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ENERGY-LOSS OF POSITRONS IN FOILS

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The Giessen slow positron source TEPOS delivers intense beams in the energy range between some eV and 6 keV; with postacceleration up to 80 keV. Results for remoderation are described shortly. Further the energy-losses of positrons with incident energy of 6–20 keV through thin aluminium foils were measured. Cross sections for K- and L-shell ionization of thin silver and gold targets by positron and electron impact have been determined at projectile energies of 30–70 keV. The experimental results are presented in detail; they are confirmed by calculations in plane-wave-Born approximation which include an electron exchange term and account for the deceleration or acceleration of the incident projectile in the nuclear field of the target atom.

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1. Experimental

1.1. Positron source

An intense source for low-energy positrons (TEPOS) with a magnetic transporting system has been provided at the Giessen 65 MeV pulsed electron linear accelerator (LINAC) at the Strahlenzentrum of the University, and is described elsewhere in detail [1–2]. The source set-up consists of a vacuum chamber, containing the watercooled tungsten *converter-bremstarget*, and the tungsten *moderator* with a repeller plate. A solenoid system and different adequate Helmholtz coils transport the positrons to the experimental area.

1.2. Remoderation

To improve the beam quality of our positron source TEPOS (smaller beam diameter and lower energy spread) we performed experiments with various remoderation arrangements in transmission mode using thin (1000 Å) monocrystalline tungsten foils and different electrostatic positron extraction systems. At the end of the set-up a deflecting spherical condensor (with an adequate diaphragm) to analyze the energy of the positrons, and channel plates are installed.

The incoming positrons (e^+_{in}) penetrate into the W-foil, where some of them obtain thermal energies. Then, they diffuse in the foil and a part arrive at the surface without annihilation. There, they may be reemitted (remoderated positrons e^+_{remod}) with kinetic energies corresponding to the work function and are subsequently submitted to a postaccelerating system. The maximum yield of remoderated positrons is achieved at an energy of the incoming positrons of about 5 keV [2–3]. An arrangement for remoderation in a 1000 Å thick W-foil is shown in Fig. 1.

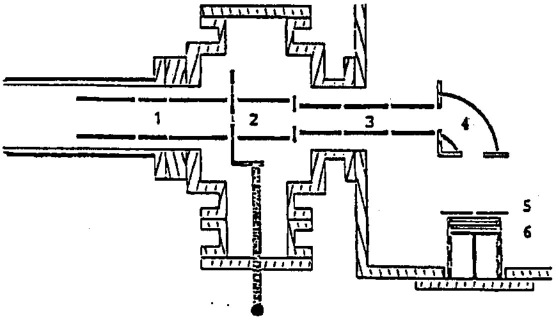

Fig. 1. Arrangement for remoderation and measurement of energy-losses, respectively; 1, 3 — electrostatic lenses, 2 — target, 4 — spherical capacitor or tandem spectrometer, 5 — diaphragm, 6 — channel plates or channeltron, respectively.

2. Experimental results

2.1. Energy-losses

The same arrangement as for the remoderation with, however, the spherical condenser replaced by an electrostatic parallel-plate tandem spectrometer was used to study the energy-loss of 6–20 keV positrons and electrons in thin metal foils. First results for the mean energy-loss of forward-scattered positrons and electrons in aluminium are presented in Fig. 2.

2.2. Inner shell ionization

The interaction of an incident projectile with a target atom may give rise to a variety of different elastic and inelastic scattering processes. Ionization of inner atomic shells, for example, is one of these processes which are of fundamental importance for our understanding of collision dynamics and also of practical relevance for a number of fields [4–6]. For a quantitative analysis, reliable cross sections for impact ionization are required. Calculated cross sections are frequently based on first order perturbation theories (for example, plane-wave-Born approximation (PWBA) [7–8]), which provide reliable cross sections for sufficiently "fast" collisions. These theories predict total cross sections which are independent of the sign of the projectile's charge.

In this paper we present experimental results for K- and L-shell ionization of atoms by electron and positron impact, respectively, at incident energies close to

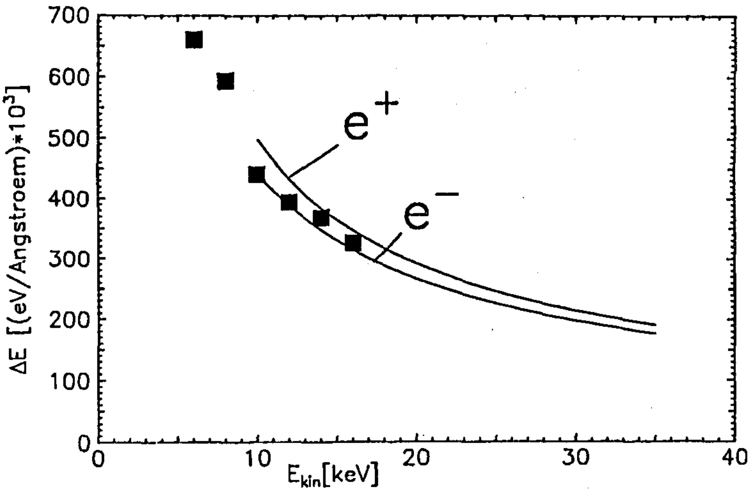

Fig. 2. Experimental energy-losses of positrons in a 2500 Å thick Al-foil (■). The curves represent tabulated stopping powers (M.J. Berger and S.M. Seltzer; National Bureau of Standards, Washington, D.C., USA).

the ionization threshold I. At the present experiments the positrons or electrons enter a special vacuum chamber, containing the target support with the target foil [9–10].

Partly the electron measurements are carried out with an electron gun, placed in the transporting solenoid system at a distance of about 4 m from the target chamber. To center the positron beam, channel plates were utilized. The kinetic energy E_0 of the impinging positrons or electrons, respectively, can be varied by a suitably chosen electrical potential at which the target foil is held. The target is connected therefore sideways to a high voltage power supply, and it is hit under 45°. The X-rays emitted from the target had to pass through a 50 μm mylar window, and are registered perpendicular to the incident beam by a Si(Li) detector.

2.2.1. K-shell ionization

Former experiments on K-shell ionization were performed for silver and copper targets [9]; the thickness of these foils ranged from 950 Å to 4950 Å (100 to 520 $\mu g/cm^2$). In the silver case the X-rays resulting from K-shell ionization ($I = 25.52$ keV; $E_0/I = 1.7 \ldots 2.7$) were normalized to the simultaneously recorded X-rays from the silver L-shell ($I \simeq 3.35$ keV; corresponding to $E_0/I = 12 \ldots 21$). Such a normalization procedure is useful as long as the cross section ratio σ_L^- / σ_L^+ for L-shell ionization by electron and positron impact equals unity, which holds for $E_0/I > 9$. It circumvents the problem which otherwise arises from a normalization to the incident beam current.

2.2.2. L-shell ionization

In this communication we present and discuss also new experimental results for L-shell ionization of gold by lepton (electron, positron) impact at incident energies between 35 and 70 keV [10]. We performed the experiments with Au/Ag-multilayer targets; several targets were used, e.g. Au 400 Å/Ag 125 Å, Au 600 Å/Ag 1000 Å on a carbon backing, and Au 1450 Å/Ag 3500 Å. Further, recent measurements were performed for electron and positron impact at an incident energy of 30 and 35 keV with a thin multilayer target of Au 800 Å/Ag 1800 Å on a carbon-backing; it yielded identical results compared to the thicker target. This confirms that the measurements presented here are not influenced by the energy-loss inside the target foil. The purpose of these multilayer targets was to use also the Ag-L X-ray as reference data to which the Au-L X-ray data were normalized; as we shall see below, due to its comparatively low ionization energy only a small sign-dependence of the Ag-L ionization cross sections may be expected at the incident energies of interest.

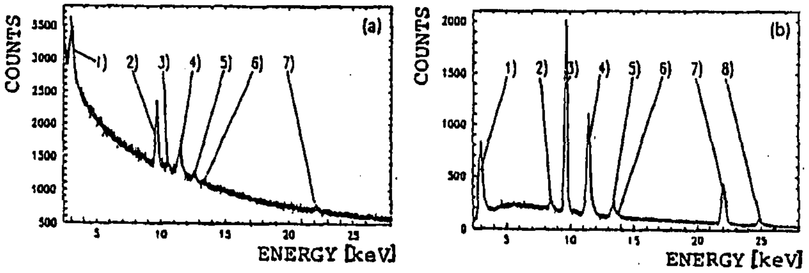

Fig. 3. X-ray spectrum from 45 keV (a) positron and (b) electron impact of a Au 1450 Å/Ag 3500 Å multilayer target. (a) — Ag-L (1), Au-L_α (2), Pb-L_α (3), Au-L_β (4), Pb-L_β (5), Au-$L_{\gamma 1}$ (6), Ag-K_α (7); (b) — Ag-L (1), Au-L_l (2), Au-L_α (3), Au-L_β (4), Au-$L_{\gamma 1}$ (5), Au-$L_{\gamma 2,3,6}$ (6), Ag-K_α (7), Ag-K_β (8).

The X-ray spectra resulting from Au L-shell ionization obtained at a projectile energy of 45 keV are shown in Figs. 3a and 3b for incident positrons and electrons, respectively. The peak at $\approx$ 3 keV is due to the ionization of the L-shell of silver (Ag-L); the peaks at 9.7 keV, 11.5 keV and 13.8 keV originate from the L_α, L_β and L_γ transitions, respectively, of gold. The additional peak at 8.5 keV (Fig. 3b) comes from the (Au-L_l) transition. Further, the course of the bremsstrahlung spectrum induced by electron impact indicates that the efficiency of our Si(Li)-detector decreases for photon energies $E_\gamma \leq 5$ keV.

The obtained cross section ratios σ_K^-/σ_K^+ and σ_L^-/σ_L^+ for positron and electron impact are displayed in Fig. 4 [9–10]. As is shown by our calculations, the cross section ratio $\sigma_{e^-}/\sigma_{e^+}$ as a function of the reduced incident energy E_0/I displays a pronounced energy dependence below $E_0/I \leq 5$, whereas due to the near cancellation of the combined Coulomb and exchange effects, this ratio is close to unity already for $E_0/I \geq 10$.

In the energy region of interest here corresponding to E_0/I = 2.5...5.5

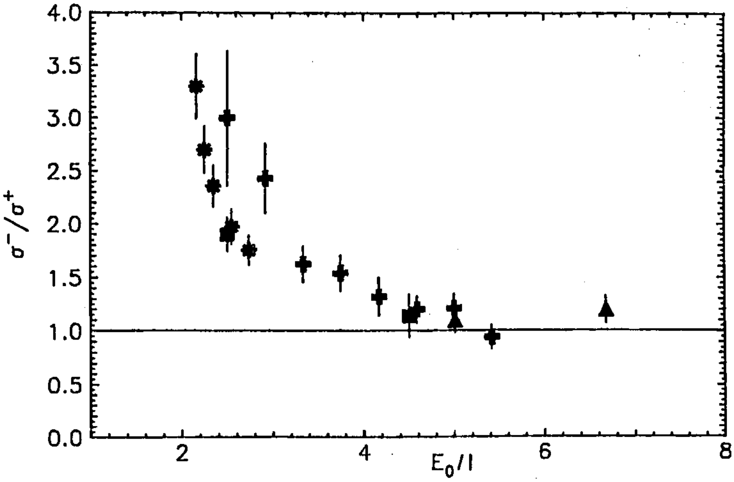

Fig. 4. Cross section ratios σ^-/σ^+. (stars) — Ag-K-shell [9], (triangles) — Cu-K-shell [9], (crosses) — Au-L-shell [10], (squares) — Cu-K-shell [6].

for Au-$L_{\rm III}$ ($I \simeq 11.92$ keV) but $E_0/I = 9...19$ for Ag-L our calculations give $\sigma(\text{Ag-}L)_{\rm e+}/\sigma(\text{Ag-}L)_{\rm e-} = 1.047 \pm 0.011$. This implies that the silver L-shell data can in fact serve as a reference to which the Au-$L_{\rm III}$ data can be normalized. With the above result for the Ag-L cross section ratio by positron and electron impact, we can form the double ratio [10]

$$\frac{\sigma^-}{\sigma^+} \equiv \frac{[\sigma(\text{Au-}L_\alpha)/\sigma(\text{Ag-}L)]_{\rm e-}}{[\sigma(\text{Au-}L_\alpha)/\sigma(\text{Ag-}L)]_{\rm e+}} = \frac{\sigma(\text{Au-}L_\alpha)_{\rm e-}}{\sigma(\text{Au-}L_\alpha)_{\rm e+}}(1.047 \pm 0.011),$$

i.e. it is a ratio of ionization cross sections for the (Au-$L_{\rm III}$)-shell only.

3. Conclusion

The measurements of energy-losses are due to further investigation. Of special interest are differences between positrons and electrons.

We show that the departure from the prediction of PWBA observed for K- and L-shell ionization by electron and positron impact [7–8] is mainly due to two effects: (i) the projectile-target nucleus interaction (Coulomb-effect, C), and (ii) electron exchange between the incident and the bound electron (exchange effect, Ex). The measured ratio increases with decreasing projectile energy; this result is in fair agreement with our present calculations and can be explained by the Coulomb effect which is most important at small E_0/I. Our results, hence, stress the importance of the projectile-target nucleus interaction. This means that the cross section ratio σ^-/σ^+ increases with decreasing energy of the projectiles, because electrons are accelerated, whereas positrons are slowed down in the nuclear field of the target. This effect overcompensates the exchange effect. The cross section ratio would otherwise increase with increasing incident projectile energy. Summarizing, the main difference of the PWBA-C and PWBA-C-Ex compared to the usual PWBA and PWBA-Ex calculations is the inclusion of the projectile-target nucleus interaction by means of a simple correction; it takes the deceleration or acceleration of the incident positron and electron, respectively, in the target nuclear field into account (cp. [11]).

Acknowledgments

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