Antihydrogen synthesis in a double-CUSP trap towards test of the CPT-symmetry

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Abstract The aim of the ASACUSA-CUSP experiment at CERN is to produce a cold, polarised antihydrogen beam and perform a high precision measurement of the ground-state hyperfine transition frequency of the antihydrogen atom and compare it with that of the hydrogen atom using the same spectroscopic beam line. Towards this goal a significant...
step was successfully accomplished: synthesised antihydrogen atoms have been produced in a CUSP magnetic configuration and detected at the end of our spectrometer beam line in 2012 [1]. During a long shut down at CERN the ASACUSA-CUSP experiment had been renewed by introducing a new double-CUSP magnetic configuration and a new semi-cylindrical tracking detector (AMT) [2], and by improving the transport feature of low energy antiproton beams. The new tracking detector monitors the antihydrogen synthesis during the mixing cycle of antiprotons and positrons. In this work the latest results and improvements of the antihydrogen synthesis will be presented including highlights from the last beam time.

Keywords Antihydrogen · Antimatter micromegas · Tracking · Vertex reconstruction · CPT symmetry

1 Introduction

The ASACUSA-CUSP experiment at CERN aims to measure and compare the ground-state hyperfine (GS-HFS) transition frequency of antihydrogen and hydrogen, which is a direct test of the CPT-symmetry. In order to achieve this goal the experiment successfully produced antihydrogen atoms and detected them at and of dedicated spectrometer beamline [1]. Positrons are injected from a buffer gas trap operating with a $^{22}$Na source. Antiprotons are provided by the Antiproton Decelerator (AD) at Cern. An ultra-low energy antiproton beam source (MUSASHI) traps and cools the antiprotons from the AD complex before injection into the cusp trap to mix antiprotons and positrons in a nested-well electrical potential combined with a custom made cusp magnetic field. The cusp trap produces a spin-polarized beam of antihydrogen atoms, and a microwave cavity tuned around the GS-HFS frequency induces spin-flip transitions. Finally, a sextupole magnet can test the polarity of the beam by focusing or defocusing depending on the different spin states. By scanning the microwave frequency and detecting annihilation signals by BGO scintillator crystal at the end of the spectrometer beamline the resonant frequency can be measured. The experiment scheme is illustrated in Fig. 1. In this work the various upgrades to the existing experiment setup and new developments, which took place during a two-year long shutdown period, are summarised.

2 Improvement on low-energy antiproton transport

During the shutdown period at the AD the ASACUSA-CUSP experiment took measures to improve on the low-energy antiproton transport between the MUSASHI and the cusp trap. This in order to achieve adiabatic transport of antiprotons such that they do not gain energy and they have a low and narrow energy distribution when arriving at the cusp trap. The main goal is to avoid heating up of the positron plasma during direct injection of antiprotons into nested well potential in the cusp trap. The multi-ring electrode potential configuration was tuned to achieve better performance inside the MUSASHI trap and this is illustrated in Fig. 2.

With the improved MUSASHI potential configuration used to trap and extract antiprotons a mean kinetic energy of $\approx 25$ eV with a width of $\approx 15$ eV has been reach. Previously, the mean kinetic energy was $\approx 125$ eV with a width of $\approx 27$ eV.
3 Double-cusp magnet

To reach better polarization of antihydrogen atoms emerging from the cusp trap a new magnetic field configuration was designed. It was found that a double-cusp configuration enhances the polarization of antihydrogen atoms at kinetic energies below 100 Kelvin. The difference between single- and double-cusp magnetic configurations and the calculated improvement in polarization is illustrated in Fig. 3. The polarization is a measure of fraction of Low-Field Seeker (LFS) or High-Field Seeker (HFS) states per 1 antihydrogen atom. LFS (HFS) atoms are attracted to low (high) magnetic field regions because of the direction of bending of the corresponding binding energies with respect to a variation of the magnetic field. In general, an order of magnitude improvement in polarization for LFS states at antihydrogen temperatures below $T = 20 \text{ K}$.

4 Asacusa Micromegas Tracker (AMT) 3D vertex detector

During the shutdown period a new high-resolution, cylindrical annihilation vertex detector was designed and realised in order to monitor antihydrogen production closest to the antihydrogen mixing region. The AMT detector [2] has been installed between the space of the double-cusp magnet bore and cryogenic ultra-high vacuum trap. The detector and its placement is illustrated in Fig. 4. Briefly, the AMT detector consists of two, half-cylinder Micromegas layers, and a full-cylinder layer of plastic trigger scintillator bars between the Micromegas layers, segmented into eight bars. We have trapped antiprotons and tested the AMT by reconstructing the annihilation vertices. The reconstruction algorithm selects
Fig. 2 Manipulation of trapping (black lines) and extraction (red and blue lines) of antiprotons inside the MUSASHI trap. The figure on the top illustrates the configuration used before the shutdown, and the bottom figure illustrates the new, improved potential configuration. The thick blue arrows indicate the potential well minimum just before extraction of antiprotons.

events with at least 2 hits on each layers. The hits are matched together and used seed track fitting. Finally, the fitted tracks are used to find the three-dimensional point of closest approach point which is assigned as the vertex candidate position in the event. Measurements were carried out with cosmic rays and trapped antiprotons to tune the algorithms and to test the 3D vertex reconstruction capability of the AMT. An example of such a measurement is shown in Fig. 5.

During mixing of antiprotons and positrons in the double-cusp trap the AMT recorded the triggered events and the reconstructed vertex position distribution as a function of time is illustrated in Fig. 6. The top left figure shows the axial vertex position distribution as a
Fig. 3  Left: Single cusp field is produced by a pair of anti-Helmholtz coils (top: a, b), double-cusp field is produced by two pairs of anti-Helmholtz coils (bottom: a, b). Right: improvement on polarization comparing the single- and double-cusp magnetic configurations. The solid line in the middle indicates the solid angle limit when no polarization takes place.

Fig. 4  Left: Illustration of the cylindrical AMT vertex detector. Right: placement of the AMT detector around the cryogenic, ultra-high vacuum bore of the double-cusp trap (the double-cusp magnet is not shown in this illustration).

function of time, where the beginning of the time is defined as the time of the injection of antiprotons into the double-cusp trap. The top right figure shows the nested well potential configuration and the on-axis magnetic field values. The injection took place from the upstream end direction of the nested well, at around \( Z \sim -40 \, \text{cm} \), towards the downstream end, \( Z \sim -15 \, \text{cm} \). The annihilation distribution shows the following features: in the first 10 seconds there is a large excess of annihilations at a position consistent with the downstream end of the nested well. This is understood as the potential barrier height is at the downstream end slows down the antiprotons. Annihilation can take place due to antiprotons annihilating on residual gas atoms and molecules in the vacuum. After \( \sim 10 \, \text{seconds} \) the initial excess reduces and the excess of annihilations takes place at \( Z \approx -23 \, \text{cm} \), which is
consistent with the positron plasma position. This feature lasts until around 40 seconds. At the bottom left of the figure a subfigure shows the radial coordinate versus the axial coordinate of the reconstructed vertices at this time. The distribution on this subfigure indicates that annihilation takes place at this axial position and up to radial coordinate $R \approx 4$ cm, which value is consistent with the radius of the multi-ring electrode trapping the antiprotons and positrons. Because the antihydrogen atom is neutral it can escape the trap and a fraction of these antihydrogen atoms is expected to annihilate on the multi-ring electrode, while antiprotons continue to annihilate at the axial centre. Finally, the bottom right figure illustrates that towards a time of $\sim 100$ seconds after injection two separate excess appears in the annihilation position distribution consistent with the position of the two minima of the nested-well potential, and the excess of annihilations at radii around the multi-ring electrode disappears. This behaviour indicates that the antiprotons settled in the nested well and stopped overlapping with the positron plasma, therefore antihydrogen production has already stopped.
5 Antihydrogen formation simulation with classical-trajectory Monte Carlo simulation

In addition to improvements and new detectors around the ASACUSA cusp trap results have been also achieved in understanding the formation and level population evolution of antihydrogen atoms from classical-trajectory Monte Carlo simulations. The simulation uses previously calculated rate coefficients for the following processes: three-body recombination, radiative recombination, collisional (de)excitation, collisional ionisation, spontaneous radiative decay and stimulated radiative transitions. We have set up a system of rate equations to model the population and depopulation of the quantum levels of antihydrogen by all of these processes and evolved the system for a certain amount of time. The evolution time we choose to correspond to the time needed roughly for one passage of antiproton through a positron plasma of typical length. The evolution time used is 10 μs. Because of the positron temperature and density and external magnetic field dependence of the rates of some of these processes we have performed Monte Carlo simulation scanning all these parameters in order to extract the scaling behaviour of the level population close to the ground-state of antihydrogen. The result is illustrated in Fig. 7. The results indicate that the ground-state antihydrogen yield in the experimentally currently accessible positron temperature and density scales ($T \simeq 300$ K and $n \simeq 10^{14}$ m$^{-3}$) can be greatly improved by either density or temperature improvements. However, the scaling is not linear and furthermore the model code described above can be used as a guidance to tune the experiment towards optimal ground-state yield or extended for additional processes and effects. Further details of the simulation can be found in [3].

6 Summary and outlook

In summary the ASACUSA-CUSP experiment performed several improvements during the long shutdown of the AD from 2012-2014. In particular, the low-energy antiproton transport has been improved to achieve a lower energy and more adiabatic transport from the MUSASHI trap to the cusp trap. A new, double-cusp magnetic field was realised in
order to enhance the antihydrogen polarization by as high as an order of magnitude at low temperatures. A dedicated high-resolution 3D vertex detector (AMT) has been designed, realised and tested and successfully demonstrated its capability to recognise antihydrogen production as a function of space and time. Finally, a new collisional-radiative code, based on a classical-trajectory Monte Carlo atomic scattering code, has been made to simulate the formation of antihydrogen during mixing of antiprotons and positrons and the subsequent scattering processes and their dependence on the positron temperature and density conditions. With the improvements the ASACUSA-CUSP experiment is looking forward to taking further steps in achieving the first direct measurement of the GS-HFS of antihydrogen.

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