Heavy-Ion–Induced Shock Electrons from Sputter-Cleaned Solid Surfaces

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(Received 19 February 1987)

Heavy-ion (C^+,N^+,Kr^+)-induced low-energy electron emission ($E_e \leq 30$ eV) has been measured from controlled surfaces of thin solid targets (C,Al,Cu) under ultrahigh-vacuum conditions ($p \simeq 10^{-7}$ Pa). The angular distributions of low-energy electrons exhibit prominent structures. In each studied detail these structures agree with the predicted directed emission of "shock electrons" produced by the collective response of the electron plasma of the solid to the distortion of the penetrating heavy ion.

PACS numbers: 79.20.Rf

Penetrating through a thin solid foil target a charged particle can give rise to (1) a number of single-excitation processes and (2) a collective coherent excitation of the electron plasma of the solid.[1] If we consider the mechanism of collective excitation in a linear-response model of the electron plasma of the solid, the distortion caused by energetic (megaelectronvolt) heavy ions consists of periodic electron density oscillations propagating behind the moving ion.[2,3] The corresponding damped oscillatory wake potential[4] shows the characteristic behavior of Mach cones[5] if the projectile velocity v_p exceeds the Fermi velocity v_F of the electrons in the medium ($v_p > v_F$).[5] Heavy-ion–induced Mach shock waves are predicted to lead to the interesting phenomenon of directed electron emission ("shock electrons") from the solid surface.[5-7] The preferential emission angle θ_{em} of shock electrons is perpendicular to the shock front; θ_{em} is given by the Mach relation

$$\cos\theta_{em} = v_s/v_p, \tag{1}$$

where v_s is the group velocity of the shock front.[5]

Because of the ultrasonic propagation of the projectile ($v_p > c_s$) through an electron plasma with the sound velocity c_s, the induced density fluctuations ρ are large compared to the mean plasma density ρ_0 ($\rho > \rho_0$) of the medium; the shock velocity $v_s(\rho)$ then is a function of density ρ.[8]

It has been suggested[5,6] to find experimentally shock electrons in both the projectile velocity dependence and the mean target-electron–density dependence of ion-induced electron spectra differential in energy and in angle. The first experimental indications of directed electron emission in heavy-ion–solid collisions had been given by Frischkorn *et al.*[9] using the system C^+ (3.6 MeV) $\rightarrow$ C (20 μg/cm^2). Since the shock electrons are predicted to be emitted with velocities $v_e \simeq v_s$,[5] i.e., with kinetic energies $E_e \leq 20$ eV, they are extremely sensitive to surface properties, i.e., surface structure, surface potential, and coverage with adsorbed substances. Because of uncontrolled surface conditions the results of the quoted paper[9] had not been fully convincing concerning the shock electrons.

The results presented in the present Letter have been obtained, however, for the first time from sputter-cleaned, controlled solid surfaces under ultrahigh-vacuum (UHV) conditions ($p \simeq 10^{-7}$ Pa) with a residual surface coverage of less than at least 0.3 atomic layer. The experimental setup and the UHV-measuring system, especially developed for low-energy electron spectroscopy, will be described in detail elsewhere.[10] In addition, a three-dimensional system of Helmholtz coils compensates the Earth's magnetic field inside the scattering chamber to better than 8×10^{-7} T. The surface condition of the target foils has been controlled by means of Auger electron spectroscopy (AES), secondary electron spectroscopy (SES), and Rutherford backscattering (RBS).[11] The sputter-cleaned C, Al, and Cu targets ($1000\ \text{Å} \leq x \leq 3700\ \text{Å}$) with tilt angles $20° \leq \alpha \leq 60°$, respectively, to the beam direction have been bombarded with C^+, N^+, and Kr^+ ions with velocities $1 v_B \leq v_p \leq 2.85 v_B$ (v_B denotes the Bohr velocity). In this velocity range we expect the predicted formation of shock waves to be most pronounced on the assumption of a constant projectile charge, because the coupling between the projectile charge and the electron plasma of the solid reaches a maximum at projectile velocities $v_p \simeq 2.5 v_B$.[12]

Five experimental aspects of shock electron emission will be discussed below.

(1) In Fig. 1 we present three sets of angular distributions of electrons ($40° \leq \theta \leq 105°$) at three projectile velocities $v_p = 1.65 v_B$, $2.30 v_B$, and $2.85 v_B$, resulting from C^+-C foil collisions. In every data set a structure appears at electron energies $E_e < 20$ eV with an intensity maximum at 5 ± 2 eV, which is in agreement with theoretical predictions.[6] The observed structures correspond to an additional fraction of low-energy electrons superimposed on the continuous secondary-electron background, which is indicated in Fig. 1 by the interpolating thin solid lines.

(2) One of the most important fingerprints of the ex-

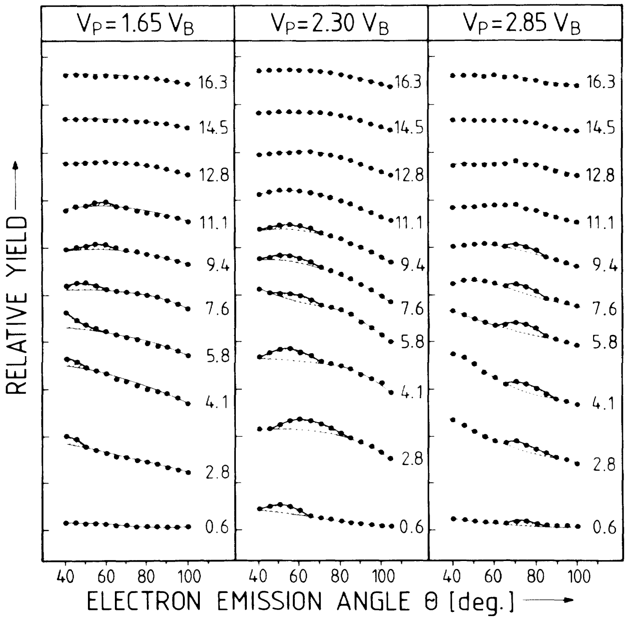

FIG. 1. Angular distribution of low-energy secondary electrons ($0.6\,\mathrm{eV} \leq E_e \leq 16.3\,\mathrm{eV}$) from a carbon foil induced by C^+ ions for three different projectile velocities v_p. The thin solid lines guide the eye through the secondary-electron contribution. The numbers on the right-hand side of each column denote the electron energy (in electronvolts).

istence of shock electrons is to prove experimentally the validity of the Mach relation for the measured low-energy structure. As can be seen clearly in Fig. 1 the mean angle of the peak structure between 48° ± 2° and 73° ± 2° depends on the incident-ion velocity v_p and can be represented by the Mach relation Eq. (1). Figure 2 exhibits the mean emission angle θ_{em} of electrons in the measured (possible) shock peak as a function of projectile velocity v_p in comparison with the theoretical predictions of Schäfer and co-workers[5,6] made for a carbon target and a shock velocity of $v_s = 1.24 v_{\mathrm{B}}$. The earlier data at higher ion velocities of Frischkorn and co-workers[9,13] which have been measured under high-vacuum conditions ($p \simeq 10^{-4}$ Pa), indicated by the much larger error bars, are also given in Fig. 2. These data[9,13] have been included in Fig. 2 since we found that the mean angle of the structure was independent on the target surface condition. In all cases studied, however, the width of the peak structure both in angle and in electron energy was significantly smaller in the case of a sputter-cleaned target than in the case of an uncleaned target. Surprisingly, the Mach relation Eq. (1) is fulfilled for all experimental data obtained from different target materials. Compared to the theoretical values the experimental data from the carbon foil are shifted systematically to higher emission angles ($\Delta\theta_{\mathrm{em}} \simeq 9°$). A possible explanation is that the calculations are based on

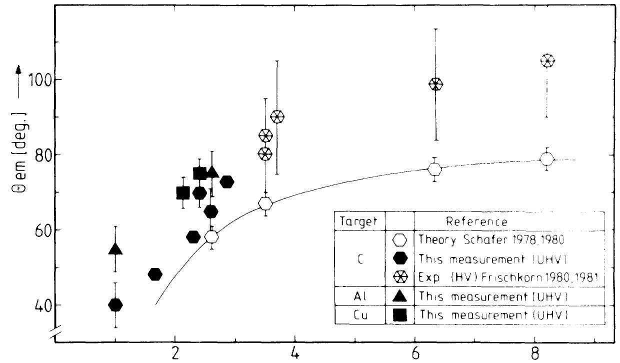

FIG. 2. Mean emission angle θ_{em} of shock electrons as a function of the projectile velocity v_p. The theoretical values (interpolated by the solid line) are given for a carbon target and a shock velocity $v_s = 1.24 v_{\mathrm{B}}$. The data are taken from this experiment (carbon, solid hexagon; aluminum, solid triangle; copper, solid square). Additional experimental data are from Ref. 9 and Ref. 13 (carbon, open hexagon with asterisk); calculations from Ref. 5 (carbon, open hexagon).

the mean plasma density of diamond-structured carbon ($\rho_0 = 3.5 \times 10^{23}/\mathrm{cm}^3$) (Ref. 5) instead of the mean plasma density of amorphous carbon foils ($\rho_0 < 3.5 \times 10^{23}/\mathrm{cm}^3$).[14] Furthermore, the influence of the solid surface on the shock electron emission is not included in the calculations.[5,6] Electrons, also shock electrons, penetrating a solid and approaching its surface may be scattered by the surface potential of the solid and suffer an energy loss when transiting the surface.[15] This diffraction, which is not included in the theory,[5,6] leads to a broadening of the shock structure and consequently to a smearing of the emission angle. This broadening also occurs if the surface plane has geometric inhomogeneities. An inspection of our sputter-cleaned target surfaces with a scanning electron microscope did not reveal any structure (resolution better than 0.05 μm). Detailed results concerning the important influence of surface properties on low-energy electron emission, especially caused by collective excitation of the electron plasma in solids, such as shock electrons and single-electron excitation by plasmon decay, will be given in a forthcoming paper.[16]

(3) As a result of the lower plasma electron density of Cu [$\rho_0(\mathrm{Cu}) = 0.85 \times 10^{23}/\mathrm{cm}^3$] and Al [$\rho_0(\mathrm{Al}) = 1.8 \times 10^{23}/\mathrm{cm}^3$] compared to that of carbon [$\rho_0(\mathrm{C}) < 3.5 \times 10^{23}/\mathrm{cm}^3$] the emission angle θ_{em} of shock electrons from Al and Cu is enhanced. Consequently, with lower plasma electron density the Mach angle of the wake at $v_p = \mathrm{const}$ is decreasing and the emission angle [Eq. (1)] is increasing, in agreement with the experimental observation.

(4) Further, it is predicted[6] that the Mach angle is independent of the projectile charge Z_p. The experimental data compiled in Fig. 2 have been obtained with heavy

TABLE I. Comparison of theoretical predictions (Refs. 5 and 6) of Mach-shock–induced directed electron emission with the present experimental results.

Theoretical predictions (Refs. 5 and 6)	Experimental results (This work)
(1) Energy of shock electrons: $E_e \leq 20$ eV.	$E_e(\mathrm{C}) \leq 12$ eV, $E_e(\mathrm{Al}) \leq 10$ eV, $E_e(\mathrm{Cu}) \leq 20$ eV.
(2) Mach relation $\cos\theta_{\mathrm{em}} = v_s/v_p$.	The observed mean emission angle θ_{em} can be represented by the Mach relation.
(3) θ_{em} increases with decreasing plasma electron density ρ_0 ($v_p = \mathrm{const}$).	$\theta_{\mathrm{em}}(\mathrm{Cu}) > \theta_{\mathrm{em}}(\mathrm{Al}) > \theta_{\mathrm{em}}(\mathrm{C})$ ($v_p \simeq 2.6 v_{\mathrm{B}}$).
(4) θ_{em} is independent of the projectile charge Z_p and the projectile mass M_p.	For the projectiles C^+, N^+, and Kr^+ no dependence of θ_{em} on Z_p has been observed.
(5) Shock velocity v_s: $1.5c_s \leq v_s \leq 2c_s$.	$v_s(\mathrm{C}) \simeq 1.5c_s(\mathrm{C})$, $v_s(\mathrm{Al}) \simeq 1.2c_s(\mathrm{Al})$.

ions such as C^+, N^+, O^+, and Kr^+, but do indeed reveal no Z_p dependence.

(5) The group velocity v_s (shock velocity) of the distortion in the electron plasma of the solid should be larger than the sound velocity c_s ($1.5c_s \leq v_s \leq 2c_s$).[6] Surprisingly, our data yield v_s/c_s values which are close to this range ($v_s/c_s = 1.5$ for C and $v_s/c_s = 1.2$ for Al).

In Table I we summarize the results and compare the theoretical predictions[5,6] with our experimental findings. In view of the good agreement between theoretical predictions and experimental results for all studied parameters characteristic for Mach phenomena, we conclude that the results present the first clear evidence for the existence of Mach-shock–induced directed electron emission in heavy-ion–solid collisions.

Stimulating discussions with H. Stöcker, W. Griener, and B. Müller, J.-W. Goethe University, Frankfurt am Main, and with W. Schäfer, Telenorma, Frankfurt am Main, are gratefully appreciated. This work has been funded by the German Federal Minister for Research and Technology (BMFT) under the Contract No. 06 OF 173 11.

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