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OPTIMIZATION OF ANTIPROTON-ATOM COLLISION STUDIES USING GEANT4*

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Abstract

The interaction between antiprotons and hydrogen or helium atoms is a fundamental problem in many-particle atomic physics, attracting strong interest from both theory and experiments. Atomic collisions are ideal to study the three and four-body Coulomb problem as the number of possible reaction channels is limited. Currently, only the total cross-sections of such interactions have been measured in an energy range between keV and a few MeV. This contribution investigates the discrepancies between different theories and available experimental data. It also describes a pathway for obtaining differential cross-sections. A purpose-designed experimental setup is presented and detailed Geant4 simulations provide an insight into the interaction between short (ns) antiproton bunches and a dense gas-jet target.

INTRODUCTION

Atomic ionisation resulting from antiprotons is an ideal reaction candidate to study the many-body Coulomb problem, which still represents the main challenge for various theories [1,2]. Multiple discrepancies have been observed in fully differential cross sections for the single and double ionisation caused by antiprotons [3–5] with an example shown in Fig. 1.

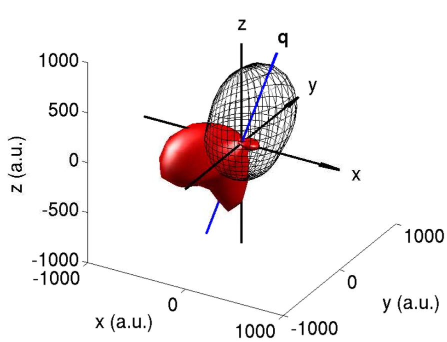

Figure 1: Comparison of differential cross-sections for He ionisation with 5 keV antiproton estimated from Born approximation (wired shape) and theory suggested in [6] (red surface). Results are reproduced with permission from the author.

Only a limited number of antiproton facilities worldwide may provide a suitable beam to investigate this problem. Among them are the Antiproton Decelerator (AD) at CERN [7], which produces antiprotons with 5.3 MeV kinetic energy and the recently commissioned Extremely Low Energy Antiproton ring (ELENA) [8,9] shown in Fig. 2. This is a small synchrotron installed within the AD complex to further decrease the energy of antiprotons to kinetic energies as low as 100 keV, thus enhancing the resolution and capability of antimatter experiments.

Figure 2: CAD model of the ELENA ring. The beam is travelling clockwise.

A common layout of experiments for the cross-section measurements uses a single-pass setup in the transfer line, however, an alternative scheme of collision of the antiproton beam with the target inside the storage ring has a number of advantages [10]. In such setup, the projectile beam can interact with the target many times, thus improving efficiency and achieving effective collision rates of ~1000 events per second. The possible experimental setup may consist of a low-density gas-jet target (~ $10^{14}\ \mathrm{m}^{-3}$ atoms) and the reaction microscope, that will measure the time-of-flight and the position of the recoil fragments, resulting from the ionisation event, using two-dimensional detectors. The top part in Fig. 3 gives a general layout of the microscope setup. However, to perform crossed-beam studies with the gas-jet, it is necessary to have bunch length in a few ns regime to allow efficient triggering on the detector and to decrease time errors for theory calculations. This requirement immediately puts other strong limitations on the beam. For equilibrium storing conditions, bunch intensities on the order of 10^4–10^5 are required to compromise an impact coming from beam heating effects, e.g. space-charge and intrabeam scattering (IBS), leading to emittance blow-up.

To prove the possibility of experimental measurements with the required antiproton beam and gas jet parameters, in this paper, we present reverse simulation studies where

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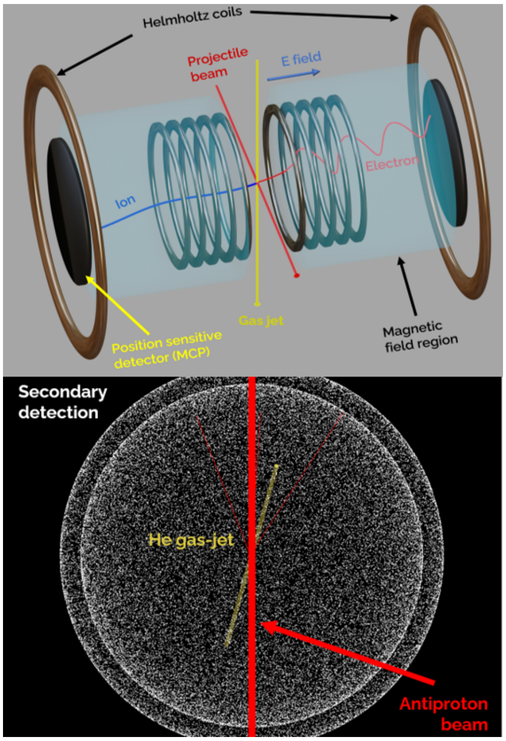

Figure 3: (Top) Demonstration of the general layout of the reaction microscope. (Bottom) A simplified simulation of beam interaction with the gas-jet in Geant4.

from the beam interaction and reaction rates we are getting to the short bunch formation inside the ELENA ring.

GEANT4 SIMULATION OF THE GAS-JET

For a better understanding of the expected reaction rates after the interaction with the gas-jet, a simple Geant4 model was created, shown in Fig. 3 (bottom). It consists of a high uniform density He gas-jet beam (10^{14} m^{-3} atoms) crossed with $4.5{\times}10^6$ antiprotons with bunch parameters equal to those of bunch extracted from ELENA ring. The gas-jet width of 3 mm was considered, which is equal to $2\sigma_{x,y}$ of the beam. The primary interaction process with atomic He in this energy range is the single ionisation. Presently, the Geant4 values calculated from the low-energy physics list **QBBC+EmOption4** are quite diverse in comparison with the recent measurements [4]. Thus, it was decided to apply biasing technique, where reaction weight was increased, as shown in Fig. 4. From the number of all detected electrons, the reaction rates were estimated to be in the order of ~5000 events per second. In the real case, this value will be an overestimation due to the fact that all electrons were detected and the density of the gas-jet might be decreased to meet the vacuum pressure requirements for the ELENA ring.

Also, in Fig. 5 we demonstrate how the time signal from electrons depends on the initial bunch length of antiprotons. The small difference between bunch length and σ_t is mostly caused by velocity and angular spreads of electrons.

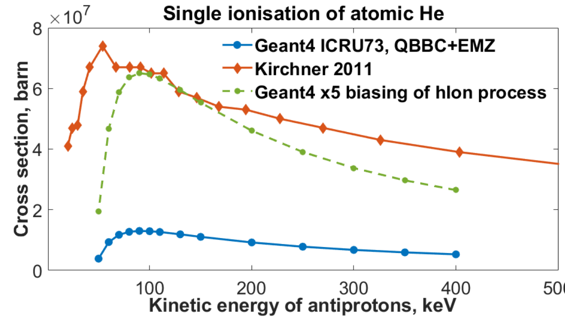

Figure 4: Dependence of cross-section value for single ionisation of atomic He from the kinetic energy of antiproton.

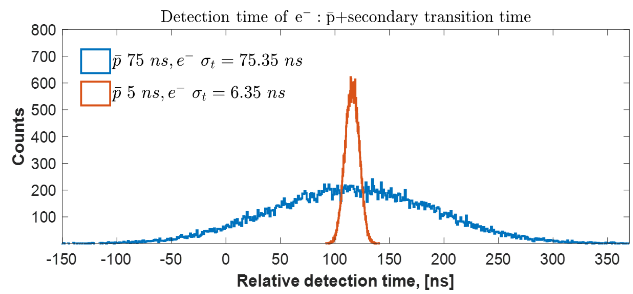

Figure 5: The difference in the time signal produced by the secondary electrons depending on the initial antiproton bunch length.

MITIGATION OF THE SPACE-CHARGE IMPACT

It worth to mention, that bunch with an initial intensity of $4.5{\times}10^6$ antiprotons and bunch length of 5 ns will experience an increase of impact from collective effects. One of the simple ways how to maintain the stability of the short bunches is to decrease the initial bunch population by a factor of 16.

Thus, we have investigated how incoherent tune shift value varies with the bunch length and bunch intensity using PyHEADTAIL [11]. The obtained distributions of the particle tune shifts with $\Delta Q_{x,y}$ of -0.07 and -0.1 for 75 or 5 ns bunches are equal in size and shown in Fig. 6. This result coincides well with values that can be obtained from analytical Eq. (1) for the Gaussian beams

$$\Delta Q_{x,y} = -\frac{r_0 \lambda}{2\pi \beta^2 \gamma^3} \frac{\langle \beta_{x,y} \rangle R}{\sigma_{x,y}(\sigma_x + \sigma_y)}, \tag{1}$$

where r_0 is the classical particle radius, $\langle \beta_{x,y} \rangle$ are the mean lattice betatron functions, $\sigma_{x,y}$ the horizontal and vertical r.m.s beam sizes, λ the linear peak density, R is the machine radius.

BUNCH COMPRESSION STUDIES

Presently ELENA ring operates with four bunches when the RF cavity voltage amplitude is around 50 V and RF frequency corresponds to the harmonic number h = 4. The tolerated bunch intensity in the case of 5 ns is lower than the number of particles in the single bunch. Therefore for

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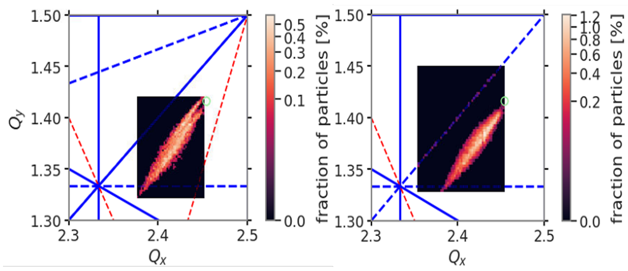

Figure 6: Tune distribution of the matched ELENA bunches. (Left) Bunch length with 75 ns r.m.s and intensity of 4.5×10^6 antiprotons.(Right) Bunch length with 5 ns r.m.s and intensity of 2.8×10^5 antiprotons.

the bunch shortening procedure, three bunches need to be extracted from the ring as shown in Fig. 7 and thereafter remaining bunch will be adiabatically de-bunched into coasting beam and then re-bunched at higher harmonic h = 16 and cavity voltage of 500 V which are peak operating parameters of ELENA RF system given in [12].

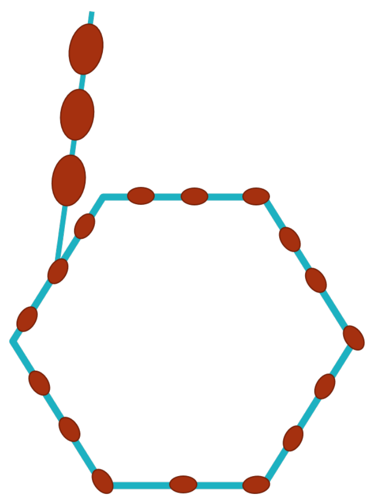

Figure 7: The proposed re-bunching scheme for ELENA ring: (1) Ejection of three bunches from the ring; (2) De-bunching of the remaining bunch; (3) Re-bunching at h = 16 with RF voltage of 500 V.

To understand what is the minimal bunch length that can be theoretically achievable, we have simulated the re-bunching step for the coasting beam using ESME [13]. An outcome of this process is depicted in Fig. 8. The final phase occupation of the single bunch within the selected contour is 1.35° r.m.s that corresponds to the bunch length of 1.66 ns r.m.s. This result demonstrates that the ELENA ring in theory can produce much shorter bunches that are suitable for the measurements of fully differential cross-sections.

CONCLUSION

The future improvements in the field of low energy physics (<100 keV) and particularly antiproton facilities like ELENA will provide unique tools for examination of the fundamental

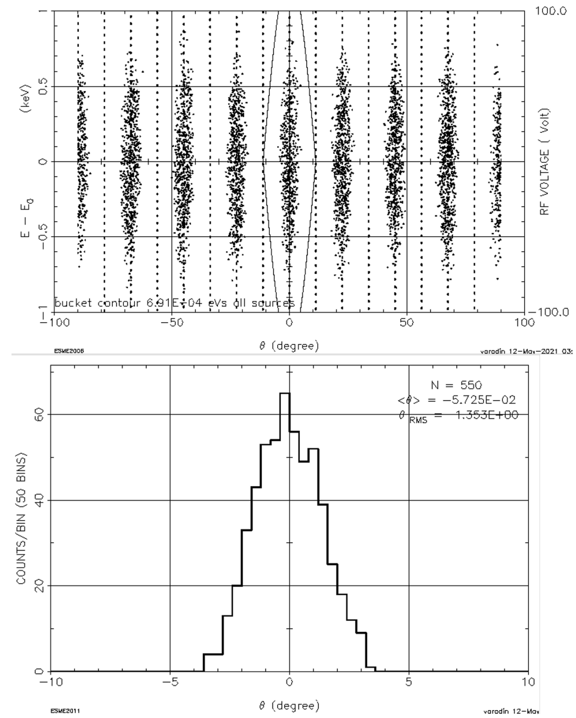

Figure 8: (Top) Longitudinal distribution of 5000 macro particles after the re-bunching process. (Bottom) Phase distribution of particles within selection contour.

physical theories, including three- and many-body Coulomb problems, and uncover a difference in the interaction of antiprotons with H, He and other atoms using differential cross-section studies. For these measurements, precise identification of properties of reaction fragments becomes particularly challenging due to poor time resolution of provided bunches.

In this work, we presented a simulation overview of various aspects of the possible experiment at the ELENA ring. These include a re-evaluation of reaction rates with the recent cross-section data and presently feasible gas-jet densities. Our estimated values are in order of thousand counts per second.

To improve the time resolution of the secondary electrons, the re-bunching scheme was proposed. The dilution of the single bunch at higher harmonics and RF voltage amplitude may produce bunches around 2 ns range and mitigate the impact of the space-charge effect.

Further investigation will include simulation of the whole re-bunching procedure with space-charge and other heating effects applied. The reaction microscope design will be designed to maximise angular acceptance and time resolution for the reaction fragments.

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