Diffraction of Low-Energy Ion-Induced Secondary Electrons Emitted in the Forward Direction from a Solid Foil

A. R. Goñi, S. Suárez, P. R. Focke, G. C. Bernardi, and W. Meckbach

Centro Atómico Bariloche (Comisión Nacional de Energía Atómica), 8400 San Carlos de Bariloche, Río Negro, Argentina, and Instituto Balseiro (Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo), 8400 San Carlos de Bariloche, Río Negro, Argentina

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By the measurement of doubly differential distributions of electrons emitted downstream when 170-keV protons pass through thin carbon foils, besides the convoy electron peak and the characteristic ridge, centered in the beam direction and found also in gas targets, a lateral structure is observed at larger angles. The location of this structure can be uniquely and quantitatively attributed to electron diffraction in the three-dimensional reticule of the polycrystalline foil. Electrons in the central ridge are found to diffract, while the convoy electrons do not.

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Recently a sharp ridge in distributions doubly differential in energy and angle of electrons emitted downstream when protons of 100–170 keV collide with He atoms has been found in this laboratory. In electron velocity space **v** it extends along the beam direction from low velocities up to the so-called convoy-electron peak localized at $\mathbf{v}=\mathbf{v}_i$, the ion velocity, and through it, appearing also at the high-velocity side of this peak where it gradually disappears. This ridge, which forms a link between the low-velocity electron peak due to target-electron emission into the Coulomb field of the ionized target atom and the convoy-electron peak of electrons transferred into the continuum of the moving ion, can be interpreted as due to electrons moving in the potential saddle between these two charged centers.

We now report about measurements of electron distributions, taken under otherwise identical experimental conditions, but using a solid foil target. Our measurements include an angular range of up to $+60°$; this enabled us to look for structure in the measured distributions at large angles. We do indeed observe prominent structure. The purpose of this paper is to present the measured distributions and to show that this structure corresponds to Bragg diffraction of electrons in the 0° ridge by crystal planes of the solid. This is one of the first observations of an interpretable, distinctly solid-state effect on the distribution of secondary electrons produced when ions interact with matter.

The proton beam, furnished by the Bariloche Cockcroft-Walton accelerator, interacted either with a He-gas target delivered by an atomic beam emerging from the 0.25-mm bore of a hypodermic needle, or with a solid C foil. These targets were localized at the object focus of our coaxial cylindrical-mirror electron spectrometer[1] which permits us to cover the angular range from $-60°$ to $+60°$ in a continuous manner without interception of the ion beam. It was thus possible to obtain electron distributions, down to $E_e=30$ eV, with negligible background due to stray electrons. This was verified by measurement of the ion beam on but without a target. Spectra were taken as a function of the electron energy E_e at a series of distinct prefixed angles θ with respect to the beam direction. This permitted us to construct three-dimensional distributions defined in velocity space v of the emitted electrons.[1,2] An example of such distributions for the case of gas and solid foil targets is seen in Figs. 1(a) and 1(b) represented as a function of the longitudinal speed $v_{\parallel}$ defined along the forward direction ($\theta=0°$) in the laboratory and the transverse speed $v_{\perp}=v_{\parallel}\tan\theta$. In order to account for deformations in these distributions caused by the increase of the instrumental resolution volume, defined in v space,[1] the measured signal has been divided by v^3. This is simply explained by the fact that this resolution volume is proportional to the third power of the electron speed.[3] We observe the typical convoy-electron peak localized at $v_{\parallel}=v_i$ and $v_{\perp}=0$. Furthermore, we see that the mentioned sharp longitudinal ridge is not only pronounced in the ion-gas collisions but is also present in the case of downstream beam-foil secondary electron emission.

We now focus our attention on two spectacular lateral humps that appear symmetrically on both sides of this central ridge. In Fig. 2 we show a cut through the distribution of Fig. 1, represented as a function of θ and for a constant $v=2$ a.u. At this electron speed the convoy electron peak, centered at $v=v_i=2.6$ a.u., has essentially decayed. The corresponding results obtained with a He-gas target are also included. It is clearly seen that the central ridge is very similar to those obtained under single-collision conditions with H^+ and neutral H^0 projectiles, respectively. The lateral hump, however, is observed only with the solid target. This means that its appearance must be attrib-

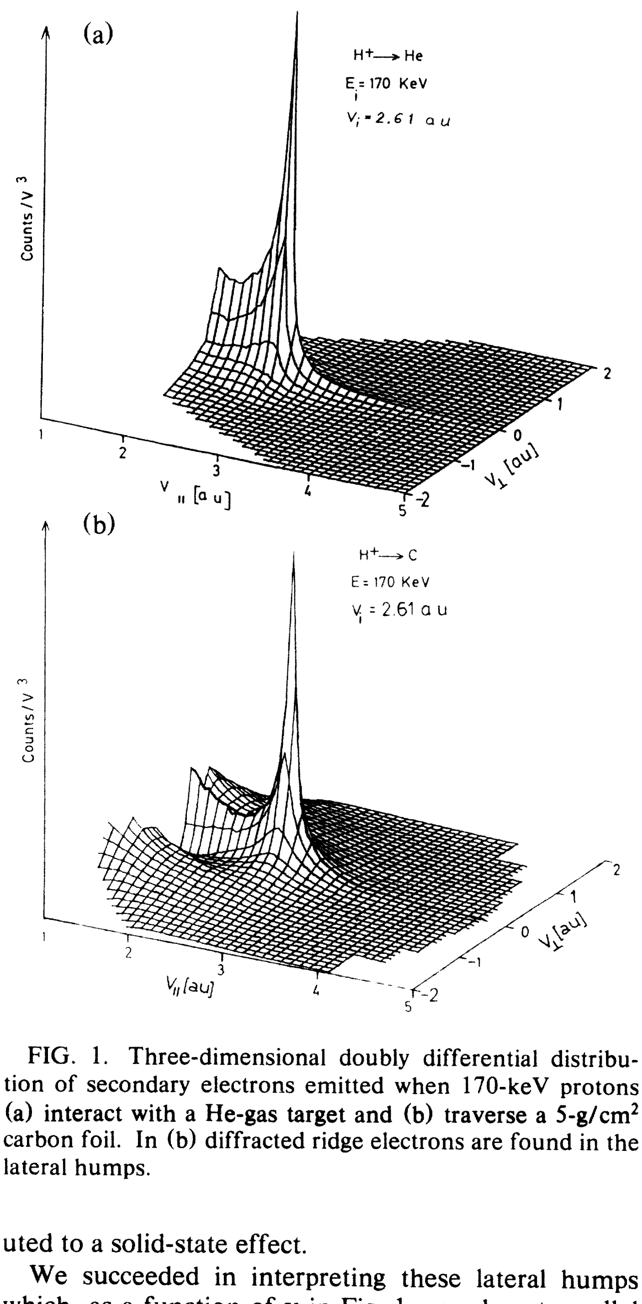

FIG. 1. Three-dimensional doubly differential distribution of secondary electrons emitted when 170-keV protons (a) interact with a He-gas target and (b) traverse a 5-g/cm^2 carbon foil. In (b) diffracted ridge electrons are found in the lateral humps.

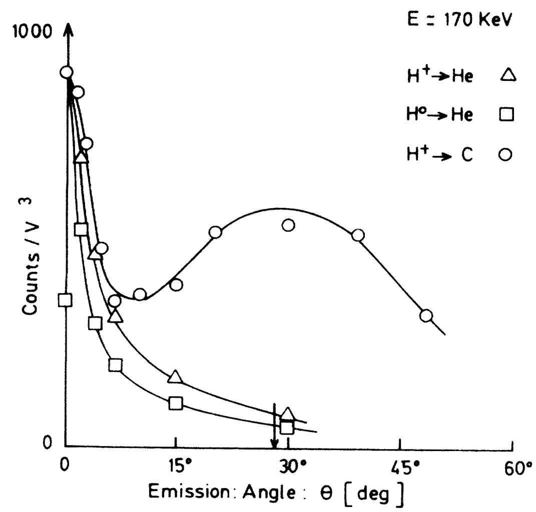

FIG. 2. Angular distributions of electrons of 2-a.u. speed measured with 2.6-a.u. protons and H^0 in He and with protons incident upon a 5-g/cm^2 carbon foil. The central ridge is seen in all cases, the lateral hump only with the solid target. The arrow shows where a diffraction pattern in the first order with $(hkl) = (002)$ is expected.

uted to a solid-state effect.

We succeeded in interpreting these lateral humps which, as a function of **v** in Fig. 1, are almost parallel to the central ridge, as due to diffractive electron scattering in the polycrystalline structure of the solid. These electrons find their origin in that central ridge. We thus deal with electron diffraction of the Debye-Scherrer type, but originating from an aligned source of electrons of different speeds.

By observation of diffraction patterns with the help of the 80-keV beam of an electron microscope it was verified that the carbon foils used contained a polycrystalline structure. This structure was found to be that of graphite, i.e., compact hexagonal with the lattice parameters $a = 1.415$ and $c = 6.696$ Å.[4] The first and most intense fringe is known to pertain to diffraction in first order $(n = 1)$ on a set of Bragg planes of distance $d_{hkl} = [(h^2 + k^2 + hk)/3a^2 + l^2/c^2]^{-1/2}$, with Miller indices $(hkl) = (002)$, that is, $d_{002} = 3.35$ Å.

We now have to understand what kind of diffraction pattern observed in electron momentum or velocity space v (we use atomic units) is expected from a beam of electrons, all emitted in the same direction—that of the central ridge—but with different speeds v. For a given set of Bragg planes the velocity vector of the diffracted electrons conserves its magnitude v, it being diffracted by an angle θ determined by Bragg's law, which expressed in v_e space reads

$$\pi n / d_{hkl} = v \sin(\theta_n/2). \qquad (1)$$

For a polycrystalline solid the velocity vectors of the diffracted electrons describe cones of half-angle θ; their end points lie on spheres of radius v. For a specific set of Bragg planes and order n, $v \sin(\theta_n/2) = \text{const} = R$. Then, if v is allowed to vary, the resulting velocity vectors of the diffracted electrons will be localized on a surface of cylindrical symmetry determined by $v_{\parallel} = v \cos\theta$, $v_{\perp} = v \sin\theta$, in a plane containing its axis $(\hat{\mathbf{v}} = \mathbf{v}_i)$ where $\theta = 2\sin^{-1}(R/v)$. In Fig. 3 a cut through this cylinder in a plane containing its axis $(\mathbf{v} = \mathbf{v}_i)$ is shown. Our spectrometer permits the localization of the emitted electrons in v_e space. Measuring their distribution as a function of electron energy, i.e., speed v, we go along radii extended from the origin forming an angle θ with the axis; measuring angular distributions at given speeds v, as in Fig. 2, we describe circles of radii v. A diffraction hump is ex-

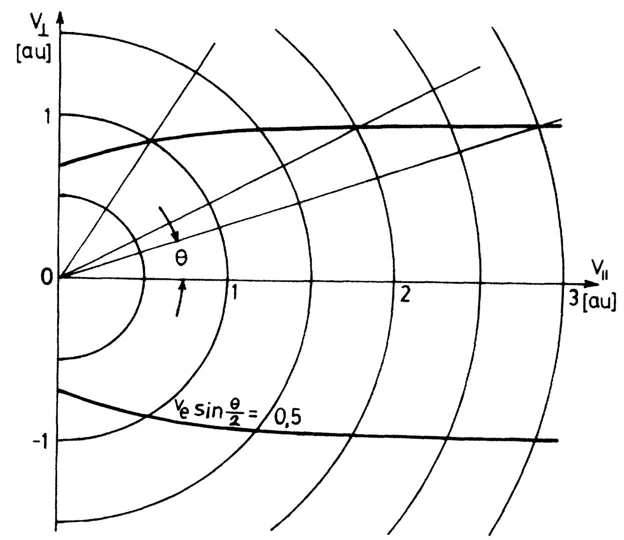

FIG. 3. Localization of the diffraction pattern in electron velocity space resulting from an aligned source of electrons of different speeds. For more details, see text.

pected where these radii or circles intersect the mentioned cylinder.

In Table I we show the angles θ_{emp} that result from the position of the lateral humps in angular spectra like that of Fig. 2, obtained at different electron speeds v. The third column contains the empirical distances d_{emp} of the Bragg planes that, assuming first-order diffraction ($n=1$) result, according to Eq. (1), from these measured diffraction angles. As expected, within experimental errors the d_{emp} are independent of the electron speed v. Furthermore, their mean value is found to be in quantitative agreement with the distance d_{002} of the Bragg planes that in first order are known to lead to the most intense diffraction.

Figure 1 calls attention to the fact that the origin of the lateral diffraction humps can be attributed only to the central ridge, but not to the convoy-electron peak. At the site where electrons diffracted from the convoy peak would be expected there is no sign of a diffraction peak. Taking into account that the signal in the convoy-electron peak is more than 10 times that in the ridge, we conclude that the convoy electrons do not contribute to the observed diffraction in the three-dimensional lattice of the solid.

This evidence is consistent with a model for production of "intrinsic convoy electrons,"[5] in which electron transfer into the continuum occurs not in the bulk but upon emergence of electrons with $\mathbf{v} \approx \mathbf{v}_i$ through the exit surface. However, it is also obvious that convoy electrons, that are strongly correlated to and described by a Coulomb wave centered at the moving ion,[6] cannot give rise to the observed diffraction which we have found to be typical for plane waves, that is,

TABLE I. Empirical angular positions of diffraction maxima as a ful ction of secondary electron speed, v_e, and corresponding empirical distances between Bragg planes, d_{emp}. Also shown is the known d_{002} for planes with Miller indices (002).

v_e (a.u.)	θ_{emp} (deg)	d_{emp} (Å)	d_{002} (Å)
1.5	35+5	3.7+0.5	
2.0	30+10	3.2+1.0	
2.25	23+3	3.7+0.5	
2.5	20+5	3.8+0.9	
Mean distance		3.6+0.3	3.4

free electrons.

To our knowledge up to date there has been no evidence of bulk diffraction in a crystalline reticule of electrons in the lower energy range of ≈ 100 eV. Furthermore, this is perhaps the first time that such a clear-cut solid-state effect has been observed in ion-induced secondary-electron emission originating in the last few crystalline layers of a solid.

We will submit a more extended description and analysis of this interesting effect including measurements with other solid targets. This analysis confirms that the diffracted electrons originate within about 20 Å of the surface, in accordance with other recent observations.[7]

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