to that of a perfect crystal. Thus the yield shows that the minimum impact parameter is not much smaller than ~*a*.

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