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MEASUREMENTS OF ELECTRON SPECTRA IN THE FORWARD DIRECTION IN SLOW-ANTIPROTON CARBON-FOIL COLLISIONS

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Abstract

The spectra of electrons emitted in the forward direction from antiproton and proton bombardments on carbon foils have been studied (Exper. PS204) for projectile energies from 500 to 750 keV. At the electron energy where the well-known convoy peak is observed for protons, the spectrum for antiprotons, of the same velocity, is smooth, with indication of a bump at ~ 50 eV below the electron energy, where an anticusp is anticipated. The energy and the relative intensity of the bump are found to be consistent with those predicted for electrons released from a wake-riding state.

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The energy and angular distributions of electrons produced in collisions of energetic ions with solid targets have been studied extensively in order to investigate interactions of charged particles with solids [1]. One of the basic aims is to investigate the charge-asymmetry effect [2], i.e. to study differences and similarities induced by positively and negatively charged particles having the same mass and velocity. Recently, high-quality beams of 100 MeV/c antiprotons have become available at the Low-Energy Antiproton Ring (LEAR) at CERN. This has made it possible to carry out various experiments on charge-asymmetry effects, such as double ionization, stopping power, K-shell ionization, etc. [3].

We have studied the energy spectra of electrons emitted from thin carbon foils in the forward direction, produced by several hundred keV antiprotons, as well as those produced by protons of the same velocity. Crudely speaking, the electron spectra in the forward direction can be divided into three parts, i.e. a low-energy part, a $v_e \approx v_{pr}$ part, and a high-energy part including a binary collision peak, where v_e and v_{pr} are the electron and projectile velocities, respectively. In this report, we will discuss mainly the $v_e \approx v_{pr}$ part, where a large difference due to the final-state interaction between the electrons and the projectile [2] is expected. For protons, a well-known cusp-shaped peak of convoy electrons is observed. On the other hand, for antiprotons, although a very deep dip is expected at $v_e \approx v_{pr}$ for gas targets, a recent Monte Carlo simulation predicts [4] that for foil targets the dip is more or less smeared by cascading electrons, which maintain very weak correlation with the projectile in the final state.

An additional structure is predicted in the $v_e \approx v_{pr}$ part, for the following reasons: A charged particle traversing a solid will induce an electronic polarization wake, which leaves an oscillatory structure behind the particle when its velocity is higher than the Fermi velocity of the target [5]. Various aspects of the wake potential in the vicinity of the projectile have been investigated [6]. Neelavathi et al. [7] had first pointed out the possibility of trapping an electron at the attractive part of the wake potential, which, in solids, proceeds with the velocity of the projectile. The electron bound in the wake potential has been called a wake-riding electron [8]. This intuitive picture is interesting because it predicts a new mechanism for inducing dynamic electronic states in a solid.

For protons, the first minimum of the wake potential appears, in atomic units, at $\sim 3\pi v_{pr}/2\omega_{pl}$ behind the projectile, where ω_{pl} is the plasmon energy of the target [5]. When the projectile exits, the attractive Coulomb potential takes the place of the wake potential, i.e. the wake-riding electron finds itself in a state with negative potential energy, $\Delta E \approx -2\omega_{pl}/(3\pi v_{pr})$. Owing to the initial momentum spread of the wake-riding electrons, the final energies of the electrons may be distributed above and below the vacuum level in the projectile reference frame [9]. As a result, the trace — if any — of the wake-riding electron, will be dissolved into a huge background of ordinary convoy and/or Rydberg electrons. For antiprotons, on the other hand, the wake-riding electron is expected to be localized at $\sim \pi v_{pr}/2\omega_{pl}$ behind the projectile, a factor of 3 shorter than for protons. The properties of wake-riding electrons for use by negatively charged particles were first studied by Rivacoba and Echenique [10]. Upon exit, a wake-riding electron finds itself in a state with a positive potential energy $\Delta E \sim 2\omega_{pl}/(\pi v_{pr})$. Consequently, the electron is accelerated in the backward direction and finally gets the kinetic energy ΔE in the projectile reference frame. The wake-riding electron energy E_{wr} in the laboratory frame is then given by

$$\begin{aligned} E_{\mathrm{wr}} &\approx \frac{1}{2}(\upsilon_{\mathrm{pr}} - \sqrt{2}\Delta E)^2 \\ &= \frac{1}{2}\upsilon_{\mathrm{pr}}^2 - 2(\sqrt{\upsilon_{\mathrm{pr}}}\omega_{\mathrm{pl}}/\pi - \omega_{\mathrm{pl}}/\pi\upsilon_{\mathrm{pr}})\,. \end{aligned} \tag{1}$$

As no strong cusp-shaped peak appears for antiprotons, electrons released from a wake-riding state may be observed at E_{wr} superimposed on a weak continuum.

The use of antiprotons in the study of wake-riding electrons has two further advantages. First, the wake potential and hence the wake-riding state is more 'well-defined' and stable since the distance from the projectile is shorter, because a target plasmon has a finite lifetime. Secondly, the capture probability into the wake-riding state is expected to be greater for antiprotons [4]. Calculating the capture of a target electron into the wake potential in the OBK (Oppenheimer–Brinkman–Kramers) approximation as a single-step process yields negligibly small cross-sections for antiproton and proton projectiles [11]. This is because the momentum spread of the wake-riding state is very narrow and the wake potential is a 'soft' potential. Therefore the requirement of momentum conservation before and after the electron capture is very hard to satisfy. Accordingly, the wake-riding electron is expected to be produced via a two-step process [12]: the scattering of a target electron with the projectile, followed by a second scattering with a target nucleus into the forward direction. In this case, the requirement on the momentum conservation is not so strict [13]. Burgdrfer et al. [4] have actually performed a second Born calculation, and have shown that the cross-section for capture into the wake-riding state is much larger for antiprotons than for protons. Their model calculation demonstrated that there is a possibility to observe wake-riding electrons in antiproton–carbon-foil collisions.

On the other hand, there are several arguments against the existence of the wake-riding electrons, because i) perturbations such as the stopping force and stochastic collisions of the wake-riding electron are comparable to or larger than its binding force, especially when the damping of the potential is important [14]; ii) the wake potential is an effective potential with its origin in the creation and annihilation of plasmons, i.e. the fluctuation of the potential may be big enough not to allow a stationary wake-riding state [14]; iii) the density of the wake-riding electron is higher than the fluctuating density of valence electrons inducing the wake potential, i.e. a self-consistent treatment is important for obtaining a realistic prediction. These theoretical questions are still left unsolved. In the following, we will shed 'experimental' light on the wake-riding electrons in question.

An experiment on electron emission in antiproton–carbon-foil collisions has been performed at LEAR. Figure 1 shows the apparatus used in the present experiment. High-quality beams of low-momentum antiprotons (105.5 MeV/c) passed through a 110 μm beryllium window at the end of the LEAR beam line, through aluminium degrader foils, and then through a 22 μm Mylar window at the entrance to the experimental vacuum chamber. The thickness of the Al degrader was determined in such a way that the central energy of the beam at the target was $\sim$ 600 keV. The beam intensity under the present experimental conditions was, on the average, $\sim 2 \times 10^4$ antiprotons per second. The degraded beam then passed through a target carbon foil, a three-slit lens and the centre hole of an electron spectrometer, and was finally detected by a thin plastic scintillator, 63 cm downstream from the target. Electrons emitted in the forward direction were energy-analysed by the 45° parallel-plate electron spectrometer, equipped with a position-sensitive microchannel plate (MCP). At the deflection voltage of −400 V, the analyser covers the electron energy from 240 eV to 400 eV with an energy resolution better than 4% (FWHM). The acceptance angles parallel and perpendicular to the deflection plane of the electron were $\sim 10°$ and $\sim 2.5°$, respectively. The velocity of an antiproton that produced an electron was evaluated using the time difference of output pulses between the MCP (start) and the scintillator (stop). The time resolution of the system was better than 2 ns. Since the degraded antiproton beam suffers a big energy straggling [$\sim$ 400 keV (FWHM)], an event-by-event recording technique based on a personal computer has been employed for the data acquisition. From the event data, electrons produced by antiprotons of 500 to 750 keV are divided into 10 groups, each group having an energy window of $\sim$ 25 keV. Noise signals due to the annihilation products of antiprotons have been carefully identified and subtracted. An additional experiment has been performed with degraded protons (5.9 MeV $\rightarrow \sim$ 600 keV) in order to obtain reference spectra with the same experimental set-up. Proton beams were supplied from the Tandem Facility at the University of Aarhus.

Figure 2 shows typical electron spectra in the forward direction, multiplied by the electron energy for a 2 μg/cm^2 carbon foil bombarded by a) 600 keV protons and b) 610 keV antiprotons. About 10^7 protons and antiprotons were used to obtain these spectra. Each spectrum is reconstructed from four narrow-range spectra measured independently at different deflection voltages of the electron analyser. The intensity of the binary collision part ($\sim$ 1200 eV) is found to be roughly the same between protons and antiprotons. A study is under way to get detailed information, such as the shape and the intensity of this part. On the other hand, a big difference is observed in the $v_e \approx v_{\rm pr}$ part. For protons, the well-known convoy-electron peak is clearly visible. For antiprotons, no prominent dip is recognizable as predicted for gas targets [2]. This observation is in agreement with the recent Monte Carlo simulation by Burgdrfer et al. [4], and is understood by taking into account a smearing of the deep dip by cascading electrons.

Figure 3 shows a forward electron spectrum around the $v_e \approx v_p$ part for antiprotons bombarding a 2 μg/cm^2 carbon foil. In order to study structures around $v_e \approx v_{\rm pr}$ with better statistics, several electron spectra with projectile energies from 570 to 660 keV are added up after the abscissa is transformed into a relative energy E$_r$ with respect to $\frac{1}{2}v_{\rm pr}^2$. Equation (1) predicts that $\Delta E_{\rm wr}$ ($= E_{\rm wr} - \frac{1}{2}v_{\rm pr}^2$) varies from −61 eV to −63 eV for the above projectile energies, assuming that $\omega_{\rm pl} = 25$ eV (the plasmon energy of carbon), i.e. a structure originating from the wake-riding electron is preserved after this transformation and addition. The error bars shown in the figure are just statistical. There are indications of a bump at about −50 eV, i.e. $\sim$ 10 eV higher than $\Delta E_{\rm wr}$. As the carbon KLL-Auger electrons have the energy of $\sim$ 250 eV [15], those produced by antiprotons around 570 keV ($v_{\rm pr}^2/2 \approx 310$ eV) will overlap with the lower-energy tail of the bump, i.e. the real bump might be a bit narrower. The following arguments would suggest that further consideration should be given to relations between the bump and the wake-riding electrons: i) the distance between the wake-riding electron and the antiproton in a solid is expected to be larger than is assumed here by several per cent, because of the repulsive antiproton potential [10]; ii) $\omega_{\rm pl}$ for a thin foil will be smaller than for bulk, because the density of a thin foil is normally less than the bulk density. Although the quantitative evaluations of these effects are beyond the scope of the present paper, it is seen that they all contribute to increase ΔE_{wr} towards the energy of the bump. Furthermore, the intensity of the bump relative to the continuum is in accordance with the Monte Carlo simulation by Burgdrfer et al. [4] for $\sim$ 900 keV antiprotons.

In conclusion, we have measured, for the first time, electrons emitted in the forward direction from a thin carbon foil bombarded by 500–750 keV antiprotons. The main feature is the absence of the cusp observed for proton impact. Furthermore, no deep dip is seen, which is explained by a contribution of cascading electrons. A bump is recognized, the energy position of which is seen to be consistent with the energy of electrons released from wake-riding states.

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Figure captions

Fig. 1: Schematic drawing of the experimental set-up to measure electron spectra in the forward direction with degraded proton and antiproton beams.

Fig. 2: Wide-range electron spectra versus the electron energy in the forward direction for a) 600 keV protons and b) 610 keV antiprotons bombarding a 2 μg/cm^2 carbon foil. Electron intensities are normalized to the same number of projectiles.

Fig. 3: Electron spectra of the $v_e \approx v_{pr}$ part observed in the forward direction for 570 keV to 660 keV antiprotons bombarding a 2 μg/cm^2 carbon foil. The abscissa is given relative to $v_{pr}^2/2$.

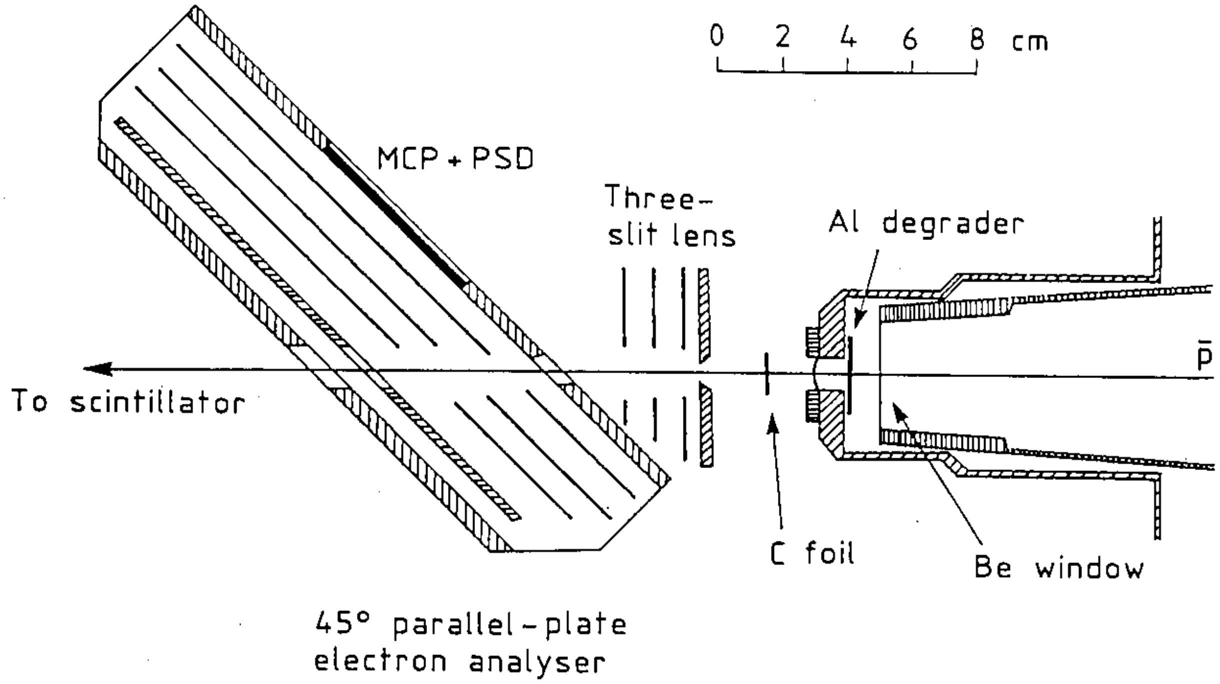

Fig. 1

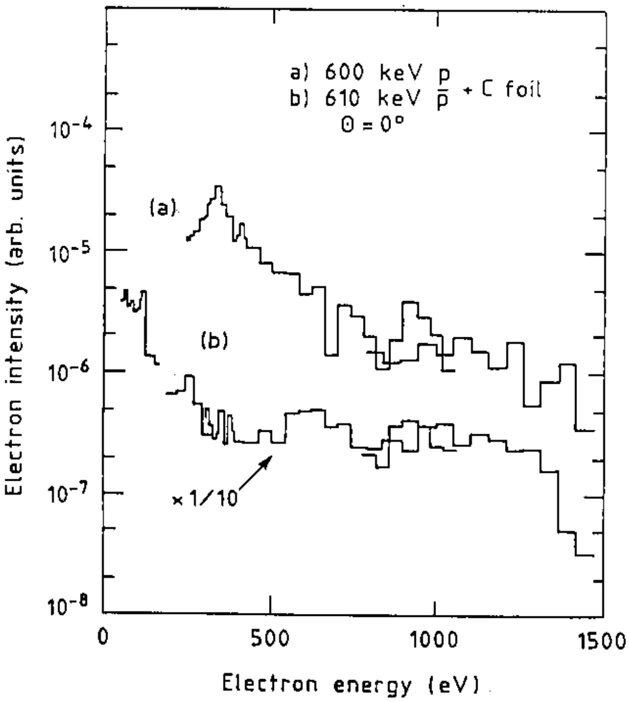

Fig. 2

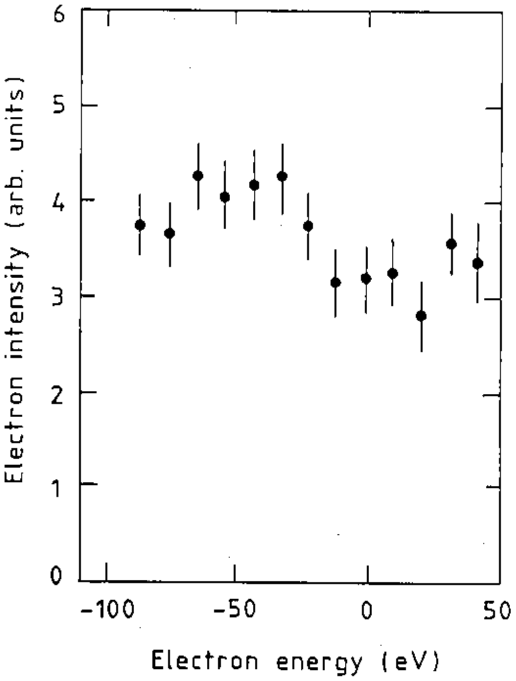

Fig. 3

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