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LETTER TO THE EDITOR

Auger decay of excited Ar projectiles emerging from carbon foils

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Abstract. The absolute yield of Ar L Auger electrons emitted by 48–722 keV argon beams emerging from carbon foils has been measured. It is found that the Auger process is not the main effect which determines the difference between the mean charge of Ar projectiles in solid and gaseous targets in this energy range.

The electronic states of fast projectiles moving through solids has been a subject of great interest since 1951, when Lassen (1951) found that the average charge q_s of heavy ions emerging from solids is higher than the mean charge state q_g for ions emerging from gases. Several arguments have been given to explain this effect. Bohr and Lindhard (1954 to be referred to as BL) suggested that collisions with the target atoms lead to excitation of the most loosely bound electron in the heavy ion and that because of the rapid frequency of collisions the excitation will not be dissipated by radiation or electron emission like in a gas, but would lead to an enhanced probability for electron loss in subsequent collisions. A further increase in the mean charge would also occur by Auger transitions immediately after the excited ions emerge from the solid into vacuum. On the basis of experimental data on collisions in dense gases, Betz and Grodzins (1970, to be referred to as BG) suggested that the electron loss per atom is hardly affected by the excitation of a single electron and, as a consequence, that substantial excitation due to successive collisions is probable for all of the outer electrons. These highly excited ions would then decay by electron emission after emerging from the solid, thus increasing the mean charge. In this model supported by the similar stopping powers in gases and solids, the mean charge q_i inside the solid is assumed to be similar to q_g in disagreement with the model by BL. Therefore, the amount of electron emission by Auger processes needs to be much larger in the BG model than in the BL model. Other factors which have not been included in these models are the dynamic screening of the projectile charge by the target electrons and the electron capture of correlated electrons at the target surface (McLelland 1968, Brandt 1975) and the fact that bound highly excited electrons with large orbits may not exist as such inside the solid.

Recently, several attempts have been made to deduce the average charge inside the solid from the projectile charge-state dependence of target x-ray production cross sections (Brandt *et al* 1973, Datz *et al* 1974) and from the energy shifts in projectile

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x-ray spectra in solids caused by outer-shell vacancies (Knudson *et al* 1974, Fortner and García 1975). The results are however conflicting; the reported values of q_i are smaller and larger than q_s . This may reflect the fact that due to screening produced by electrons from the solid, q_i will depend on the distance r from which the projectiles are observed. For sufficiently large values of r , q_i is even zero, in the case of metals.

Additional information on this problem can be obtained by the measurements of the contribution to the mean charge q_s given by the inner-shell Auger effect outside the solid. In this work we present the first *absolute* Auger electron measurements with projectiles emerging from solid targets; the system chosen is medium-energy argon projectiles passing through thin carbon foils.

Beams of 100–800 keV Ar^+ or Ar^{2+} ions were collimated by 2 mm diameter slits and entered the scattering chamber described in detail previously (Stolterfoht 1971, Stolterfoht *et al* 1975). In this work, the chamber was modified to incorporate a multiple-foil holder. Beam currents were kept low (~ 10 nA) to minimize damage to the (10 ± 2) $\mu\text{g cm}^{-2}$ carbon foils. Energy and angular distributions of forward-emitted electrons were measured with a calibrated, rotatable electron spectrometer of 2.6% energy resolution (Stolterfoht *et al* 1975). The foils were positioned normal or tilted by 45° with respect to the incident-beam direction. With the tilted foils it was found that the angular distribution of forward-emitted electrons is symmetrical to the normal to the foil.

Figure 1 shows a typical spectrum taken with 400 keV Ar^+ incident on a tilted foil. The plot indicates Ar L and C K Auger electrons superimposed on a continuous background. (The background may contain unknown contributions of spurious stray electrons at energies larger than 400 eV.) The inset of figure 1 shows the Auger spectrum after background subtraction. The uncertainty in the subtraction procedure is small since in all cases the Auger peaks were substantially higher than the background. After subtracting the small ($\sim 10\%$) contribution of C K electrons, the Auger peak was integrated to obtain $d\Gamma/d\omega$, the probability for producing Ar L Auger electrons per incident ions and unit solid angle. Typical angular distributions for beams incident normal to the foils are shown in figure 2 after correcting for kinematic

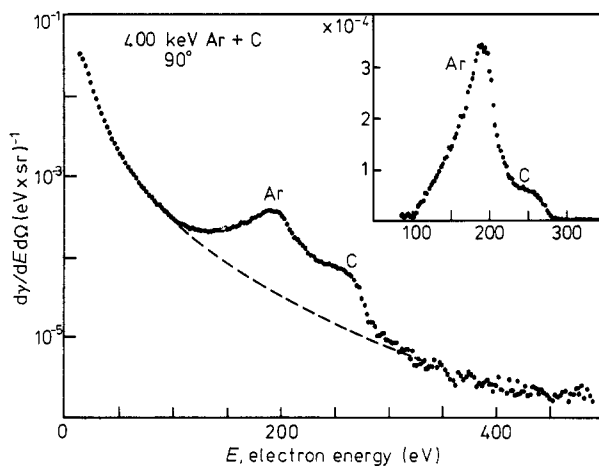


Figure 1. The number of electrons emitted per unit energy and solid angle and per argon ion incident at 400 keV on a tilted (45°) carbon foil. The observation angle is 90° relative to the beam, i.e. 45° relative to the foil normal. The inset shows the Auger spectrum only.

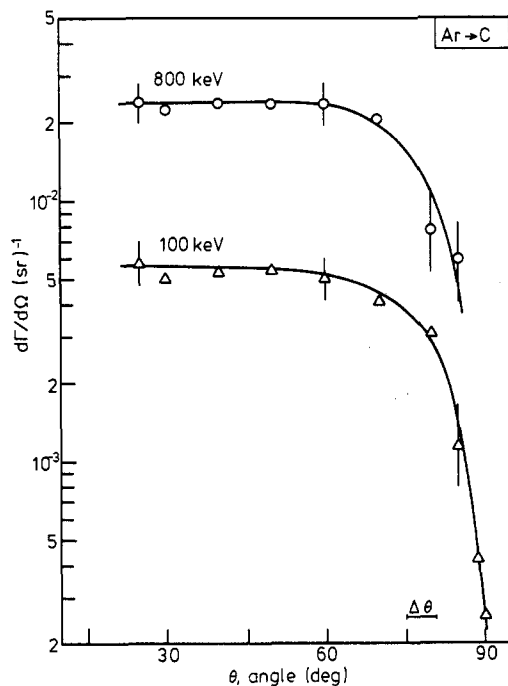


Figure 2. The angular distributions of forward-emitted Ar L Auger electrons for 100 and 800 keV incident argon ions normal to the foil, corrected for kinematic effects. $\Delta\theta = 6^\circ$ is the angular acceptance of the spectrometer.

effects (Stolterfoht *et al* 1975). (The data at angles larger than 75° may be influenced by effects of surface topography and foil distortion.) In table 1 results are given for Γ which were obtained by integrating $d\Gamma/d\omega$ in the forward 2π hemisphere. Also shown in table 1 are the mean charge q_s (Wittkower and Betz 1975, Turkenberg *et al* 1975) and the average energy E_e of the emerging beam particles calculated from the incident energy E_i and known values of electronic and nuclear stopping powers (Der *et al* 1971).

The contribution of Auger electrons emitted inside the foils is expected to be small, since their escape depth ($\sim 8 \text{ \AA}$) is short (Powell 1974) compared with the decay length of 30–50 \AA at our lowest velocity, using the lifetime value

Table 1. Probability Γ for Ar L Auger electron production in the forward 2π hemisphere. E_i and E_e are the incident and emerging energies of the Ar projectiles, respectively. The average charges q_s of the emerging ions are taken from Wittkower and Betz (1975) and Turkenberg *et al* (1975).

E_i (keV)	E_e (keV)	q_s †	Γ
100	48	0.40	0.027 ± 0.005
200	146	1.03	0.076 ± 0.012
400	340	1.83	0.10 ± 0.015
600	535	2.26	0.11 ± 0.016
800	722	2.62	0.12 ± 0.016

† Wittkower and Betz (1975) and Turkenberg *et al* (1975).

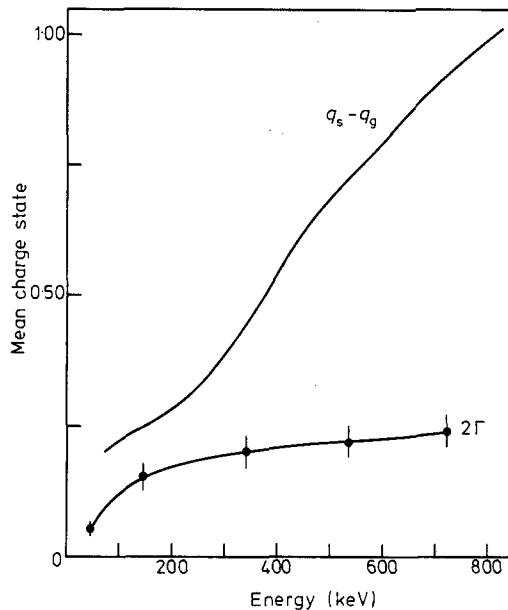


Figure 3. The increase in mean charge due to Auger processes, 2Γ , and $q_s - q_g$, the difference in the mean charge of Ar ions after traversing carbon foils and nitrogen gas.

$6.1\text{--}9.5 \times 10^{-15}$ s of Fortner and García (1975). Thus we suggest that the observed Auger electrons originate essentially from Ar particles which have left the foil. Furthermore, the contribution of backward-emitted electrons which are elastically reflected from the surface and detected, is expected to be small (Sternglass 1954). Assuming that in the projectile rest-frame the Auger emissions are equal for the backward and forward hemisphere, the fraction of the emerging beam with vacancies in the L-shell is given by $f_L = 2\Gamma$. The radiative decay of the 2p vacancies can be neglected since the fluorescence yield for Ar projectiles of low average charge is small (Fortner and García 1975). The present f_L values are substantially smaller than those derived indirectly by Fortner and García (1975) from the analysis of thick-target x-ray yields. This is probably due to the approximations made in the model from which Fortner and García (1975) extracted their results.

Near the surface the Auger process increases the charge state of the Ar projectiles by one. Hence, the contribution of Auger processes to the projectile charge 2Γ as shown in figure 3. Unfortunately, the mean charge state q_g of Ar particles emerging from carbon-gas targets is not known. However, it is expected that q_g for carbon ($Z = 6$) is nearly equal to that of nitrogen ($Z = 7$). In figure 3, the difference in the mean charge of Ar emerging from carbon foils $q_s(\text{C})$ and nitrogen gas $q_g(\text{N})$ is plotted (Wittkower and Betz 1975, Turkenburg *et al* 1975). It is clear that Auger processes account only for part (at our highest energy only 25%) of the difference in the mean charge between solids and gases in the studied case. For other projectile-target combinations this contribution is expected to be even smaller, since in the Ar-C system the cross section for inner-shell vacancy production is particularly high due to level matching (García *et al* 1973).

In conclusion, Auger electron emission by projectiles emerging from solids is not, at least for C foils and Ar projectiles in the studied energy range, the main effect which causes the difference in the mean charge between solid and gaseous targets.

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