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LETTER TO THE EDITOR

Quasi-discretization of the electron continuum emitted in collisions of 0.6 MeV u^{-1} Au^{11+} with noble gases

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Abstract. We have measured relative doubly-differential cross sections for electron emission in collisions of 0.6 MeV u^{-1} Au^{11+} projectile ions with He, Ne and Ar targets for laboratory electron-detection angles between 17° and 80° and electron energies from 100 eV to well above the classical binary encounter region. We observe that, independent of the target Z_t, the electron spectra display three characteristic peak-like structures whose energies are nearly invariant with observation angle. These structures are attributed to the diffraction of quasi-free target electrons in the potential of the projectile.

Continuous electron spectra, also called δ electrons emitted in the collisions of swift projectiles with neutral targets generally exhibit three distinct prominent features (Macek 1970, Rudd and Macek 1972, Stolterfoht *et al* 1974): a monotonic approximately exponentially decreasing continuum, dominantly due to soft collisions; the sharp cusp, or equal velocity peak ($v_e = v_p$, where v_p and v_e are the projectile and electron velocities respectively) at $\theta_L = 0°$ observation angle, called electron loss peak from the projectile at $\theta_L \neq 0°$; and the broad binary encounter (BE) peak which is due to target electrons ionized through hard collisions with the projectile. The simplicity of the last process results in a BE peak energy given kinematically by

$$E_{BE} = 4\frac{m_e}{M_p} E_p \cos^2\theta_{lab} \tag{1}$$

and a cross section which was thought until recently to be treatable theoretically as the collision between a point projectile core charge and quasi-free target electrons. Although this treatment is successful for bare nuclear projectiles, e.g. for F^{9+} on He (Lee *et al* 1990), the results of Richard *et al* (1990), Quinteros *et al* (1991) and Jagutzki *et al* (1991) for lower charge states of fluorine and Cu projectiles incident on H_2 and He showed that the ionization cross section at 0° laboratory angle increases rather than decreases with decreasing ionic charge. This behaviour was interpreted (Olson *et al* 1990, Shingal *et al* 1990) to be the result of electronic screening of the projectile potential which causes an enhancement of the differential cross section for electron scattering at large angles in the projectile frame (small θ_{lab}) over the bare nucleus cross section.

A more dramatic violation of the simple interpretation of the BE peak was the observation of a dip-like structure in the BE peak at one well defined observation angle in 1.4 MeV u^{-1} U^{32+} and 1.0 MeV u^{-1} U^{21+} incident on Ar (Schmidt 1987, Kelbch *et al* 1989). This result was subsequently interpreted (Kelbch *et al* 1989, Reinhold *et al* 1991, Kelbch 1991) as being caused by marked diffraction maxima and minima in the elastic differential cross section for the scattering of target electrons from the partially stripped projectile ion.

Both of the above observations suggest that the parameter q/Z_p, the ratio of ionic to nuclear charge of the projectile, has a strong influence on the shape of δ-electron spectra, and that the most pronounced diffraction patterns should appear when this ratio tends to zero and Z_p is sufficiently large. In elastic scattering of electrons from Hg—which is the associated kinematically inverted collision for the classical binary encounter mechanism in Hg-ion–atom collisions—Kessler and Lindner (1965) find strong diffraction patterns in the differential cross sections for electron velocities 3 au $< v_e <$ 6 au. Partially guided by these results, we chose Au projectiles and the collision energy range associated with the strongest features in Kessler and Lindner's diffraction pattern, 200–1900 eV incident electron energy, that is 0.4–3.6 MeV u^{-1} collision energy for heavy ion projectiles, to investigate the doubly differential BE electron production cross section.

In the present letter, we present electron energy spectra measured between laboratory observation angles of 17.5° and 80° for 0.6 MeV u^{-1} Au^{11+} projectiles incident on He, Ne and Ar targets. These spectra show pronounced structures. These features persist over a wide range of bombarding energies (0.4–3.6 MeV u^{-1}) and q values (9+ to 23+), as will be presented in a longer forthcoming publication. We interpret these observations as resulting mainly from diffraction of the target electron from the projectile.

The experiment was performed at the Emperor Tandem accelerator of the Max Planck Institut für Kernphysik in Heidelberg (0.4–0.6 MeV u^{-1}), and at the accelerator of GSI-Darmstadt (1.4 to 3.6 MeV u^{-1}). Highly collimated beams of Au ions in various preselected charge states traversed a target gas cell (at the MPI) or a gas jet (at GSI) whose pressure was kept in the 10^{-4} to 10^{-3} mbar range. Electrons emitted in the target zone were energy analysed using a double focusing hemispherical sector analyser whose energy resolution was set at 5% and then detected with a channeltron. The electron analyser could be rotated around the target zone from 15° to 110°. The beam current was integrated in a shielded Faraday cup and the integrated beam current was used to advance the voltage on the spectrometer plates in steps of equal amounts of integrated charge. Details of the experimental procedure are given elsewhere (Kelbch *et al* 1989).

Figure 1 presents the doubly differential cross sections (DDCS) for the production of electrons from the collision of 0.6 MeV u^{-1} Au^{11+} with Ar. Three broad structures, peaking around 330 eV (peak I), 600 eV (peak II) and 1000 eV (peak III) dominate the DDCS. The corresponding spectra for He, Ne and Ar targets are very similar, as is shown in figure 2, suggesting that the target is mainly serving as a source of electrons to be scattered by the projectile. While the strengths of the three peaks vary strongly with the angle of observation, their positions stay nearly fixed. In figure 1, it is observed that the nominal BE locations (equation (1)) indicated by the broken lines lie above

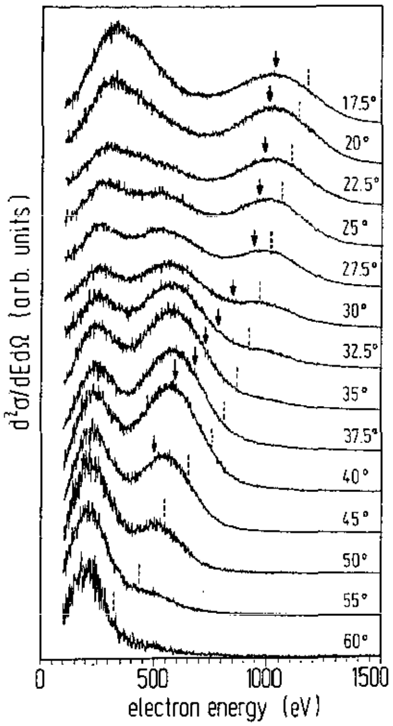

Figure 1. Double differential cross section for the production of electrons from the collision of 0.6 MeV u^{-1} Au^{11+} with argon. The linear vertical scale, in arbitrary units, is the same for all angles. The centre positions of the BE peak calculated with a *n*CTMC code are indicated by arrows, the kinematic BE peak positions from equation (1) by broken lines.

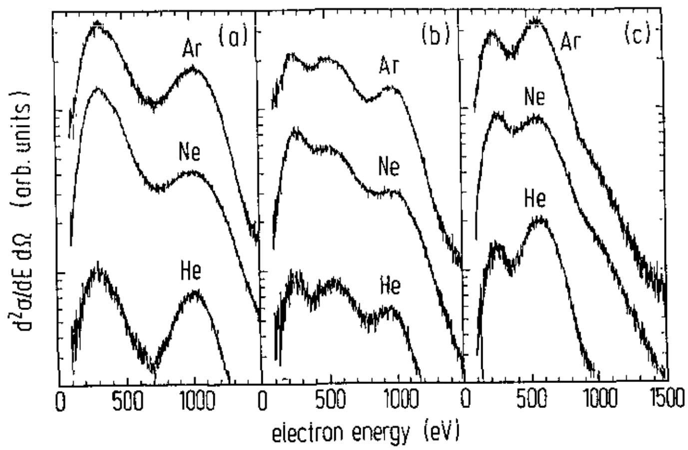

Figure 2. Comparison of double differential cross sections for the production of electrons from the collision of 0.6 MeV u^{-1} Au^{11+} with He, Ne and Ar for laboratory observation angles of 17.5° (*a*), 27.5° (*b*) and 35° (*c*).

all three peaks. An *n*CTMC calculation was performed for Au^{11+} incident on He. The approximate positions of the *n*CTMC BE peak, indicated by arrows in figure 1, are located well below those given by equation (1), indicating the importance of target-binding-energy effects. The *n*CTMC BE peak position agrees well with the position of the high energy structure III at angles around 20°, and with the position of the intermediate energy structure II at angles around 40°. It appears that the BE peak intensity is being gradually shifted, with increasing observation angle, from peak III to peak II and from peak II to peak I. We further note that, whenever the position of the *n*CTMC BE peak happens to coincide with the centre of peak III or peak II, that peak reaches maximum intensity.

For further discussion it is helpful to plot the experimental electron peak energy positions in a universal velocity diagram where the transformation from the projectile rest frame to the laboratory rest frame is easy to visualize. In this plot (figure 3) the experimental peak positions are shown as open circles with the size of each circle proportional to the measured peak intensity. The full curve (circle around P with length v_p) indicates the expected locus of free electrons elastically scattered from the projectile with a velocity equal to the projectile velocity. The crosses connected by the chain curve represent the positions of the BE peak from the *n*CTMC calculation.

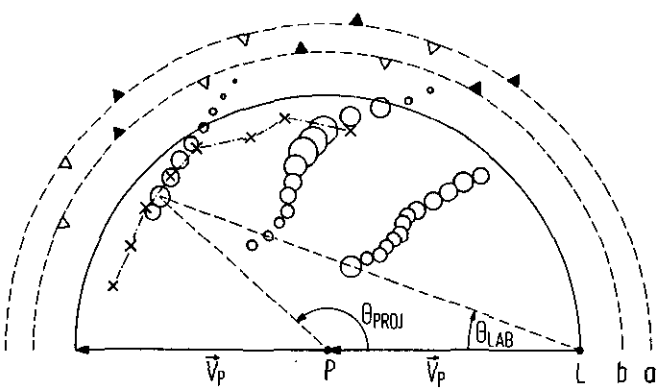

Figure 3. Universal velocity diagram for the collision of a 0.6 MeV u^{-1} Au^{11+} projectile (reference frame centred on P) with velocity v_p incident on an Ar target (reference frame centred on L). The full curve (circle around P with length v_p) indicates the expected locus of free electrons elastically scattered from the projectile with a velocity equal to the projectile velocity. The experimental electron peak positions are shown as open circles with the size of each circle proportional to the experimental intensity. The crosses connected by the chain curve represent the positions of the BE peak from the *n*CTMC calculation. The angular positions of the diffraction minima (▽) and maxima (△) for the scattering of free electrons from Hg (*a*) (Kessler and Lindner 1965) and from Au^{11+} (*b*) are indicated on the outer semicircles.

A calculation for the elastic scattering of electrons with energies between 175 eV and 530 eV on Au^{11+} was performed using the method previously given in Schultz and Olson (1991). The calculated diffraction patterns show strong maxima and minima, quite similar to the experimental data of Kessler and Lindner (1965) for the elastic scattering of electrons with energies between 200 eV and 500 eV on neutral Hg. The location of the maxima and minima for electrons of $v_e = v_p$ are indicated on outlying rings in figure 3 by outwardly and inwardly directed arrowheads respectively. Ring a indicates maxima and minima of Kessler and Lindner's experimental data. If the angular locations of the maxima and minima for the Au^{11+} case were only weakly dependent on the electron energy in the energy range of interest within the present context, the locus of the corresponding ridges and valleys for other free electron energies would be approximately represented in figure 3 by lines extending from the point P radially outward to the arrowhead locations on the outer indicator ring b.

In the experimental data, the target Compton profile roughly accomplishes a scan of the effective electron energy (from 175 eV to 530 eV approximately) so as to cover a large range in velocity space in that figure. It is seen that the experimental peaks move roughly within the confines of the calculated diffraction minima as would be expected from the diffraction interpretation. As the laboratory angle is increased the average intensity moves slowly to lower electron energies as would be expected from the kinematic shift of the BE feature, but the presence of diffraction minima at angles which move only slowly with the electron energy causes this to be observed as a slow shift of intensity from peak III to peak II and from peak II to peak I. The locations of the peaks are determined not by kinematics but by the diffraction structure.

Closer observation reveals that the peak locations follow loci which are centred not on the projectile centre P in figure 3, as would be expected on the basis of this simple single-centre diffraction model, but roughly on the laboratory centre L, corresponding to the observed invariance of peak energies in the laboratory frame L. It is shown below that this is satisfactorily explained in a single collision diffraction process. However, this behaviour would also be expected if, after scattering from the projectile, the target electron is rescattered elastically from the residual target ion from which that electron originally came. Such a rescattering would redistribute any feature originating at one location in the velocity space diagram of figure 3 over a curve of constant velocity centred on the point L. The redistribution would occur because a broad range of impact parameters of the electron relative to the residual ion came into play. In this picture, it would be the diffraction maxima originally generated by scattering in the screened potential of the projectile potential which are being redistributed. It is not certain how this contribution could be identified experimentally beyond doubt.

We have investigated whether the main features of the experimental data can be predicted by the classical binary encounter theory (BE) (Brandt 1983, Richard *et al* 1990). The elastic differential cross sections of electron–Au^{11+} collisions were calculated within the Hartree–Fock atomic model that included the zero-order relativistic mass velocity and Darwin corrections and the exchange of the free electron with the bound orbitals (Bhalla and Shingal 1991). The doubly differential cross sections in atom–Au^{11+} collisions were obtained by folding the Compton profile of the target atom with the differential cross sections. In this impulse approximation the bound electrons of the target are considered as 'quasi' free with the momentum distribution given by the Compton profile of the target. Figure 4 contains a comparison of BE calculations with experimental data for helium at laboratory angles, 17.5°, 27.5° and 35°. The relative experimental data were scaled by a common factor for all angles to compare with the absolute theoretical cross sections. We note that the low-energy electrons produced in these collisions can also arise from soft collisions. Such contributions are only partially included in BE theory, and these can be better described either by a proper quantum calculation or by a *n*CTMC calculation. It is clear from figure 4 that the locations of the maxima and the minima are well described by the binary encounter theory without invoking the double-collision mechanism, as discussed earlier.

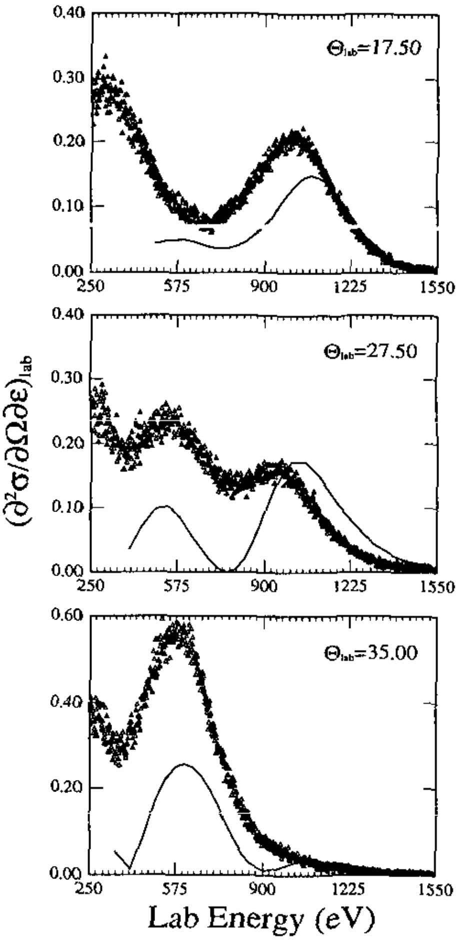

Figure 4. Double differential cross sections in au for the production of electrons in 0.6 MeV u^{-1} Au^{11+}-He collisions at laboratory observation angles 17.5°, 27.5° and 35°. Full curves, theory; triangles, scaled experimental data (see text).

We attribute the discrepancy between experimental and theoretical relative intensities of lines partially to non-inclusion of soft collision electrons, especially at low electron energies, and to possible breakdown of the impulse approximation.

In summary, we have measured double differential cross sections for δ-electron emission in 0.62 MeV u^{-1} Au^{11+} + noble gas collisions and shown that the observed quasi discretization in the continuum can be explained as diffraction of target electrons scattered in the projectile potential. Further, more detailed, experiments are in progress.

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