Influence of ionic charge state on the stopping power of 27.8- and 40-MeV oxygen ions in the [011] channel of silver

C. D. Moak, S. Datz, B. R. Appleton, J. A. Biggerstaff, M. D. Brown*, H. F. Krause, and T. S. Noggle
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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In many cases, it has been assumed that the stopping power of an ion is not strongly influenced by its ionic charge because screening electrons would largely mask the effect of charge-state differences. Usually it is difficult to tell whether an ion moving through a solid is highly stripped but highly screened or less highly stripped and screened. Earlier experiments had demonstrated that fast prestripped oxygen ions are able to survive passage through crystal channels of $\sim$ 1-μm length and more without electron capture or loss. An experiment to detect slight differences in screening which would cause small differences in the stopping powers of O^{8+}, O^{7+}, and O^{6+} ions has been performed with 27.8- and 40-Mev O ions in the [011] channel of a Ag crystal with 0.8-μm pathlength. The differences are not small. The stopping powers follow the simple relation $S = kq^2$. The result in this case indicates that dynamic screening by conduction electrons plays no significant role in equalizing stopping powers.

I. INTRODUCTION

The effect of screening upon ionic stopping powers has been discussed in the theoretical work of Lindhard, Nielsen, and Scharff,[1] Firsov,[2] and others,[3] following earlier work by Bohr.[4] Recently Brandt *et al.*[5] have developed the concept of dynamic screening, first introduced by Bohr,[4] to account for a strong dependence of the Al K-x-ray cross section in solid Al targets on the charge state of the incident oxygen projectiles of energy 12–68 MeV, for target thicknesses ranging from 0.5 to 25 μg/cm^2. According to the conclusion of Brandt *et al.*, an oxygen ion in the energy range 12–68 MeV will become screened at a rate $\lambda = 5.5 \times 10^{14}$ sec^{-1}. Thus, for a 40-MeV O ion, with ion velocity 2.2×10^9 cm/sec, the ion will become screened within a pathlength of 0.04 μm. It occurred to us that one could utilize the unique constraints imposed on the behavior of well-channeled energetic oxygen ions to evaluate these screening effects.

Several experiments have been reported wherein oxygen ions have been shown to have the unusual property of remaining at one charge state for very great distances when passing along crystalline channels.[6,7] Charge states 8+, 7+, and 6+ are the bare nucleus, the nucleus plus one, and nucleus plus two bound electrons, respectively. Apparently these three ions are almost unable to capture electrons when passing along channels.[7] Both capture and loss cross sections were found to be $\sim 10^{-19}$ cm^2 so that, in a channel, the ionic charge state remains "frozen" for pathlengths $\sim$1 μm. However, throughout this distance the channeled ions would be free to interact with conduction (and weakly bound) electrons. Thus by measuring the stopping power of well-channeled oxygen ions as a function of input charge state one might deduce a mean free path for screening. If oxygen ions are screened within 0.04 μm as suggested, then in the crystals available to us (0.8-μm pathlength) the ionic stopping powers for different input charge states would differ only in the first 5% or so of their total path before screening would equalize their stopping powers. In the absence of screening the stopping powers would be expected to depend on the input charge as $S = kq_i^2$. This then appeared to be a chance to observe screening effects for heavy ions without the uncertainty as to the point-by-point instantaneous ionic charge state.

II. EXPERIMENTAL ARRANGEMENT

The arrangement is shown in Fig. 1. Oxygen ions of 27.8 and 40 MeV were accelerated by the Oak Ridge Tandem Accelerator, passed through a thin carbon foil, and various beam charge states were selected by a 30° analyzer magnet; the selected beam was collimated to an angular acceptance of $\lesssim 0.06°$ and then passed through a single crystal of Ag. The crystal thickness was 0.56 μm and, when oriented to the [011] axial channel at 45°, the effective crystal pathlength was 0.8 μm. A set of collimators selected the central $0.06° \times 0.06°$ of the emergent channeling pattern and these particles were charge analyzed in an electrostatic analyzer. Particle energies were measured with a surface-barrier detector having an energy resolution of 100 keV. Charge-state distributions were measured with a position-sensitive detector for each case. Thus it was possible for a given input charge to measure energy losses of channeled ions as a function of their emergent charge states.

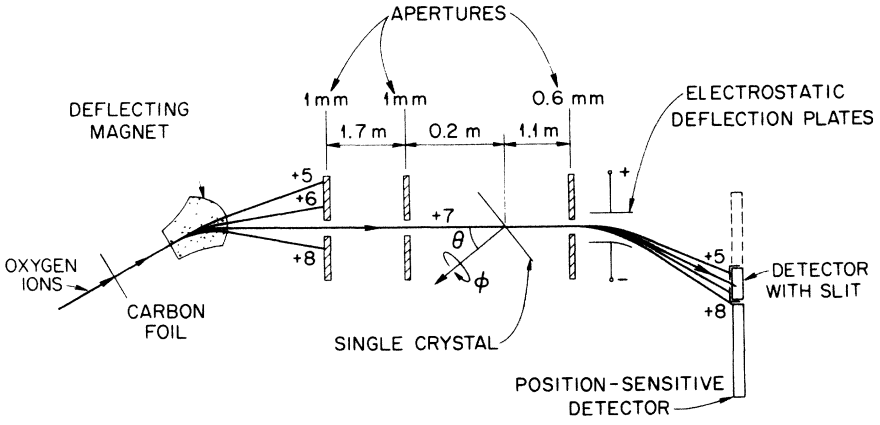

FIG. 1. Experimental arrangement.

III. RESULTS

The first data presented were taken to ascertain whether oxygen charge states behaved in the same fashion in Ag crystals as they had with Au crystals in earlier experiments.[7] Figure 2 shows that, as in the case of Au crystals, 8+, 7+, and 6+ ions do not reach charge-state equilibrium in paths of 0.8-μm length. As before, many (but not all) of these particles pass through without a change of charge and, as before, the fraction surviving without change is larger at 40 MeV than that for 27.8 MeV. From these data it is clear that 8+ is the most probable charge state of the channeled ions

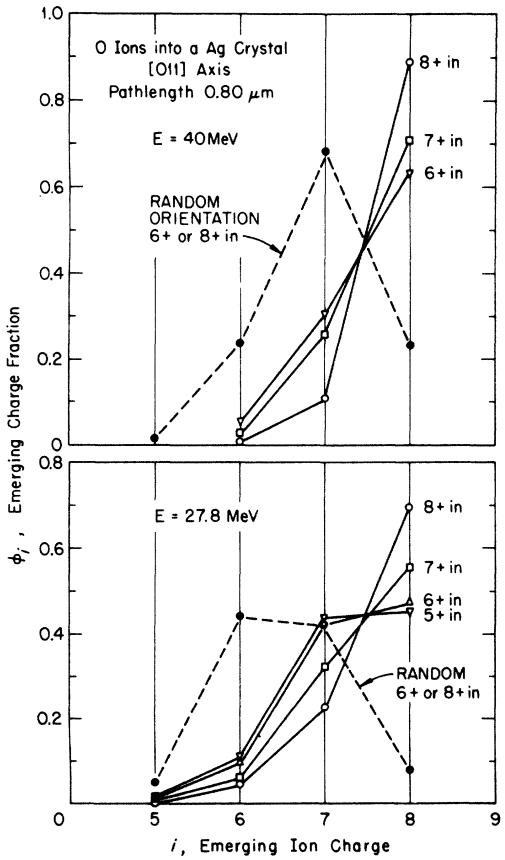

FIG. 2. Charge-state distributions of 27.8- and 40-MeV O ions in Ag.

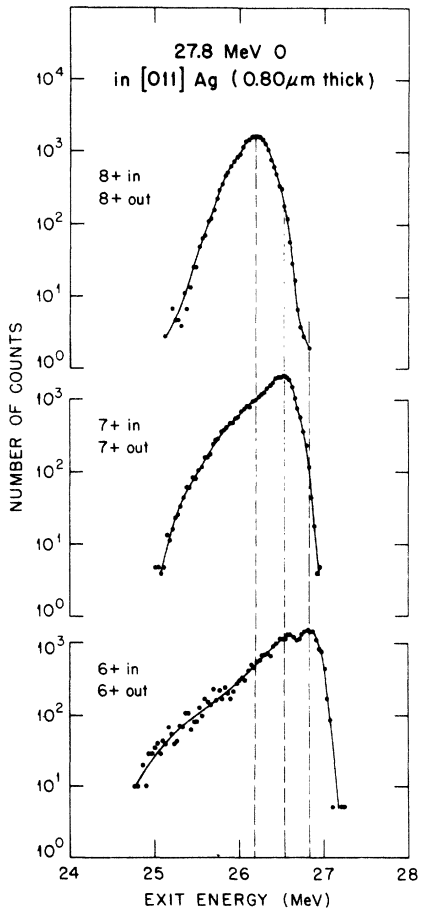

FIG. 3. Emergent energy spectra, 27.8-MeV O ions, 0.8-μm pathlength in [011] channel in Ag. $\Delta q = 0$.

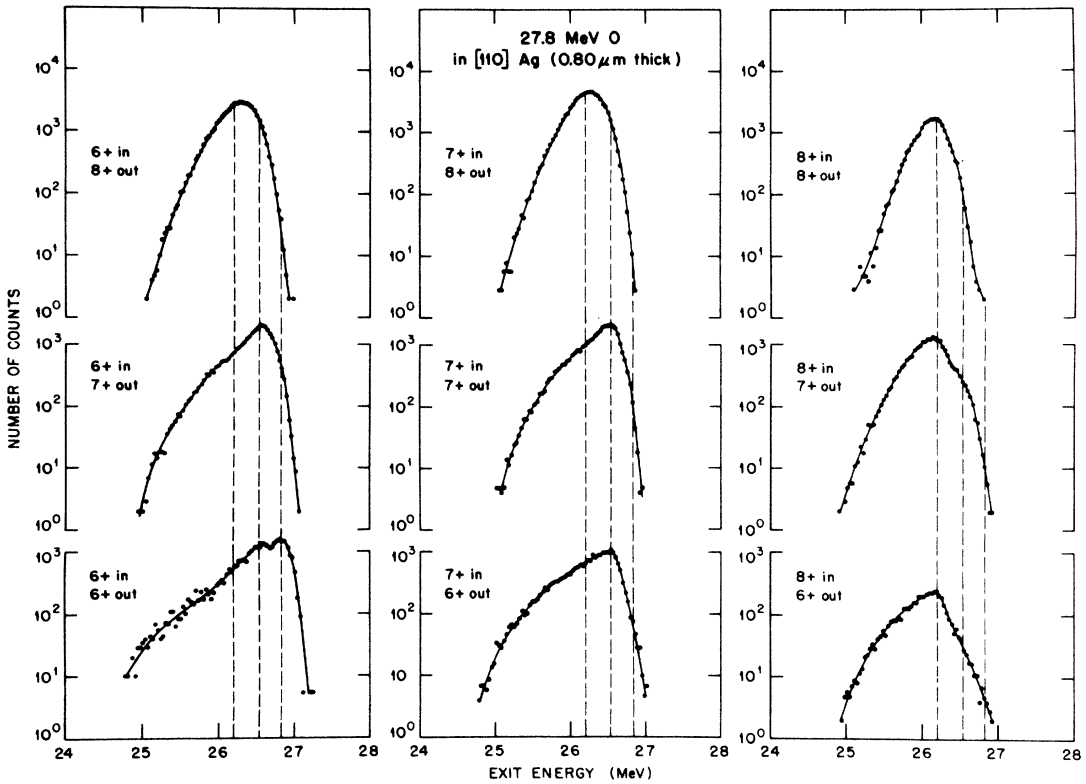

FIG. 4. Emergent energy spectra, 27.8-MeV O ions, 0.8-μm pathlength in [011] channel in Ag. Charge-state combinations, $6 \leq q_{in} \leq 8$ and $6 \leq q_{out} \leq 8$.

and that, e.g., the electron-loss cross section for charge 7+ is greater than the capture cross section for charge 8+.[7]

For each initial charge state, energy-loss distributions were taken for each emergent charge state, a total of nine channeled-particle energy-loss spectra. The first three are shown in Fig. 3 for the case 27.8 MeV. The distribution shown as 8 in, 8 out is simple and narrow and appears to be a typical channeling energy-loss spectrum. The 7-in 7-out distribution is somewhat more complex and wider. The most probable energy is clearly larger than that for 8 in 8 out. It appears that some of the particles changed charge twice and spent part of their time in the crystal as charge 8. The 6-in 6-out pattern is similar to the 7-in 7-out pattern with an added group at higher energy (smaller energy loss). We believe this additional group at higher energy represents those 6+ ions which did not change charge while passing through the crystal and the trends of other data strengthen this belief. The full set of nine spectra is shown in Fig. 4. The vertical dashed lines represent losses in the ratio $8^2 : 7^2 : 6^2$.

If the results are converted to energy-loss units, they can be summarized as shown in Fig. 5, where energy loss is plotted against the square of the ion charge. Clearly the 8-in 8-out, 7-in 7-out, and 6-in 6-out losses follow the relation $S = kq^2$, indicating that screening has not removed their stopping-power differences. Similar data for 40 MeV are shown in Figs. 6 and 7 and the stopping power relation is shown in Fig. 8.[8]

A number of conclusions drawn from the data as to the behavior of typical ions in each group is consistent with what is known about the charge-changing cross sections for oxygen ions in crystal channels. Referring to Fig. 5, it can be seen that the three points labeled 8 in 7 out, 8 in 6 out, and 7 in 6 out indicate that they changed their charge near the point of emergence from the crystal, perhaps at the exit surface itself. The three points labeled 5 in 8 out, 6 in 8 out, and 7 in 8 out indicate that these particles spent most of their time in charge state 8+. The points 5 in 7 out and 6 in 7 out show a stopping power for charge change near foil entry. The conclusions are summarized by the statement that electron capture is more suppressed by channeling than is electron loss, in agreement with earlier conclusions.[7] The same general conclusions apply to the 40-MeV data summarized in Fig. 8.

To observe the contrast between the behavior of

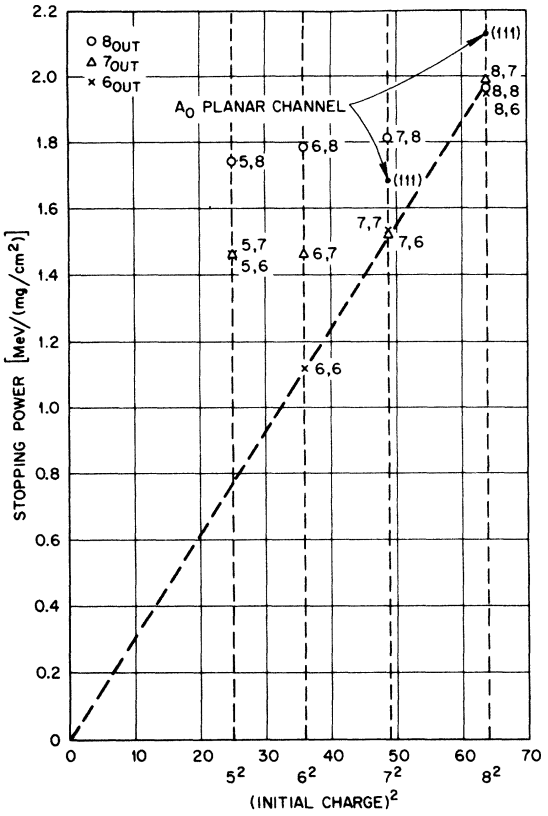

FIG. 5. Stopping powers of 27.8-MeV O ions, [011] axis and (111) planar channel, in Ag, for various charge-state combinations, q_{in} and q_{out}. Points labeled (111) are $8_{in}8_{out}$ and $7_{in}7_{out}$, respectively.

channeled and nonchanneled ions, stopping powers were measured in the same crystal oriented in a nonchanneling direction. As expected, the stopping powers did not vary measurably with initial ionic charge. In this case the ions came to charge-state equilibrium soon after entering the crystal and the distinction with respect to initial charge was quickly lost.

Protons of 1.75-MeV energy and oxygen ions of 28-MeV energy have the same velocity. One of us (B. R. A., unpublished data) has observed a stopping power of 26 keV/μm, or 0.0248 MeV/mg/(cm^2) for 1.75-MeV protons transmitted parallel to the [011] axis of a 0.44-μm-thick Ag single crystal. The coefficient k in the relation $S = kq^2$ taken from the graph of Fig. 5 is 0.0307 MeV/(mg/cm^2). The difference between the two values, 0.0248 and 0.0307 MeV/(mg/cm^2), for protons and oxygen ions is relatively small and in the wrong direction to support the prediction of a screening effect upon oxygen-ion stopping power (see *Note added in proof.*)

As an additional check upon the fact that the channeled ions behave differently according to their charge state, planar channeling group spectra were measured.[9] In this case the crystal was oriented with the beam incident at slight angles to the (111) planar channel. It was expected that if the effective ionic charge of two ions were different then, in addition to showing different stopping powers, they might be expected to oscillate differently in the channel due to the charge dependence of the planar continuum potential. The data in Fig. 9 show that in addition to a simple energy-loss shift, the pattern of peaks has been altered, giving additional qualitative corroboration to the statement that the ions do, in fact, have different effective charges. This new observation should provide a sensitive means of extending our understanding of the ion-atom potential interactions in solids, as determined by planar group-structure measurements and hyperchanneling investigations.[10] The planar stopping powers derived from Fig. 9 demonstrate that during the experiments with the [011] axial channel conditions were suitable for

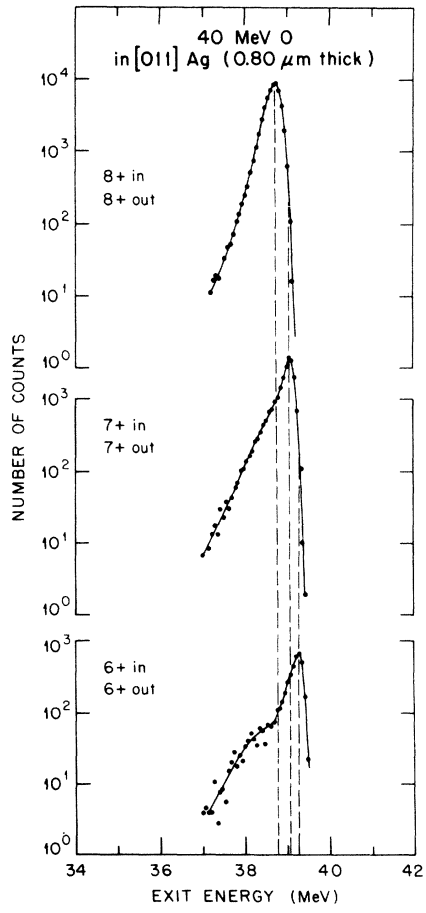

FIG. 6. Emergent energy spectra, 40-MeV O ions. 0.8-μm pathlength in [011] channel in Ag. $\Delta q = 0$.

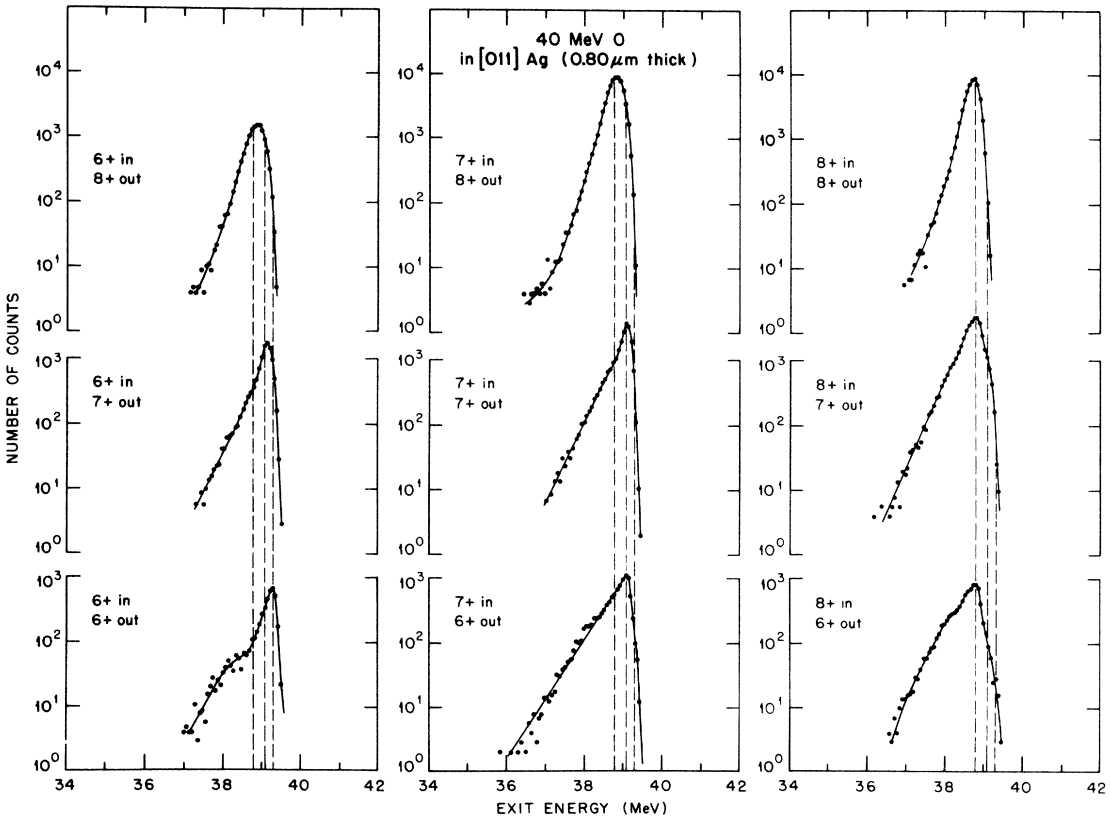

FIG. 7. Emergent energy spectra, 40-MeV O ions, 0.8-μm pathlength in [011] channel in Ag. Charge-state combinations $6 \leq q_{in} \leq 8$ and $6 \leq q_{out} \leq 8$.

hyperchanneling to occur, since the stopping powers for the [011] case were approximately 8.5% less than those measured for the (111) planar channel.[10] The stopping power of the best-channeled ions in the (111) planes, called A_0 on the two curves of Fig. 9, is shown in Fig. 5.

IV. CONCLUSION

Screening by conduction electrons has little effect on stopping in this case. A calculation for $v_1 > v_0$ by Neelavathi and Ritchie[11] shows that the ion is followed by a wake in which there are oscillations in the electron density both above and below the unperturbed densities. Immediately following the ion there is an enhanced density which has a node at a distance $\pi v/\omega_p$ behind the ion, where ω_p is the plasmon frequency inside the metal. The number of electrons contained in this wave is equal to the charge on the moving ion. For 40-MeV O ions the enhanced-density lobe is ~60 Å long, it is symmetric with a peak 30 Å behind the ion, and the enhanced density at the nucleus is close to zero. The effect of adding a bound electron to the

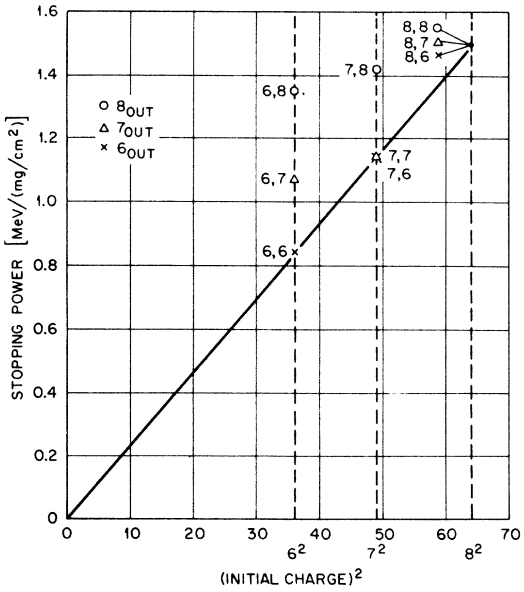

FIG. 8. Stopping powers of 40-MeV O ions, [011] axis in Ag, for various charge-state combinations, q_{in} and q_{out}.

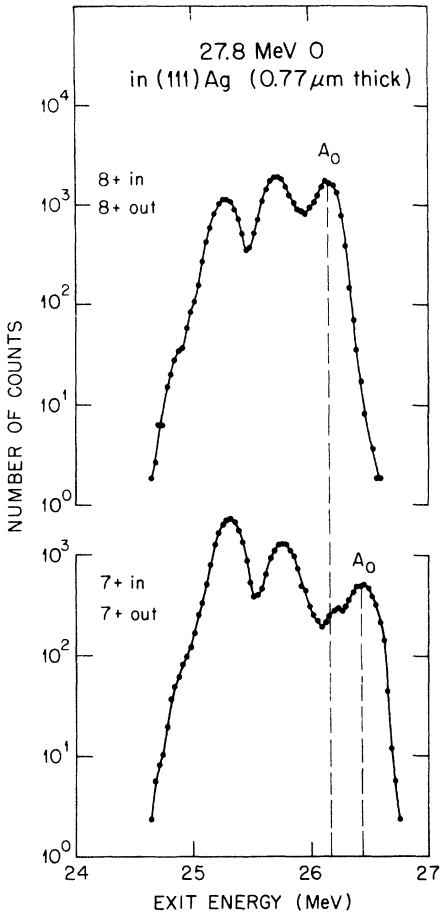

FIG. 9. Group structure for 27.8-MeV O ions emerging from (111) planar channels in Ag.

nucleus would be to totally screen one unit of the nuclear charge at a distance of about 0.1 Å (i.e., somewhat larger than $\frac{1}{8}a_0$). The bulk of the stopping power arises from interaction with more distant electrons. In addition, bound electrons would screen the nucleus by one unit of charge each and the trailing electron wake would be ineffective in influencing the stopping power.

Earlier unreported work on the stopping powers of heavy ions in very thin polycrystalline carbon foils gave some indication of dependence upon the initial ion charge state. In this case the evidence was that the ions approached charge-state equilibrium very rapidly. Charge-state distributions of 100- and 140-MeV Br ions emerging from thin polycrystalline foils have been reported to show that charge-state equilibration occurs in very short distances.[12] At 40 MeV the cross sections for 7-8 and 8-7 charge change in oxygen were measured by Martin and MacDonald.[13] The values, 3×10^{-18} and 1.5×10^{-17} cm^2, respectively, in argon, would indicate a mean free path for charge change of $\sim10^{17}$ atoms/cm^2. This corresponds to the depth in aluminum over which Brandt *et al.* observed variations in x-ray yield with incident charge state. It appears that charge-state equilibration phenomena could account also for the data reported by Brandt *et al.*

Note added in proof. The 24% difference reflects the Z_1^3 term in the stopping power [cf. Jackson and McCarthy, Phys. Rev. B 6, 4131 (1972)]. The term accounts for 21% of the 24% difference and brings the proton and oxygen numbers into agreement within experimental error.

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