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K- and *L*-shell electron emission from carbon atoms by antiproton and proton impact

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Electron emission from the K and L shells of carbon by 1-MeV antiproton and proton impact is studied. Double differential cross sections as a function of the electron ejection energy and angle are calculated using the continuum-distorted-wave–eikonal-initial-state model. Contributions to the formation of a recently measured anticusp from electrons of different shells are analyzed for impact of antiprotons. The same effect is studied for the capture-to-continuum peak that appears for proton impact.

Electron ionization by impact of antimatter on atomic targets has become a subject of increasing interest. Using new experimental facilities at CERN, antiproton beams with energies as low as a few hundred keV are now available. Moreover, the possibility of obtaining very-low-energy antiproton beams down to 20 keV is being persued.[1] With these facilities, we would be able to analyze the electronic behavior in the combined field of repulsive (antiproton) and attractive (residual target) potentials, for heavy projectiles ($M_P \gg 1$, M_P being the mass of the projectile in electronic mass units). It must be noted that the channels of charge exchange, which can influence the single ionization process at intermediate energies, are not present in the case of antiprotons. Different physical effects have been thus measured, as, for example, the determination of the ratio of total cross sections for double and single ionization of He targets by antiproton impact[2,3] and the Barkas effect in the stopping power of negative particles.[4] More complete information concerning the physics involved in the reaction, sometimes overshadowed in total cross sections, can be obtained from double differential cross sections (DDCS) as a function of the final energy E_k and scattering solid angle Ω_k of the electrons.

Last year, Fainstein, Ponce, and Rivarola[5] compared DDCS for impact of protons and antiprotons on He$(1s^2)$ targets at 300 keV and 1 MeV impact energies. Differences in the spectra of emitted electrons were found when proton and antiproton cases were compared not only qualitatively but also quantitatively. This fact is further evidence that single ionization must be treated as a three-body process even at high collision velocities, as predicted in previous works.[6–8] The more significant difference is the presence for antiprotons of an "anticusp" located at electron velocities where the well-known "capture to the continuum" (CTC) peak appears for protons (i.e., at $\mathbf{k} \cong \mathbf{v}$, with $\mathbf{k}$ and $\mathbf{v}$ the final electron velocity in the laboratory frame and the projectile velocity, respectively). This behavior arises from the different density of continuum states corresponding to protons and antiprotons for $\mathbf{k} \cong \mathbf{v}$. In other words, electrons tend to be repelled by antiprotons and attracted by protons. A short time after, the anticusp was measured by Knudsen *et al.*[9] for impact of antiprotons on carbon foils at a 1-MeV collision energy.

The aim of the present work is to study this measured system in order to determine the theoretical profiles of DDCS as a function of the final electron energy for fixed electron scattering angles in the range of the angular experimental resolution (5°, Ref. 9) and the contribution to the DDCS coming from the different shells of the carbon atom. A main difference with the $\bar{p}+\mathrm{He}$ system is that in the latter there is only K-shell emission. Atomic units will be used in the following.

The continuum-distorted-wave–eikonal-initial-state model[8] (CDW-EIS) is employed within the straight line version of the impact-parameter approximation. In the entry channel, the initial distorted wave function is chosen as

$$\chi_i^+ = \phi_i(\mathbf{x}) e^{-i\varepsilon_i t} \exp\left[-i\frac{Z_P}{v}\ln(vs+\mathbf{v}\cdot\mathbf{s})\right], \tag{1}$$

where $\mathbf{x}$ ($\mathbf{s}$) is the position vector of the active electron with respect to a reference frame fixed on the target (projectile) nucleus, $\phi_i(\mathbf{x})$ and ε_i are the Roothaan-Hartree-Fock active electron initial bound wave function[10] and the corresponding binding energy, respectively, and Z_P is the nuclear charge of the projectile. The active electron-projectile interaction is included in the entry channel through an eikonal phase. In the exit channel, the distorted wave function is proposed as

$$\begin{aligned}\chi_f^- = {} & (2\pi)^{-3/2} e^{i\mathbf{k}\cdot\mathbf{x}-iE_k t} \\ & \times N^*\left(\frac{\zeta_T}{k}\right) {}_1F_1\left(-i\frac{\zeta_T}{k};1;-ikx-i\mathbf{k}\cdot\mathbf{x}\right) \\ & \times N^*\left(\frac{Z_P}{p}\right) {}_1F_1\left(-i\frac{Z_P}{p};1;-ips-i\mathbf{p}\cdot\mathbf{s}\right),\end{aligned} \tag{2}$$

where p is the momentum of the active electron with respect to a reference frame fixed on the projectile, $E_k = k^2/2$, $N(a) = \exp(\pi a/2)\Gamma(1-ia)$, and $\zeta_T = (-2n^2\varepsilon_i)^{1/2}$, with n the principal quantum number of the initial state. So, the electron is represented in the exit channel in the combined field of the residual target and the projectile. The exact final continuum wave function is thus approximated by a plane-wave distorted by a product of Coulombic continuum factors associated with the separated interactions of the active electron with the projectile and residual target. It must be noted that in multielectronic cases the active electron-residual target interaction is simulated by an effective Coulombic one corresponding to an effective nuclear charge ζ_T.

The DDCS can be obtained from

$$\frac{d\sigma}{dE_k d\Omega_k} = k\int d\eta\,|R(\eta)|^2 , \tag{3}$$

where $R(\eta)$ is the scattering amplitude as a function of the transverse-momentum transfer η. For details on the calculation of $R(\eta)$ the reader is referred to previous works.[8,11]

In Figs. 1 to 3 DDCS are presented for impact of antiprotons at fixed electron scattering angles $\theta_k = 0°$, 2°, and 5° together with the corresponding ones for proton impact for comparison. As was previously indicated, the target studied is carbon and the impact energy is 1 MeV. Contributions to electron ejection coming from K and L shells are discriminated and summed.

For both projectiles, L-shell contributions prevail at low electron energies. At larger energies E_k, the process becomes dominated by K-shell contributions, except in the region of the binary encounter peak. This last effect is explained by the fact that L-shell electrons move slower than

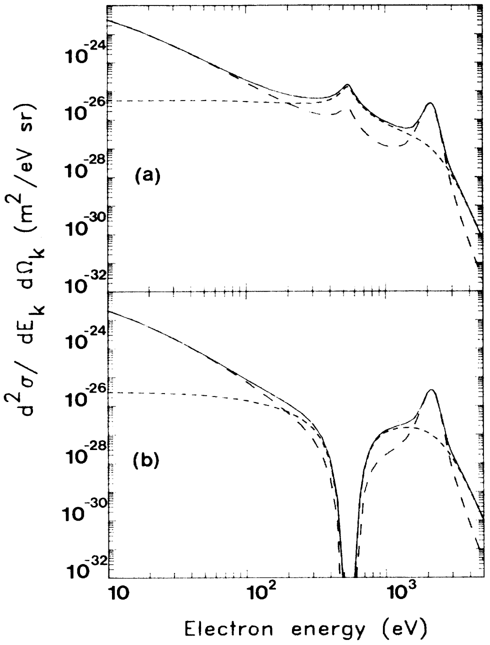

FIG. 2. Double differential cross sections for ionization of carbon by 1 MeV (a) proton and (b) antiproton impact as a function of the electron ejection energy for 2° ejection angle calculated with the CDW-EIS model. Theory: ——, $K+L$ shell; ---, K shell; — — —, L shell.

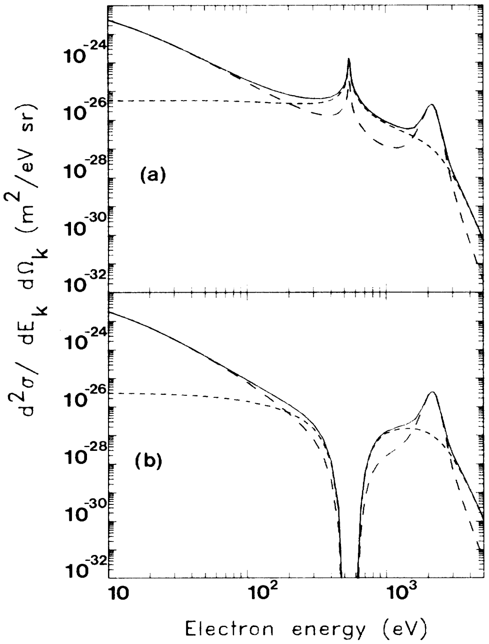

FIG. 1. Double differential cross sections for ionization of carbon by 1 MeV (a) proton and (b) antiproton impact as a function of the electron ejection energy for 0° ejection angle calculated with the CDW-EIS model. Theory: ——, $K+L$ shell; ---, K shell; — — —, L shell.

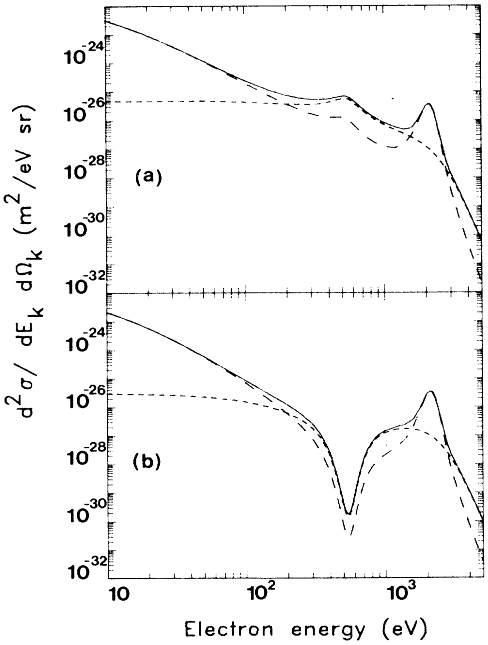

FIG. 3. Double differential cross sections for ionization of carbon by 1 MeV (a) proton and (b) antiproton impact as a function of the electron ejection energy for 5° ejection angle calculated with the CDW-EIS model. Theory: ——, $K+L$ shell; ---, K shell; — — —, L shell.

K-shell electrons in the initial state, satisfying in a more approximate way the classical condition for binary encounter. It is important to note that although the L-shell emission gives the main contribution to the total cross section, the region of the anticusp is dominated by the K shell at this impact velocity. The same behavior is observed for the CTC peak. The impact parameters that produce the main contribution to ionization are related to the longitudinal momentum transfer in the collision $q_z = (E_k - \varepsilon_i)/v$ as[12,13] $\rho \cong q_z^{-1}$. We are interested in electron velocities close to that of the projectile $k \cong v$; therefore, the impact parameters that contribute most to this transition are $\rho \simeq 2v/(v^2+v_i^2)$ where $v_i = (2\varepsilon_i)^{1/2} = \zeta_T/n$ is the characteristic electron speed in the initial state. In the present case $v/v_i = 1.32$, 5.18, and 8.00 for the 1s, 2s, and 2p orbitals, respectively, so the impact-parameter region varies from 0.16 to 0.32 a.u. As the radial expectation values[14] for the 1s, 2s, and 2p states of carbon are 0.27, 1.59, and 1.71 a.u. the impact-parameter region which gives the main contribution to the anticusp (or cusp) overlaps the mean radius of the K shell. So, K-shell electrons will dominate this part of the spectra of emitted electrons at the impact energy here considered. For lower impact energies the form of the anticusp (or cusp) will be given by L-shell electrons. For larger electron velocities $k \gg v \gtrsim v_i$, contributions to the DDCS come from $\rho \cong 2v/k^2 \ll 2/k$, and it is clear that the main contribution to this part of the spectra comes again from K-shell electrons. As in this electron ejection energy domain the impact-parameter region is independent of v, for high enough velocity k, DDCS will be dominated by K-shell electrons at any impact energy.

In conclusion, DDCS for single electron ionization by impact of antiprotons and protons on carbon atoms at 1 MeV collision energy are studied. This system of current experimental interest is analyzed in order to determine the contribution of different shells on the spectra of emitted electrons. It is shown that K-shell electrons give the main contribution to the anticusp (or cusp) region at the impact energy considered.

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