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LETTER TO THE EDITOR

Structure in the electron energy spectrum from multi-keV Ar^+ — Au and Ar^+ — Cu collisions

In a recent paper Fano and Lichten [1]) suggested a mechanism for the ionization of atoms and ions during violent collisions, which differs from the statistical theory of Russek [2]). They assume the non-adiabatic formation of an excited molecular ion. The particles then separate into states highly excited through electron promotion, and subsequently emit electrons by auto-ionization. With this mechanism they can explain the discrete inelastic energy losses found by Afrosimov *e.a.* [3]) and by Kessel *e.a.* [4]) for Ar^+–Ar collisions. It follows that the energy spectrum of the ejected electrons will be a test for this mechanism and Fano and Lichten predict the presence of discrete electron groups at energies simply related to the level structure of the colliding particles. In particular for collisions involving Ar, they predict strong peaks in the neighbourhood of 200 eV and suggest that such peaks be sought. At lower energies analogous peaks have been observed by Berry [5]).

It has been shown earlier in this laboratory that some aspects of two-body atomic collisions can be studied using solid target materials [6]) [7]). We have applied this technique to examine the energy spectrum of electrons ejected as a consequence of collisions of Ar^+ and Ne^+ ions with energies of 60 keV, 80 keV, and 90 keV on polycrystalline Au

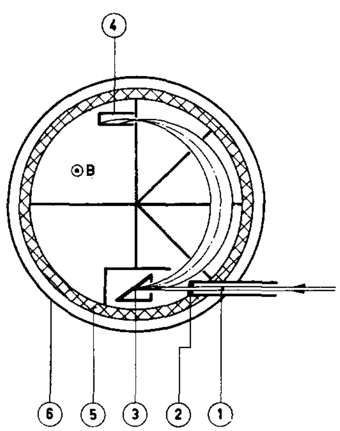

Fig. 1. Cross section of the apparatus.
The ion beam (1) enters through an aperture of 1 mm diameter (2) and hits the target (3). Electrons of a certain energy from the target are focused into the collector (4) by the magnetic field caused by the coil (5). The magnetic shielding (6) prevents outside fields to influence the electrons. The length of the coil is 100 mm, the diameter 50 mm

and Cu targets. A cross section of the analyzing instrument is shown in fig. 1. Electrons ejected by ion bombardment move in a magnetic field of variable strength and ideally can reach the collector only if their energy, E, satisfies the equation

$$E = cI^2 \tag{1}$$

in which I is the current through the analyzer magnet coil, and c is a constant determined by the apparatus. The solid angle accepted by the analyzer $d\Omega = 6 \times 10^{-2}$ sr and the energy half width is 10%.

The analyzer was calibrated with the help of the low energy electrons. These were accelerated by a known potential applied to the target. For calibration the target arrangement differed from that indicated in fig. 1 in that the accelerating field was

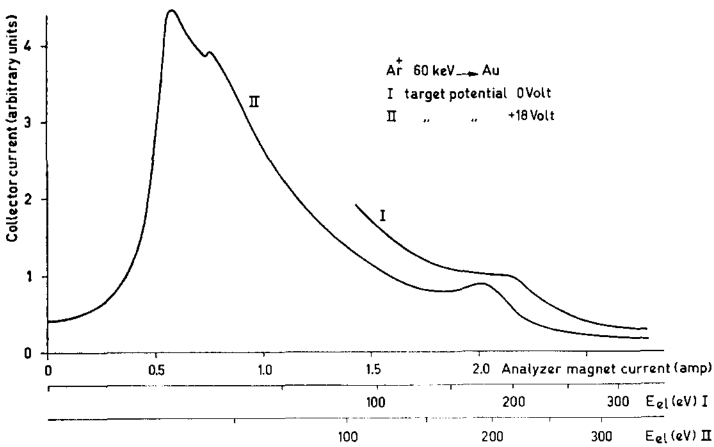

Fig. 2. Magnetic analysis of the electrons ejected during the bombardment of Au with Ar^+ ions of 60 keV. The energy scales corresponding to the curves I and II are corrected for the retarding potential applied to the target

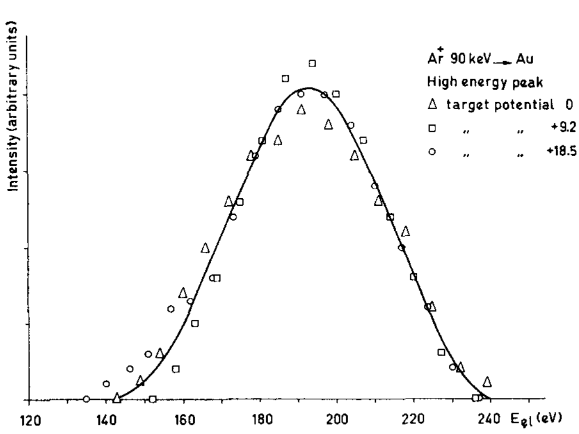

Fig. 3. Energy distribution of the electrons in the energy region 125 eV–250 eV (background subtracted). An Au target is bombarded with 90 keV Ar^+ ions. The experimental points are corrected for the retarding target potential. The height of the maximum corresponds to about 10^{-5} electrons/ion

parallel to the initial beam direction. In the range from 75 V to 250 V, c in eq. 1 was constant within 5%.

During the measurements the low energy electrons were suppressed by potentials up to 30 V on the target. The intensity of the ion beam was about 2 μA/mm^2.

Fig. 2 shows a typical electron momentum distribution for Ar^+ on Au at 60 keV. The portion corresponding to energies greater than 100 eV shows a hump on the continuously decreasing background. This hump shifts with a changing target potential in a manner expected for electrons of energy indicated by the calibration. The hump becomes more prominent as the retarding potential is increased, an effect to be expected if some of the background is due to low energy electrons following complex trajectories.

In fig. 3 we show the results obtained from Ar^+–Au runs at 90 keV for retarding potentials of zero, 9.2, and 18.5 V. We have subtracted the background, making reasonable assumptions about its behaviour and have plotted the points on an energy scale corrected for retarding potential. The ordinates are unaltered. It will be noted that a single curve represents the three sets of data within experimental scatter. The breadth of the curve at half maximum is about 40 eV. At the maximum the number of collected electrons per incoming ion, n^-/n^+, is about 10^{-5}. If we assume the electrons being isotropically distributed and the target density $N = 1.5 \times 10^{15}$ atoms per cm^2 (one atom layer), the cross section for the production of these electrons is

$$\sigma = \frac{4\pi}{\mathrm{d}\Omega} \frac{n^-}{n^+} \frac{1}{N} \approx 10^{-18}\ \mathrm{cm}^2.$$

The results of determinations of the most probable energy for Ar^+ bombardment are given in table I. Energy values have been corrected for retarding potential. The scatter among peak energies for a given target is less than $\pm 5\%$. For each primary ion energy at least two retarding potentials were used, one of which was at least 9.2 V. Evidently there is a group of ejected electrons at about 192 eV arising from Ar^+–Au; the most probable energy of this group is practically independent of the energy of the bombarding ions. Similarly, arising from Ar^+–Cu there is a group at about 182 eV. We place a precision of $\pm 10\%$ on these values; however, the difference of 10 eV

TABLE I

Energy groups in electron spectra

Primary energy (keV)	Ar^+–Au		Ar^+–Cu	
	No. of trials	Average energy at peak (eV)	No. of trials	Average energy at peak (eV)
60	9	192	3	182
80	2	191	2	182
90	12	193	4	181

between the two values appears to be neither instrumental nor statistical in origin.

A number of trials were made using Ne^+ ions on the same targets and at the same ion energy values. The energy spectrum from Ne^+ has no structure in the region of interest, at least to the sensitivity of our analyzer.

A number of runs with the Au target and with both kinds of ions exhibited a small peak at about 50 eV (fig. 2). Because the total signal is quite large and because the energy at this peak is comparable with the retarding potentials employed, we have not attempted to interpret this structure.

The survey of the electron energy spectrum was extended to about 1200 eV but no further evidence of structure could be found.

According to Fano and Lichten the result of a collision involving an Ar ion in the energy range of our experiments may be to raise an electron from the L shell into a higher unfilled level. The internal vacancy is filled by an Auger process which involves two outer electrons. One of these is ejected with kinetic energy equal to the particular L shell ionization potential (about 250 eV) less the energy for a double ionization from the outer shells ($\gtrsim$ 43 eV). Electron kinetic energies of 200 eV or somewhat less can be expected. The spectrum of energies should be independent of increasing primary ion energy as long as no new level crossings are produced.

The term values of Ne and Cu lead to the prediction that no energy groups should be expected from these sources in the interval from 50 eV to at least 700 eV. The target material Au could give many groups in the energy interval we have examined.

The experimental results given in table I and also the negative results found with Ne^+ bombardment can be understood in terms of the Fano-Lichten mechanism. The electron groups of table I appear to be associated with argon rather than the target materials. The breadth of the hump is consistent with the possibility for superposition of alternative multi-electron M shell excitations. The 10 eV difference between the positions of the peaks found with Au and Cu targets may be explained by a difference in the distributions of these excitations caused by differing details of the level crossing. The appearance of a strong group of electrons at 180 or 190 eV, the lack of ion energy dependence of this energy, the striking difference in behaviour between Ar and Ne, and the magnitude of the cross section, cannot be explained on the basis of a purely statistical model of electron ejection.

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