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Kinematically complete experiments for positron-impact ionization of helium atoms at the NEPOMUC facility

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Abstract. Positron impact ionization of helium is studied with fully resolved momentum vectors of all continuum particles. An imaging multi-particle momentum spectrometer (reaction microscope) detecting all final state particles over the full solid angle was applied. This apparatus was connected to the NEPOMUC facility delivering intense positron beams tuneable over a large energy range with good beam quality. At 80 eV impact energy about 5000 triple coincidence events were collected. Cross sections as function of the longitudinal particle momentum show strong differences compared to respective electron impact ionization data most likely originating from the reversed post collision interaction in both cases. Calculations using the 3 Coulomb wavefunction method show clear discrepancies from the experimental results.

1. Introduction

The scientific and technological uses of low energy positrons are numerous including the formation of neutral antihydrogen atoms in order to test quantum electro dynamics (QED), fundamental symmetries in nature (the CPT theorem) or the action of gravity on antimatter. Examples for technological applications of positrons are positron emission tomography (PET) for material characterization or the study of metabolic processes, plasma diagnostics and new ways to study clusters and nanoparticles. All applications depend on the quantitative understanding of the basic interactions of positrons with matter. The project presented here aims to study ionizing collisions of positrons with light atoms (H, He) or molecules (H_2), representing the most fundamental dynamical few-body systems, in unprecedented detail. Insight into the dominant dynamical mechanisms involved and benchmark data for theory are urgently required since, while nearly exact ab initio calculations are available for static bound states of quantum mechanical few-body systems, dynamical reactions have proven to be much more difficult to be solved. Even for the simplest non-trivial system, the three-body problem as it is realized in low energy electron impact single ionization of hydrogen, accurate theoretical calculations have become available only within the recent years [1]. More complex systems, e.g., involving multi-electron targets as helium still pose severe problems for theory [2] and can be treated only in an approximate way. The most stringent test of calculations and the most detailed insight into the reaction is obtained by kinematically complete experiments in which the momentum vectors of all continuum particles are determined. For electron impact, such so-called (e,2e) experiments became possible very early, beginning from 1969, and a large part of our present knowledge on ionization of atoms by charged particle impact is based on these studies.

Collisions involving positrons are expected to be significantly different from analogous collisions involving electrons in particular in the low energy range up to ≈ 100 eV providing new tests of our understanding of basic atomic physics [3] (for a recent review see [4]). Reasons are the absence of the Pauli exclusion principle and therefore of the exchange interaction characteristic of electrons, the added richness of the positronium channel and the repulsive short-range positron-atom interaction, in contrast to the attractive electron-atom interaction. Experimental data in particular for differential cross sections are scarce. For ionization, so far, mainly integrated cross sections were measured and fully differential cross section data exist only for one distinguished collision geometry where both, the ionized target electron and the positron projectile are emitted into the forward direction after the collision [5, 6]. Reasons are the lack of available intense positron beam sources and the low efficiency of conventional experimental coincidence spectrometers. Recently, first results from highly efficient multi-particle imaging spectrometers were presented at higher impact energy [7]. The project described here aims to set-up a multi-particle imaging spectrometer (reaction microscope) with large phase space acceptance, improved momentum resolution and high efficiency. Here we report on the results of a first pilot beam time at the NEPOMUC positron beam facility at the neutron research reactor FRMII in Garching.

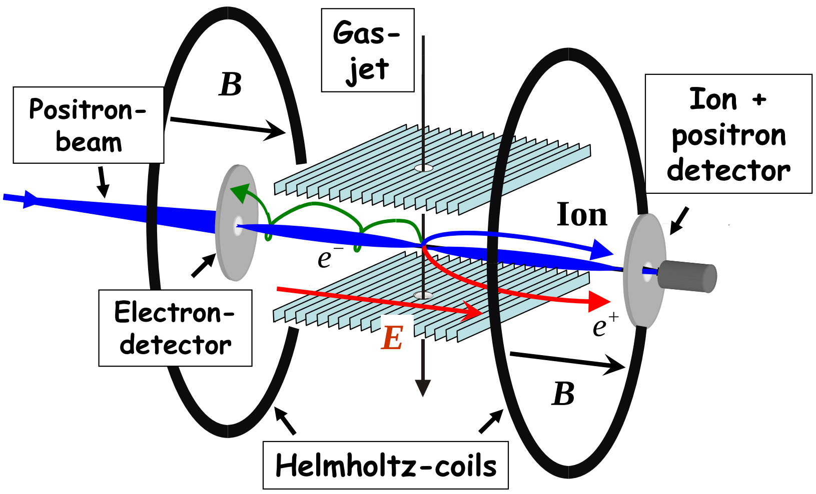

Figure 1. Scheme of the apparatus.

2. Experimental technique

2.1. The reaction microscope

A sketch of the apparatus is shown in Figure 1. This reaction microscope is normally used for electron impact ionization studies [8] and has been adapted for the use of a positron projectile beam. A collimated projectile beam crosses a target gas jet producing a well defined reaction volume of mm size. The reaction microscope technique [9] is based on the projection of all charged final state particles produced in an ionization reaction by means of homogenous electric and magnetic fields parallel to the projectile beam axis onto microchannel plate (MCP) detectors. The scattered positrons and the recoiling ions are registered by the detector in forward direction with respect to the incoming beam and the ejected electron by the backwards detector. The momentum vectors which the particles obtained in the collision then are calculated from their times-of-flight (TOF) and detection positions. As indicated in Figure 1, the cyclotron trajectory of the electron in the 6 Gauß magnetic spectrometer field serves to transversally confine the trajectories of the final state electron to the sensitive area of the detectors which is 8 cm in diameter. Furthermore, it guides and focuses the incoming projectile beam into the target gas jet and subsequently into a central bore of the MCPs of the forward detector. The target gas beam is produced by supersonic expansion of the gas with 20 bar stagnation pressure through a 30 µm nozzle into the vacuum. A two stage collimation and differential pumping using subsequent skimmers finally delivers a gas beam of 2 mm cross section with 10^{12} 1/cm^3 density in the collision point of the main chamber at a background pressure of 10^{-8} mbar. The supersonic expansion delivers an internal cold target with a temperature of roughly 1 K. This is required to provide a low target atom momentum spread and, therefore, a momentum resolution of about 0.1 – 0.2 a.u. for the ions produced in collisions with the positrons.

2.2. Attachment to the NEPOMUC facility

The spectrometer was attached to the open beam port of the NEPOMUC positron beam facility at the research reactor FRMII [10]. Here, nominally a flux of 10^7 positrons per second with 20 eV kinetic energy is delivered. The beam diameter is 2 mm and it is guided in a 60 Gauß solenoidal magnetic field. In order to transfer the beam into the reaction microscope an adiabatic field transition stage was used along which the field smoothly decreased over a distance of 60 cm from 60 Gauß to 6 Gauß. For optimal conditions the B-field reduction by a factor of 10 gives rise to the increase of the positron beam cross section area by the same factor. Therefore, a subsequent collimation with an aperture to the original beam size of 2 mm should result in a positron flux of 10^6 1/s. In reality only about $2{\cdot}10^5$ 1/s were obtained using a collimation aperture of 5 mm measured with the positron MCP detector of the spectrometer. The reasons could not be unambiguously clarified during the beam time and have to be investigated in the future. There could be imperfections in the magnetic field transition stage or in the beam transportation line geometry which was passing by the reaction microscope rather close and therefore the B-fields from the spectrometer and the beam line interfered. During the experiment a triple coincidence rate for He ionization of roughly 1/120s and altogether 5000 events within the available beam time were obtained.

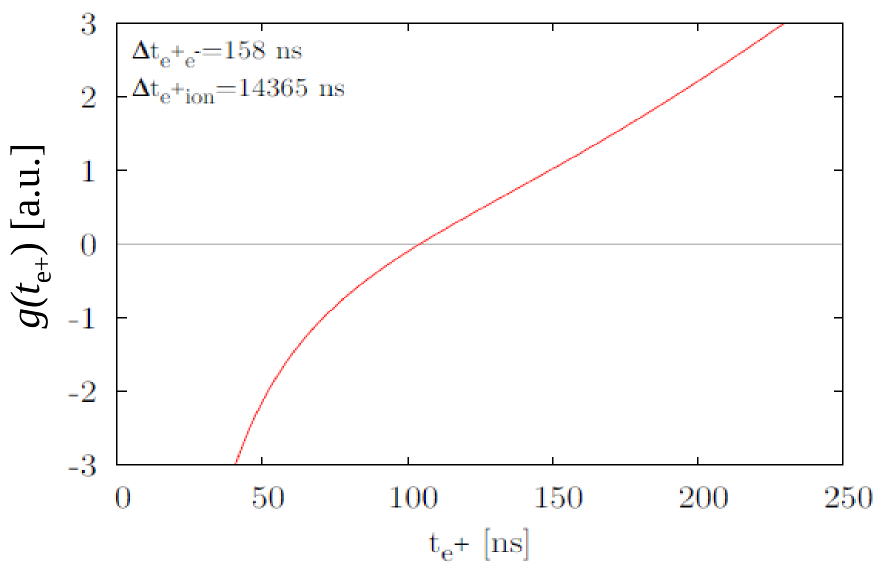

Figure 2. The dependence of the functional given in equation (1) from the positron TOF for particular relative TOFs of the particles shown in the diagram

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2.3. Particle time of flight determination

In order to calculate the initial momentum of the charged particles produced in a collision their TOF to the MCP detector is required. Since the projectile beam is not pulsed the collision time is not provided directly. For high projectile beam energies in the range of several hundred eV the timing signal of the scattered and detected positron is a good time reference for the collision time since in most cases the relative energy loss in the collision is small compared to absolute positron energy and its TOF, therefore, in a good approximation is a constant. At low energies as it is the case here the scattered positron's TOF varies considerably from collision to collision and this is a signature of the full three body complexity of the reaction we are interested in.

Experimentally measured quantities are the relative TOF of the particles with respect to each other, i.e. the time difference between the positron and the electron Δt_{e+e-} and between the positron and the recoiling ion Δt_{e+He+}. If we take the positron TOF t_{e+} as an unknown variable we can express the longitudinal momena of all particles to be a function of this quantity:

$$\begin{aligned} k_{e+}^{\|} &= f(t_{e+}) \\ k_{e-}^{\|} &= f(t_{e-}) = f(t_{e+} + \Delta t_{e+e-}) \\ k_{He+}^{\|} &= f(t_{He+}) = f(t_{e+} + \Delta t_{e+He+}) \end{aligned}$$

Now we make use of momentum conservation requiring that the sum of all final state longitudinal momenta is equal to the incoming projectile momentum assuming that the target atom is standing still initially.

$$k_{Sum}^{\|}(t_{e+}) - k_0^{\|} = g(t_{e+}) = 0 \tag{1}$$

Thus, finding the root of the functional $g(t_{e+})$ provides the required positron TOF t_{e+} from which the other particles' TOFs t_{e-} and t_{He+} can be obtained. As an example in Figure 2 $g(t_{e+})$ is plotted as function of t_{He+} for particular relative TOFs Δt_{e+e-} and Δt_{e+He+}. The accuracy of this procedure is about 0.1 – 0.2 a.u. in longitudinal momentum, i.e. the longitudinal momentum resolution of the spectrometer.

3. Results

Altogether about 5000 triple coincidence events were collected during a data accumulation time of roughly 5 days. This number is not sufficient for the extraction of fully differential cross sections requiring the selection of a small subset of these data by fixing, e.g., the projectile scattering angle, an ejected electron solid angle element with respect to the projectile scattering plane and its kinetic energy within certain constraints. In order to do so about one to two orders of magnitude more events are required. Therefore, here partially integrated data are presented. In Figure 3 (top diagram) the cross section is plotted as function of the longitudinal momentum of the scattered positron as well as function of the ejected electron. For comparison a respective cross section for electron impact ionization at slightly higher impact energy of 100 eV is also shown in Figure 3 (bottom diagram). Since in this case ejected and scattered electrons cannot be distinguished only one curve is plotted showing also a sharp peak at high forward momentum which can be assigned to forward scattered projectiles and a broad maximum around zero momentum corresponding to ionized electrons. For positron impact, the situation is clear since the projectile and the ejected electron can be distinguished. As expected a clear forward emission of the positron is found with a rather sharp cut-off close to the maximum momentum at 2.1 a.u. corresponding to a forward scattered positron which has lost just the He ionization energy. Interestingly also the emitted electrons are strongly forward emitted with the cross section maximum close to 1 a.u. This is in strong contrast to the results obtained for electron impact ionization where the maximum of the emitted electrons is found at zero momentum. A likely explanation for this behaviour is the different post collision interaction (PCI) in both cases. For positron impact, the emitted electron is attracted by the scattered positron and dragged forward. For electron impact the ionized electron is repelled by the scattered projectile. As a result, the projectile peak is also broader for positron impact, since there is additional energy loss due to PCI while the contrary is true for electron impact.

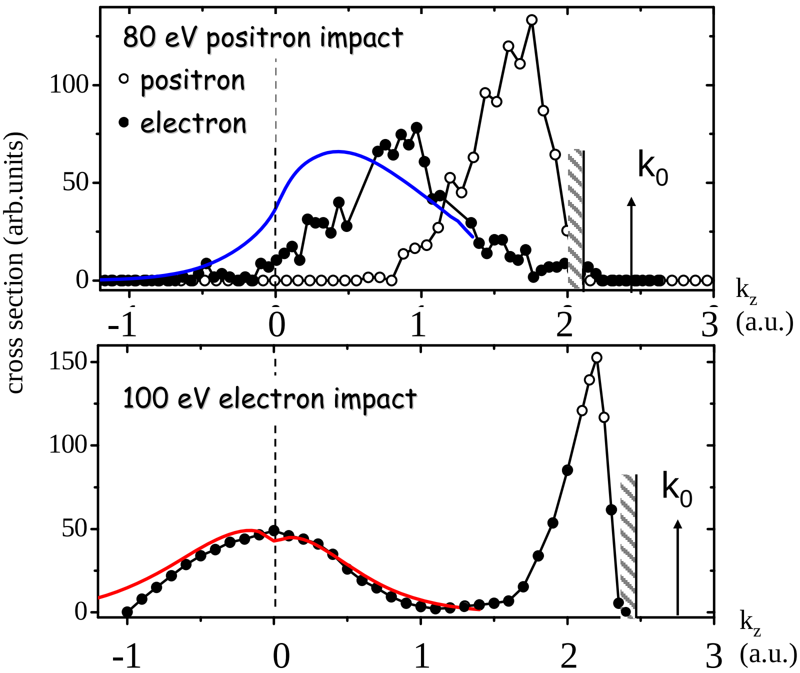

Figure 3. Positron (top) and electron (bottom) impact single ionization cross sections as a function of the longitudinal momentum of one final state continuum particle. This is the scattered positron or the ejected electron in case of positron impact and one free electron in case of electron impact. The plotted curves are 3C-calculations.

The measurements are compared with calculations using the 3-Coulomb wavefunction method (3C) which takes into account the Coulomb interactions within each two-body subsystem in the final state continuum. While this wavefunction is not an exact solution of the three-body problem at small inter-particle distances it has proven to yield reliable fully differential cross sections for electron impact ionization in the energy range down to about 100 eV [8]. Indeed, the calculation compares rather well with experiment in case of electron impact ionization showing its cross section maximum also close to zero momentum and a width slightly larger than experimentally observed. For positron impact, there is a significant deviation of the cross section maximum which is shifted to lower momentum by almost 0.5 a.u. The origin of this discrepancy is not clear and might indicate difficulties of the model to describe the increased interaction of two forward emitted Coulomb particles.

4. Conclusions

In summary we have demonstrated the feasibility of kinematically complete experiments for low energy positron impact ionization of atoms using a reaction microscope in combination with a magnetically guided continuous positron beam. For 80 eV impact energy, triple coincidences of all final state particles were recorded allowing the reconstruction of their absolute times-of-flight by exploiting momentum conservation. As an example, cross sections as function of the longitudinal momentum of the scattered projectile and the ejected electron were presented and compared with respective electron impact ionization data and calculations using the 3C model. Significant differences of the emitted electron distribution were found between positron and electron impact ionization and assigned to the reversed PCI in both cases. The origin of the discrepancy found in comparison with 3C theory is not clear so far. Here a respective calculation within a different theoretical approach would be helpful. In future fully differential cross sections will be obtained using longer data accumulation times or higher positron beam intensities combining a reaction microscope with the Australian Positron Beamline Facility [11].

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