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Selective production of Auger electrons from fast projectile ions studied by zero-degree Auger spectroscopy

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Abstract. Projectile L-Auger electrons were measured with high resolution in collision of 91.6 MeV Ar^{q+} on gaseous target atoms. Kinematic (Doppler) broadening effects were significantly reduced by observing the Auger electrons at an angle of zero degrees. Light target atoms were used to avoid considerable changes in the outer shell of the projectile during L-shell ionisation. Thus, the predominant excitations of the configurations $1s^22s^22p^53s^23p$ and $1s^22s^22p^53s^2$ are achieved for incident Ar^{5+} and Ar^{6+}, respectively.

High-resolution Auger spectroscopy in energetic ion–atom collisions has received a great deal of attention in the past few years (Rudd and Macek 1973, Stolterfoht *et al* 1977, Mann *et al* 1981). In particular, increasing interest has been devoted to studies of highly ionised particles extracted from the accelerator or produced in collisions. Unfortunately, Auger electrons ejected in ion–atom collisions are considerably affected by kinematic line broadening effects (Dahl *et al* 1976, Stolterfoht *et al* 1975). The broadening effect for the target electrons is primarily produced by momentum transfer on the recoil atom. This effect may greatly be avoided by using incident projectiles of high energies (Matthews *et al* 1973). In this case, however, complicated Auger spectra are often produced due to the creation of numerous Auger states. To obtain simple Auger spectra, the target atom has to be stripped to a few electron system (Stolterfoht *et al* 1977, Matsuo *et al* 1983). The broadening for the projectile electrons originates from the finite acceptance angle of the electron spectrometer and it increases with increasing projectile energy. This effect cannot easily be avoided for high incident energies. Hence, the number of high-resolution studies of Auger electrons from fast projectiles is still limited at present (e.g. Haselton *et al* 1975, Bisgaard *et al* 1981, Schneider *et al* 1981).

In this work, the method of zero-degree Auger spectroscopy is introduced for fast incident ions. For electron observation angles of zero degree, the broadening effect due to the finite acceptance angle of the spectrometer cancels in first order. Hence, it is shown that high-resolution Auger spectroscopy is possible for multiply charged Ar projectiles of nearly 100 MeV. In particular, it is found that the Auger spectra are dominated by a few distinct peaks which are characteristic for the charge state of the projectile. This opens up the possibility of studying selectively Auger transitions in highly charged particles, since the projectile charge state may readily be prepared in the experiment.

The experiments were performed at the heavy-ion accelerator facility VICKSI at the Hahn-Meitner-Institut Berlin. The apparatus has been described before (Schneider *et al* 1982), so that only information concerning the zero-degree method will be given. Beams of 91.6 MeV $^{36}Ar^{5+}$ and $^{40}Ar^{6+}$ passed through a target cell of 10 cm length. The gases H_2, He and Ne were used as targets at pressures of some millibars in the cell. Care was taken to retain single-collision conditions. In the vacuum chamber the pressure of the target gas was better than 10^{-2} mbar and its effect could be neglected in the present experiments. Electrons ejected from the projectile were analysed by an electrostatic spectrometer located at a distance of 35 cm from the target cell. For the zero-degree measurements the ion beam was directed through the spectrometer using various apertures of diameters from 2 mm to 4 mm. To avoid slit scattering, the ion beam was carefully collimated to 1 mm diameter. Typical beam currents of 10 nA were obtained. The electron acceptance angle of the spectrometer was $\pm 0.3°$.

Two types of spectrometers were used in the experiments. Firstly, the single electrostatic spectrometer was applied as described previously (Stolterfoht *et al* 1973). To ensure a safe passage of the ion beam through the spectrometer, rather large apertures were used. Hence, with the single spectrometer set up only the relatively low resolution of 1% was obtained. Secondly, a tandem spectrometer was constructed where two devices of the usual type were combined. One spectrometer with relatively large slits had the purpose to deflect the electrons out of the ion beam. The electrons were directed into the other spectrometer used for the energy analysis. In this case smaller apertures were applied so that the resolution could essentially be improved. For the tandem spectrometer the resolution of 0.1% was achieved.

Kinematic effects may easily be analysed for the electron observation angle of zero degrees. The energy E of the Auger electron in the laboratory frame of reference is obtained from the electron energy E' in the projectile rest frame by

$$E_{H,L} = (t_p^{1/2} \pm E'^{1/2})^2 \tag{1}$$

where $t_p = T_p m/M$ is the projectile energy reduced by the electron–projectile mass ratio. Since we deal with fast projectiles ($t_p \gg E'$), there are two solutions (+ and − sign) referring to Auger electrons ejected at 0° and 180° in the projectile rest frame. Thus, in the laboratory frame Auger electrons are produced in a high (H) energy range and a low (L) energy range, respectively. The electron production cross section differential in electron energy and solid angle transforms as follows:

$$\frac{d\sigma}{dE\, d\Omega} = \left(\frac{E}{E'}\right)^{1/2} \frac{d\sigma'}{dE'\, d\Omega'}. \tag{2}$$

Similarly, the width ΔE of an Auger line transforms according to

$$\Delta E = \left(\frac{E}{E'}\right)^{1/2} \Delta E'. \tag{3}$$

Consequently, because of $E_{H,L} \gg E'$, the width of an Auger line decreases by the transformation from the laboratory into the projectile rest frame. However, on the contrary, the *relative* width $\Delta E/E$ increases by the frame transformation.

In first order the kinematic line broadening ΔB_θ (Stolterfoht *et al* 1975) produced by the finite acceptance angle $\Delta\theta$ of the spectrometer cancels at zero degrees. There,

the second-order term is obtained as

$$\Delta B_\theta = \Delta\theta^2 t_p \left[\left(\frac{t_p}{E'} \right)^{1/2} + \left(\frac{E'}{t_p} \right)^{1/2} \pm 2 \right]. \tag{4}$$

For the present collision systems the kinematic broadenings were calculated to be smaller than 0.2 eV. It could be neglected in the present experiments. (For comparison, at 15° observation angle it follows in first order that the broadening is much larger, i.e. $\Delta B_\theta \simeq 30$ eV.)

For 91.6 MeV $^{40}Ar^{6+}$ projectiles the low (L) and high (H) energy Auger spectra are observed in the ranges from 450 to 680 eV and from 1800 to 2800 eV. After subtraction of the continuous background, the spectra were transformed from the laboratory frame into the projectile rest frame by means of equations (1) and (2). In figure 1, examples are given for Ar^{6+} on He as obtained with the single spectrometer set up. The widths of the Auger peaks are essentially determined by the energy resolution of the spectrometer, since the Doppler broadening is negligible in the present zero-degree measurements. It should be recalled that the transformation of the spectra increases the relative width of the Auger lines. Effectively, this 'stretching' effect results in a loss of resolution. Hence, the effective resolution of 5% was achieved for the spectra shown in figure 1.

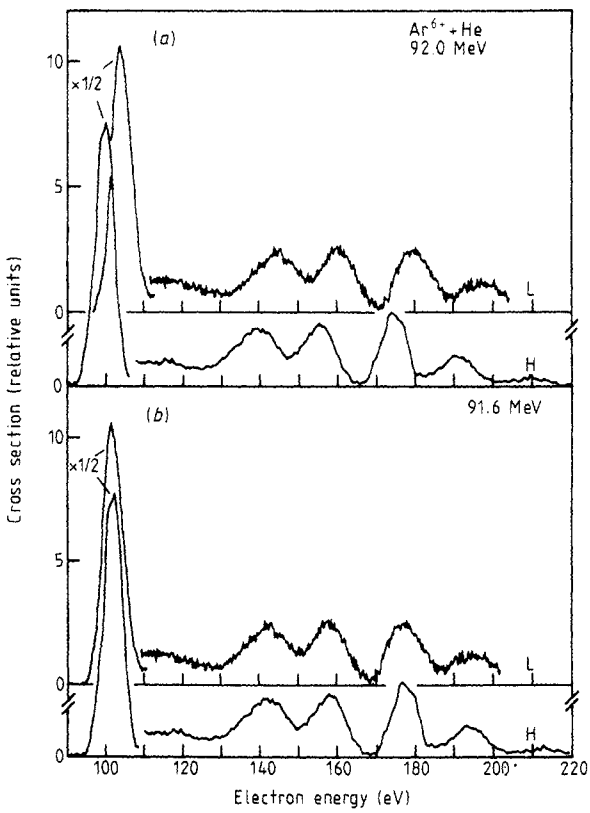

Figure 1. Ar–L Auger spectra from $^{40}Ar^{6+}$ on He transformed from the low (L) energy range and the high (H) energy range of the laboratory rest frame into the projectile rest frame. Projectile energies of 92.0 MeV in (*a*) and 91.6 MeV in (*b*) are adopted.

In figure 1 the spectral labelled L and H are identical within the statistical errors indicating that the Auger electrons ejected at 0° and 180° in the projectile rest frame are equal in intensity. The comparison of the Auger spectra measured in the low and high energy ranges allows for the calibration of the Auger energies. This was achieved by adjusting the projectile energy in equation (1) (which was not exactly known) until the corresponding Auger lines acquired in the two energy ranges coincide in position. In figure 1 results for projectile energies of 92.0 MeV and 91.6 MeV are given. The adjustment procedure yields projectile energies as well as Auger energies with relatively high accuracy. (Note that relation (1) implies two equations which allows for the determination of both t_p and E'). From the width formula (3) it follows that the error of E' is equal to $\Delta U(E'/t_p)^{1/2}$ where $\Delta U \leqslant 2$ eV is the uncertainty of $(E_L + E_H)/2 \simeq t_p$ produced primarily by contact potentials. This shows that the Auger spectroscopy with fast projectiles ($t_p \gg E'$) allows for reducing the error created by contact potentials. In this work the absolute Auger energies are determined with an uncertainty of ±0.5 eV.

Figure 1 shows that the spectrum produced in 91.6 MeV Ar^{6+} + He collisions is dominated by one peak at 102 eV. To obtain more information about the spectral structure, the charge state q of the projectile was varied. In figure 2 the data for $q = 6$ are compared with results acquired with $q = 5$. The corresponding Auger spectra are seen to be completely different. The peak at 102 eV is relatively weak in the Ar^{5+} spectrum. It exhibits additional structures which are dominated by the peak at about 112 eV.

It should be emphasised that the use of the relatively light target atom He facilitates the task of line assignment. During the L-shell excitation, He only weakly affects the outer shell of the projectile, as shown further below. Hence, it is expected that apart

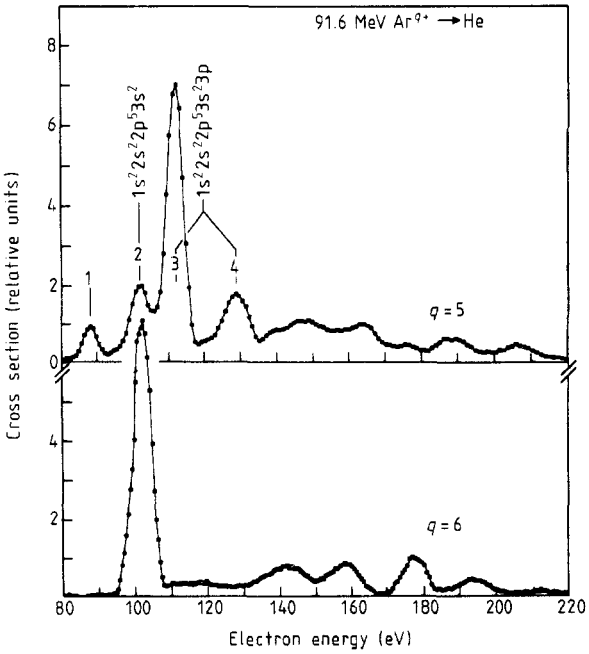

Figure 2. Ar–L Auger spectra from 91.6 MeV $^{36}Ar^{5+}$ and $^{40}Ar^{6+}$ incident on He. The electron energy refers to the projectile rest frame.

from the removal of the 2p electron the configuration of the incident projectile is essentially retained in the collisions. The ground-state configuration of Ar^{6+} is $1s^2 2s^2 2p^6 3s^2$ while Ar^{5+} has an additional 3p electron. Thus the most prominent peaks 2 and 3 are attributed to the configurations $1s^2 2s^2 2p^5 3s^2$ and $1s^2 2s^2 2p^5 3s^2 3p$, respectively. Also, peak 4 is attributed to the initial configuration $1s^2 2s^2 2p^5 3s^2 3p$ which, however, decays to a final state different from that for peak 3. The origin of peak 1 is unknown. However, it should be referred to the presence of the 3p electron.

It is noted that each peak in figures 1 and 2 refers to a group of unresolved lines. For instance, doublets of 2.2 eV separation are expected following from the $2p_{1/2}$–$2p_{3/2}$ fine-structure splitting in the initial state (Larkins 1977). Individual lines are observed in the spectra acquired with the high-resolution tandem spectrometer. This is seen in figure 3 showing part of the Ar^{5+} + He spectrum where the effective resolution is 0.5%. Spectroscopic data for the lines observed in figure 3 are summarised in table 1. The present Auger energies agree well with recent results obtained by the well known method of target Auger spectroscopy (Matsuo *et al* 1983). Also shown in table 1 are estimated results obtained by extrapolation of theoretical data given by Dahl *et al* (1976). Peak group 2 clearly shows the two lines produced by fine-structure splitting. The peak groups 1, 3 and 4 exhibit additional lines due to term splitting. Here, further theoretical work is needed to identify the individual lines.

The occurrence of the (weak) peak 2 in the Ar^{5+} spectrum shows that there is a possibility of ionisation of the 3p electron in addition to removal of the 2p electron. The corresponding probability is expected to increase when the nuclear charge of the target atom increases. This can be seen from figure 4 where Ar^{5+} Auger spectra are compared for different target species. The intensity of peak 2 normalised to the total intensity of the Auger spectrum is equal to 0.062, 0.095 and 0.102 for H_2, He and Ne, respectively. Under the assumption that the 3p ionisation is independent of the removal of the 2p electron, the relative intensity of the peak 2 is equal to the probability for 3p ionisation by the target atom passing through the L-shell radius of the projectile. Theoretical ionisation probabilities estimated using the scaling procedure of Hansteen *et al* (1975) are found to be consistent with the present results for H_2 and He. For Ne the perturbation theory implied by Hansteen *et al* (1975) is expected to loose significance for the ionisation of Ar 3p electrons.

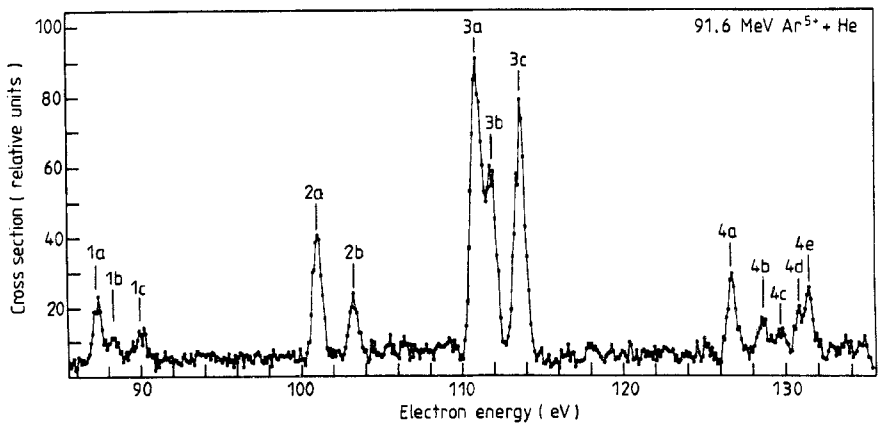

Figure 3. Part of the $^{36}Ar^{5+}$ on He spectrum measured with the high-resolution tandem spectrometer.

Table 1. Spectroscopic data for some prominent Auger lines shown in figure 3. Relative and absolute values of the Auger energies have uncertainties of 0.1 and 0.5 eV, respectively.

Peak group	Label	Transition		Energy (eV)	
		Final	Initial	Experiment	Theory†
	1a			87.4	
1	1b	—	—	88.5	—
	1c			90.1	
2	2a	$1s^2 2s^2 2p^6$	$1s^2 2s^2 2p^5(P_{3/2})3s^2$	101.2	102.5
	2b		$1s^2 2s^2 2p^5(P_{1/2})3s^2$	103.4	
	3a			111.0	
3	3b	$1s^2 2s^2 2p^6 3p$	$1s^2 2s^2 2p^5 3s^2 3p$	111.9	112.5
	3c			113.7	
	4a			126.7	
	4b			128.6	
4	4c	$1s^2 2s^2 2p^6 3s$	$1s^2 2s^2 2p^5 3s^2 3p$	129.7	128
	4d			130.8	
	4e			131.4	

† Data obtained by extrapolation of theoretical results summarised by Dahl *et al* (1976).

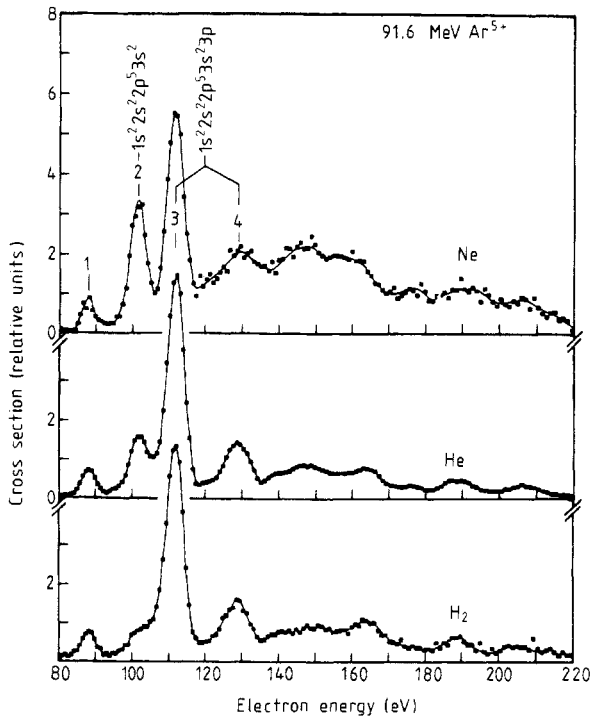

Figure 4. Ar–L Auger spectra from 91.6 MeV $^{36}Ar^{5+}$ incident on H_2, He and Ne as indicated. The electron energy refers to the projectile rest frame.

In conclusion, the method of zero-degree Auger spectroscopy for electrons from fast projectile ions was found to have various advantageous features. Line broadening effects are strongly reduced so that high-resolution spectroscopy is possible for electrons from fast projectiles. The transformations of the Auger spectra from the laboratory to the projectile rest frame yield energies of the projectile and the Auger electrons with relatively high accuracy. These frame transformations, however, increase the relative width of the Auger lines. Moreover, the use of light target atoms allows for the excitation of a few distinct peaks. Thus, problems are avoided concerning line blending which often inhibits the detailed analysis of Auger spectra produced in heavy ion–atom collisions. The observed peaks are characteristic for the projectile charge state which may readily be varied in the experiments. Consequently it is possible to obtain selective information about Auger transitions in ions for a great variety of charge states.

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