ASACUSA STATUS REPORT

ASACUSA progress during 2008
and plans for 2009

ASACUSA collaboration

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Executive Summary

In this report we present the main achievements of ASACUSA in 2008 and discuss plans for 2009.

Antiprotonic helium ($\bar{p}$He$^+$) spectroscopy

1. Doppler-free laser spectroscopy of $\bar{p}^4$He$^+$ ($m_e/m_\bar{p}$ determination)

   (a) Near-resonant two-photon laser spectroscopy (page 3): In 2008, we successfully observed a new $\bar{p}^4$He$^+$ two-photon transition, at the deep ultraviolet (DUV) wavelength $\lambda = 139.8$ nm. This transition, between states with principal and angular momentum quantum numbers of $(n, \ell) = (33, 32)$ and $(31, 30)$, was excited by two simultaneous laser beams of $\lambda = 264.7$ and 296.1 nm. This two-photon result, together with the data taken in 2007, is expected to lead to a better determination of $m_e/m_\bar{p}$, and will be published in 2009 after finishing the data analysis and various systematic studies.

   (b) Two-color saturation spectroscopy (page 6): this new method, introduced in 2008, used two laser beams, $\lambda = 296.1$ and 264.7 nm, tuned respectively on the resonances $(n, \ell) = (33, 32) \rightarrow (32, 31)$ and $(32, 31) \rightarrow (31, 30)$. The first laser selectively depopulated the part of the thermal distribution (made a “hole” in the distribution, the width of which was much narrower than the original Doppler one $\Delta \nu = 0.4–2$ GHz). This hole was then probed by the second laser, which was fired simultaneously with the first one.

   (c) Single-color saturation spectroscopy (page 7): this new method, also introduced in 2008, involved irradiating the $\bar{p}$He$^+$ with two consecutive laser pulses of the same wavelength $\lambda = 726$ nm ($(n, \ell) = (37, 35) \rightarrow (38, 34)$). As in the two-color method described above, the first laser created a “hole” in the thermal distribution of $\bar{p}$He$^+$, which was then probed by the second laser. The advantage of this method was that the first-order Doppler width $\Delta \nu$ are in principle completely canceled, whereas in the previous two methods, there is a small residual Doppler broadening.

In 2009, we allocate 7 weeks to the continuation of the Doppler-free saturation laser spectroscopy.

2. Hyperfine Structure of $\bar{p}^3$He$^+$ ($\mu_\bar{p}$ determination, page 10): Our aim in 2008 was to reduce to measure the antiprotonic helium hyperfine splitting (HFS), $\Delta \nu_{\text{HF}} = \nu_{\text{HF}}^+ - \nu_{\text{HF}}^-$, to the precision of theory (33 kHz) by performing a high statistic density dependence study. The measurements in 2008 showed that the measured precision there is no evidence of a density or power dependent shift. Averaging all the results, we achieved a precision of 36 kHz, a factor of 10 improvement over our first measurement in 2002. A publication is planned for the beginning of 2009.

In 2009, we allocate 5 weeks to measure for the first time the hyperfine structure of $\bar{p}^3$He$^+$

$\bar{p}$-atom and $\bar{p}$-nucleus collisions

1. Antiproton-nucleus annihilation cross section at low energies (page 12): In 2008, we succeeded for the first time to obtain the relative $\bar{p}$ annihilation cross sections on medium-heavy nuclei (Mylar, Ni, Sn, Pt) at low energy (5 MeV, or 100 MeV/c). This represents also the first measurements of antinucleon annihilation cross section at low energy performed with a pulsed beam. Preliminary results indicate that $\sigma_{\text{ann}}(\bar{p} - A) \propto A^{2/3}$ is compatible with the data. This suggests that the saturation effect seen with light nuclei at lower energies (below 60 MeV/c) is not present for the measured target at 100 MeV/c. Publication of these results are planned in 2009.
In 2009, we allocate 1.5 weeks to extend these measurement to a much lower energy of ~ 100 keV (using the RFQD).

2. $\bar{p}$-$D$ and $\bar{p}$-$D_2$ ionization cross section (page 38): The $\bar{p}$-He ionization cross section data taken with the MUSASHI\textsuperscript{1}+AIA\textsuperscript{2} in 2007 have recently been published. In 2009, we therefore allocate 2 weeks to take data on the more fundamental $\bar{p}$-$D$ and $\bar{p}$-$D_2$ ionization cross sections.

Towards antihydrogen ground-state hyperfine spectroscopy

1. Cusp-trap commissioning (page 16): In 2008, we accomplished the following:

(a) transported cooled antiprotons from the multi-ring trap of the antiproton trap (pbar-MRT) to the multi-ring trap of the cusp trap (cusp-MRT) with high efficiency, then trap and cool antiprotons both in the upstream and downstream spindle cusp regions (page 17),

(b) constructed an efficient positron accumulator (page 21),

(c) trapped and cooled antiprotons and positrons simultaneously (page 23), and

(d) installed and tuned the 3D detector to monitor radial as well as axial annihilation positions of antiprotons in the cusp-MRT, which is essential to study antihydrogen production processes (page 23).

In 2009, we allocate 6.5 weeks (+1 week for the MUSASHI beam development) to demonstrate $\bar{H}$ formation in the cusp trap.

2. Other developments (without using the AD beam):

(i) Construction of a superconducting radiofrequency Paul trap for antiprotons is in progress at CERN (page 28), and (ii) ASACUSA positron beam line (to be used in conjunction with the Paul trap), a conventional buffer-gas $e^+$ accumulator, has been commissioned (page 28).

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Part I

ASACUSA Progress during 2008

1 Antiprotonic Helium Spectroscopy

1.1 Doppler-free saturation and two-photon laser spectroscopy of antiprotonic helium atoms

1.1.1 Overview of the achievements

In 2008, the ASACUSA collaboration utilized three non-linear laser spectroscopy techniques to measure the transition frequencies of antiprotonic helium ($\bar{p}^3$He$^+$ and $\bar{p}^4$He$^+$) atoms [1, 2] with higher precision than before [3–5]. These methods used various combinations of two counter-propagating laser beams to cancel the Doppler broadening in the $\bar{p}$He$^+$ resonance lines. This broadening of width $\Delta \nu = 0.4$–2 GHz, caused by the thermal motions of the atoms in the experimental target, had limited the precision of all previous experiments to around $\sim 1$ part in $10^8$.

1. *Near-resonant two-photon laser spectroscopy:* these experiments were a continuation of those carried out in 2006–2007. In 2008, we discovered a new $\bar{p}^4$He$^+$ two-photon transition, at the deep ultraviolet (DUV) wavelength $\lambda = 139.8$ nm. This transition, between states with principal and angular momentum quantum numbers of $(n, \ell) = (33, 32)$ and $(31, 30)$, was excited by two simultaneous laser beams of $\lambda = 264.7$ and 296.1 nm. The virtual intermediate state involved in this transition was detuned some $\Delta \nu_D \sim 4$ GHz away from the real state $(32, 31)$. The two UV laser beams of pulse energy $E \sim 10\ mJ$ needed for this experiment was produced by third harmonic generation of Ti:sapphire lasers.

2. *Two-color saturation spectroscopy:* this new method, introduced in 2008, involved carefully adjusting the two UV laser beams to energies of around $\sim 1\ mJ$, and tuning them on the resonances $(n, \ell) = (33, 32) \rightarrow (32, 31)$ and $(32, 31) \rightarrow (31, 30)$. This induced a special kind of two-step transition, wherein the first laser at wavelength $\lambda = 296.1$ nm selectively depopulated the part of the $\bar{p}$He$^+$ thermal distribution which was in resonance with the laser. This produced a "hole" or "Lamb dip" in the $\bar{p}$He$^+$ distribution, the width of which was much more narrow than the original Doppler one $\Delta \nu = 0.4$–2 GHz. This dip was then probed by the second laser of wavelength $\lambda = 264.7$ nm, which was fired simultaneously with the first one.

3. *Single-color saturation spectroscopy:* this method involved irradiating the $\bar{p}$He$^+$ with two consecutive laser pulses of the same wavelength $\lambda = 726$ nm. As in the two-color method described above, the first laser created a Lamb dip in the thermal distribution of $\bar{p}$He$^+$, which was then probed by the second laser. The advantage of this method was that the first-order Doppler width $\Delta \nu$ are in principle completely canceled, whereas in the previous two methods, there is a small residual Doppler broadening. The disadvantage lies in the very poor signal-to-noise ratio. In 2008, we attempted to demonstrate this method on the $\bar{p}^4$He$^+$ transition $(n, \ell) = (37, 35) \rightarrow (38, 34)$.

The two-photon spectroscopy studies have not been published, in 2009 we plan to finish the data analysis and proceed with publication.

1.1.2 CODATA recommended constants and the antiproton-to-electron mass ratio

In 2008, the Committee on Data for Science and Technology (CODATA) published the latest paper [6] describing the 2006 self-consistent set of values of the basic constants and conversion factors of physics
spin-flip/cyclotron frequency of trapped hydrogenic carbon (GSI 2002)  
spin-flip/cyclotron frequency of trapped hydrogenic oxygen (GSI 2002)  
Antiprotonic helium (ASACUSA 2006)  
Trap cyclotron frequency (Washington 1995)

Electron mass in atomic mass unit $A(e)$  
0.0005485799XXXX

Figure 2: Comparisons of electron mass in atomic mass unit determined in the CODATA 2006 compilation, from the results of magnetic Penning trap (at GSI and Washington State University) and antiprotonic helium laser spectroscopy experiments.

and chemistry for international use. The high-precision values of the $\bar{p}He^+$ transition frequencies measured by ASACUSA in Refs. [3–5] were included in this compilation, and used to determine the electron-to-(anti)proton mass ratio ($m_e/m_p$). The experimental determination of $m_e/m_p$ is important for CODATA, as it influences the values of many other fundamental constants through a chain of interdependencies [6]. The $m_e/m_p$ or $m_e/m_H$ values determined by the four experiments used in CODATA are shown in Fig. 2 and Table 1. The three other experiments, carried out at GSI and Washington State University, involve measuring the gyromagnetic ratios and cyclotron frequencies of electrons, protons, and hydrogenic carbon and oxygen ions confined in magnetic Penning traps. The $m_e/m_p$ values extracted from all of these experiments agree with the $m_e/m_p$-value determined by ASACUSA.

The transition frequencies [3] of antiprotonic helium, when combined with the cyclotron frequency of the antiproton measured by the ATRAP experiment [7] to a much higher precision of $9 \times 10^{-11}$, also indicate that any CPT-violating difference between the antiproton mass and charge, and those of the proton, must be less than $2 \times 10^{-9}$. This limit was included in the 2008 edition of the Particle Data Book [8].

Table 1: Values of the electron-to-(anti)proton mass ratio determined by the CODATA 2006 compilation from the results of Penning trap (at GSI and Washington State University) and antiprotonic helium laser spectroscopy experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m_e/m_p$ or $m_e/m_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$ bound-state g-factor of hydrogenic carbon (GSI)</td>
<td>0.00054857990953(29)</td>
</tr>
<tr>
<td>$e^-$ bound-state g-factor of hydrogenic oxygen (GSI)</td>
<td>0.00054857990958(42)</td>
</tr>
<tr>
<td>Proton and $e^-$ cyclotron frequency (Washington)</td>
<td>0.0005485799111(12)</td>
</tr>
<tr>
<td>$\bar{p}He^+$ laser spectroscopy (ASACUSA)</td>
<td>0.00054857990881(91)</td>
</tr>
</tbody>
</table>

The derivations of $e^-/m_H$ from the measured $\bar{p}He^+$ frequencies critically depend on the accuracy of the three-body QED calculations [9, 10] to which the experimental values of ASACUSA are compared. The latest series of calculations carried out by Korobov include higher-order relativistic corrections of order $\alpha^4$, and have a precision of around $\sim 1$ MHz. Ongoing work attempt to calculate even more complicated corrections of order $\alpha^6$. The same numerical methods were used to calculate the transition frequencies of
three-body HD$^+$ and H$_2^+$ ions. Intensive experimental work are now being carried out by various groups in Germany and France to measure these transition frequencies with ppb-scale precision using ion traps.

### 1.1.3 Sub-Doppler two-photon spectroscopy of the DUV transition $(n, \ell) = (33, 32) \rightarrow (31, 30)$.

In conventional, single-photon spectroscopy experiments of $\overline{p}$He$^+$ [3], the observed resonance lines of frequency $\nu$ are broadened by the thermal Doppler motion of the atoms in the target to a value equivalent to,

$$\Delta \nu = 2.35 \nu \sqrt{\frac{kT}{M c^2}},$$

wherein $M$ and $T$ denote the mass and temperature of the atom, $k$ the Boltzmann constant, and $c$ the speed of light. For example in $\overline{p}$He$^+$ atoms cooled to temperature $T \sim 10$ K, transitions at wavelength $\sim 260$ nm are broadened to around $\sim 1.2$ GHz. This broadening imposes a fundamental limit to the experimental precision on $\nu$ attainable by conventional single-photon spectroscopy.

![Image](image_url)

**Figure 3:** Two-photon spectroscopy of antiprotonic helium studied in 2008.

We solved these problems and canceled the Doppler effect by utilizing a near-resonant two-photon excitation. In 2008, we extended this method to a new DUV transition $(n, \ell) = (33, 32) \rightarrow (31, 30)$ at wavelength $\lambda = 139.8$ nm. This is now the highest-energy transition of $\overline{p}$He$^+$ measured so far. The two counter-propagating laser beams of wavelength $\lambda = 264.7$ and 296.1 nm irradiating the $\overline{p}$He$^+$ had non-equal frequencies $\nu_1$ and $\nu_2$, which were adjusted such that i): their combined frequencies $\nu_1 + \nu_2$ were tuned to the two-photon transition $(n, \ell) = (33, 32) \rightarrow (31, 30)$ involving an angular momentum change of $\Delta \ell = -2$, ii): the virtual intermediate state involved in the two-photon transition was tuned to within a few GHz of a real state $(n, \ell) = (32, 31)$.

We carried out theoretical calculations to estimate the two-photon transition amplitude under these experimental conditions. The nearness (detuning $\Delta \nu_D \sim 6$ GHz) of the virtual state to the real one led to an enhancement of the two-photon transition probability, to around $10^4$. We expected that the observed width $\Delta \nu_{2\gamma}$ of the resonance line would then decrease by factor 20 compared to the thermal Doppler width $\Delta \nu$ according to the equation,

$$\Delta \nu_{2\gamma} = \left| \frac{\nu_1 - \nu_2}{\nu_1 + \nu_2} \right| \Delta \nu,$$

allowing us to determine $\nu$ with a correspondingly higher experimental precision.

An important source of systematic error associated with this two-photon spectroscopy was the so-called "ac-Stark shift" of the $\overline{p}$He$^+$ energy levels, caused by their interaction with the oscillating electric field of the laser beam. In fact, non-zero values of the scalar and tensor polarizabilities of these energy levels can induce both a shift and broadening, the magnitudes of which are roughly linear to the laser power. We carried out extensive theoretical calculations and found that these shifts and broadenings would be around 5–10 MHz at our experimental conditions. The sign of the Stark shift changes depending on the detuning $\Delta \nu_D$ of the virtual intermediate state, relative to the real one $(n, \ell) = (32, 31)$. By systematically measuring the transition frequencies at various $\Delta \nu_D$-values, we were able to cancel the ac Stark shift. All these studies
showed that by utilizing the two-photon spectroscopy method, the $\text{pHe}^+$ transition frequencies could be measured with an absolute precision of better than a few parts per billion.

In these experiments, antiprotons extracted from the AD were decelerated to energy 80 keV using the radiofrequency quadrupole decelerator (RFQD), and entered into a cryogenic helium gas target filled with helium gas of pressure $P \sim 2 \text{ mb}$ and temperature $T = 5 \text{ K}$. The $\text{pHe}^+$ atoms were irradiated by two counterpropagating laser beams of $\lambda = 296 \text{ nm}$ and 264 nm of energy $P = 5–15 \text{ mJ}$, pulse-length $\Delta t = 30–50 \text{ ns}$, and diameter $d = 20–30 \text{ mm}$. This induced the non-linear two-photon transition $(n, \ell) = (33, 32) \rightarrow (31, 30)$, which resulted in the immediate Auger emission of the electron, followed by antiproton annihilation in the helium nucleus [3]. Charged pions emerging from the annihilation were detected by Cherenkov counters made of UV-transparent Lucite which surrounded the target. This signaled the resonance condition between the two laser beams and the atom.

The laser pulses were generated by two sets of pulsed Ti:Sapphire lasers (Fig. 5) whose optical frequencies were stabilized with a precision of better than 1 part in $10^9$ [11]. Each laser produced 30–60-ns-long laser pulses of energy 80 mJ and wavelength $\lambda = 792–888 \text{ nm}$. These beams were frequency tripled in a series of LBO and BBO crystals to generate the UV laser pulses of $\lambda = 264$ and 296 nm. The frequencies of the Ti:Sapphire lasers were stabilized against an optical frequency comb generator [13,14], itself referenced to a 10-MHz quartz oscillator disciplined by a global positioning satellite (GPS) receiver.

The optical frequency of pulsed Ti:Sapphire lasers were modulated by tens of MHz, due to rapid changes in the refractive index of the Ti:Sapphire crystal. Under normal conditions, this would introduce a large shift of more than 1 part in $10^8$ to the measured $\text{pHe}^+$ frequencies. We developed a system to correct this by placing a pair of electro-optic modulators (EOM’s) made of potassium dideuterium phosphate within the laser resonator. A high voltage waveform was applied to these EOM’s, which were carefully adjusted so as to cancel the chirp in the Ti:sapphire crystal.
In 2008, we carried out an exhaustive series of systematic experiments to determine the precision of these lasers. This included measurements of the $F = 4$ hyperfine component of the $6s_{1/2}-8s_{1/2}$ two-photon transition in atomic Cs. Two counterpropagating laser pulses of wavelength $\lambda = 822$ nm irradiated a 10-cm-long Pyrex cell filled with Cs. Some of the Cs excited to the $8s$ state decayed via the transition chain $8s \rightarrow 7p \rightarrow 6s$. The 456-nm light emerging from this was isolated by an interference filter and detected by a photomultiplier. The measured transition frequency (Fig. 6) was corrected for ac Stark and residual chirp shifts. The result $\nu_{6s-8s}(F = 4) = 364,503,080.3(5)$ MHz was within 100 kHz of the latest values published by other experimental groups [12]. This implies a laser precision which is much better than 1.4 parts in $10^9$.

Fig. 7 shows the resonance profile of the two-photon transition $(n, \ell) = (33,32) \rightarrow (31,30)$ of $^3\text{He}^+$ measured in 2008. The spectral resolution was around $\sim 180$ MHz. The spin-spin interaction between the antiproton and helium nucleus give rise to four hyperfine components (the positions indicated by red lines), the spacings of which are slightly smaller than the spectral resolution. The irregular spacings of these four lines give rise to the slightly asymmetric shape of the measured profile.

Preliminary analysis indicates that the $(33,32) \rightarrow (31,30)$ transition frequency can be determined to a precision of around 3 parts in $10^9$ from the data collected in 2008. The results appear to agree with the latest QED calculations published in Ref. [9] within the experimental and theoretical error bars. This should soon lead to an improved value on the antiproton-to-electron mass ratio compared to our previously published values [3].

None of these two-photon studies have been published. In 2009 we plan finish the data analysis and
1.1.4 Sub-Doppler two-color saturation spectroscopy

We next attempted for the first time a new method called sub-Doppler two-color saturation spectroscopy, on the transition \((n, \ell) = (33, 32)\rightarrow(32, 31)\rightarrow(31, 30)\). Here a laser pulse of energy \(E \sim 1 \text{ mJ}\) and wave-
length $\lambda = 296$ nm first induced the deexcitation of antiprotons from state $(33,32)$ to $(32,31)$; since the spectral linewidth of the laser ($\Gamma \sim 15$ MHz) was much smaller than the width ($\Gamma \sim 1.2$ GHz) of the thermal Doppler distribution of $\bar{p}$He$^+$, only the portion of this distribution which was in resonance with the laser beam was deexcited, whereas the remaining atoms were unaffected. This effectively burnt a hole or "Lamb dip" in the thermal distribution, the linewidth of which was more narrow than the thermal distribution. The Lamb dip was then probed by a second, counterpropagating laser of wavelength $\lambda = 264$ nm, tuned to the resonance $(n, l) = (32,31) \rightarrow (31,30)$. Only when the sum of the two lasers frequencies $\nu_1 + \nu_2$ were exactly tuned to the energy spacing between states $(33,32)$ and $(31,30)$ was there a strong enhancement of the transition $(33,32) \rightarrow (31,30)$ which was Doppler-free. Besides this Doppler-free component, there was a weaker background due to atoms undergoing the two-step process $(33,32) \rightarrow (32,31)$, followed by $(32,31) \rightarrow (31,30)$.

In Fig. 9, the $\bar{p}$He$^+$ resonance spectrum measured in this way is shown, as a function of the detuning frequency of the 296-nm laser. The measured line had a FWHM linewidth of $\sim 600$ MHz, of which $\sim 400$ MHz is caused by Doppler broadening, the remaining caused by the four hyperfine components described above. This linewidth is a factor $\sim 3$ smaller than the Doppler broadening of 1.2 GHz. This method should in principle allow measurements of much narrower ($\sim 150$ MHz) linewidth, but we are here limited by power broadening effects.

### 1.1.5 Doppler-free single-color saturation spectroscopy

This last method involved irradiating the atom with two counter-propagating laser beams of the same wavelength (i.e., $\nu_1 \sim \nu_2$), such that the first beam generated the Lamb dip which was consequently probed by the second laser. The advantage of this technique is that the resulting resonance line should in principle be completely Doppler-free ($\Delta \nu \sim 0$), in contrast to the two-photon technique which is limited by Eq. 2. An additional advantage is that this experiment can be carried out using a single laser resonator, in contrast to the above techniques which require two. The disadvantage lies in the poor signal-to-noise ratio associated with this method.

In 2008, we attempted this method for the first time on the $\bar{p}$He$^+$ transition $(n, l) = (37,35) \rightarrow (38,34)$. A Ti:Sapphire laser was used to generate 60-ns-long laser pulses of wavelength $\lambda = 726$ nm. This beam was split into two beams of equal intensity, which were successively sent into the experimental target in an anti-collinear, counterpropagating geometry. The first laser irradiated the atom $\delta t \sim 140$ ns before the second one.

In Fig. 10, the experimental results are shown, the intensity of the antiproton annihilation signal induced by the first and second lasers plotted by red and black markers, respectively. The signal from the second laser does appear to show the expected dip. This experiment, however, suffered from large fluctuations (up to factor $\sim 3$) of the Ti:sapphire laser; the fluctuations arose from the fact that the amplifying crystals have poor power conversion efficiencies at the wavelength ($\lambda \sim 726$ nm) used here. This must be improved in future experiments.

### 1.2 Spectroscopy of the Hyperfine Structure of Antiprotonic Helium

#### 1.2.1 Introduction

A precise measurement of the antiprotonic helium ($\bar{p}$He$^+$) [1, 2, 16, 17] hyperfine structure (HFS) can be compared with three-body Quantum Electrodynamic (QED) calculations [18, 19] as a test of their predictions. The HFS of the $(n,l) = (37,35)$ state of $\bar{p}$He$^+$ has now been thoroughly measured [20, 21]. Recent results have reduced the statistical error associated with the individual transitions $\nu_{\text{HF}}^\pm$, shown as wavy line in Fig. 11a, to a factor of 50 higher precision than that of the calculations [22]. The difference
Figure 10: Resonance profile measured by single-color saturation spectroscopy on the transition \((37, 35)\rightarrow(38, 34)\) at wavelength 726 nm. The first laser pulse produces the Lamb dip in the thermal distribution, which is then probed by the second beam.

\[
\Delta \nu_{HF} = \nu_{HF}^+ - \nu_{HF}^- \]

has been resolved to a precision comparable to that of theory (36 kHz), a factor of 10 improvement over our first measurement [20].

If they agree, a comparison between the measured transition frequencies and three body QED can be used to determine the antiproton spin magnetic moment. Such a comparison between the proton and antiproton can be used as a test of CPT invariance. The most precise measurement of the proton to antiproton spin magnetic moment ratio to date is 0.3% [23]. Our new measurements of \(\nu_{HF}^\pm\) agree with the theoretical values within the calculation error of \(\sim 10^{-4} = 1.3 \text{ MHz}\) [24]. It should be noted that the experimental errors are \(< 30 \text{ kHz}\). The difference between theory and experiment \(\Delta_{th} - \text{exp}\) is at the \(\sim 300 \text{ kHz}\) level, a factor of three smaller than the estimated theoretical error. There is also good agreement between experiment and theory for \(\Delta \nu_{HF}\), from which the antiproton magnetic moment can potentially be determined to 0.1% [22].

Early this year, a publication was printed in Journal of Physics B [21], along with a proceedings paper from the Pbar08 conference [25], outlining our achievements in 2006 and 2007. A proceedings paper from the LEAP08 conference has been submitted [22] and a further publication is planned, reporting on our 2008 results. The theoreticians are also carrying out higher order calculations for a more thorough comparison.

1.2.2 Hyperfine Structure

The HFS of \(\bar{p}\)He\(^+\) arises from the interaction of the magnetic moments of its constituents and has been calculated by Korobov and Bakalov to \(\alpha^4\) order [18, 19]. They constructed an effective Hamiltonian for \(\bar{p}\)He\(^+\)

\[
H_{\text{eff}} = E_1(\vec{L} \cdot \vec{S}_e) + E_2(\vec{L} \cdot \vec{S}_\bar{p}) + E_3(\vec{S}_e \cdot \vec{S}_\bar{p})
+ E_4\{2(L(L+1))(\vec{S}_e \cdot \vec{S}_\bar{p}) - 6[(\vec{L} \cdot \vec{S}_e)(\vec{L} \cdot \vec{S}_\bar{p})]\}. \tag{3}
\]

Due to the large orbital angular moment of the antiproton \((\vec{L} \sim 35)\), the dominant splitting arises from the interaction of \(\sim \vec{L}\) with the electron spin \(\vec{S}_e\). The antiproton spin \(\vec{S}_\bar{p}\) and the spin \(\vec{S}_h\) of the ‘helion’ \(h\),

\[\text{Cold Antimatter Plasmas and Application to Fundamental Physics, Okinawa, Japan}\]
\[\text{Low Energy Antiproton Physics, Vienna, Austria}\]
the $^3$He nucleus, lead to further splittings leading to a quadruplet for $\overline{p}^3\text{He}^+$ and an octet for $\overline{p}^3\text{He}^+$. The effective Hamiltonian for $\overline{p}^3\text{He}^+$ is more complicated and contains nine terms [26].

In Fig. 11 the allowed M1 transitions that can be induced by an oscillating magnetic field are shown. In the case of $p^4\text{He}^+$, there are two types of transitions: HF transitions ($\nu_{HF}^+$ and $\nu_{HF}^-$) which are associated with a spin-flip of the electron, and superhyperfine (SHF) transitions ($\nu_{SHF}^-$ and $\nu_{SHF}^+$) which are associated with a spin flip of the antiproton.

In the case of $p^3\text{He}^+$, there is an additional set of transitions. The HF transitions are still associated with the spin flip of the electron ($\nu_{HF}^+$, $\nu_{HF}^-$, $\nu_{HF}^{++}$ and $\nu_{HF}^{−−}$). Although the helion magnetic moment is smaller than that of the antiproton, its overlap with the electron cloud (which is in the ground state and has its maximum probability at the helion site) is stronger. Therefore the helion spin contributes to the quadruplet superhyperfine splitting ($\nu_{SHF}^−$, $\nu_{SHF}^−$, $\nu_{SHF}^+$ and $\nu_{SHF}^{++}$) and super-superhyperfine (SSHF) transitions are caused by the spin flip of the antiproton ($\nu_{SSHF}^−$, $\nu_{SSHF}^−$, $\nu_{SSHF}^+$ and $\nu_{SSHF}^{++}$) [1].

The hierarchy of angular moments and the angular momentum coupling schemes are shown in Tables 2 and 3 (numerical values from CODATA2002; $\mu_P = -2.800(8)\mu_N$ (PDG)):
Table 2: Hierarchy of angular momenta, where $\mu_B = e\hbar / 2m_e$ is the Bohr magneton, $\mu_N = e\hbar / 2m_p$ is the nuclear magneton and $g$ is the gyromagnetic ratio.

<table>
<thead>
<tr>
<th>Term</th>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_e$</td>
<td>$g_e \mu_B S_e$</td>
<td>$-1.001 159 652 1859(38) \mu_B$</td>
</tr>
<tr>
<td>$\mu_\tau$</td>
<td>$g_\tau \mu_N L_\tau$</td>
<td>$\sim 1.906 159 \times 10^{-2} \mu_B$</td>
</tr>
<tr>
<td>$\mu_p$</td>
<td>$g_p \mu_N S_p = 2.792 384 751(28)$ $\mu_N(p) = 1.521 032 206(15) \times 10^{-3} \mu_B$</td>
<td></td>
</tr>
<tr>
<td>$\mu_h$</td>
<td>$g_h \mu_N S_h = -2.127 497 723(25)$ $\mu_N(p) = -1.158 671 474(14) \times 10^{-3} \mu_B$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Angular momentum couplings where HFS is the hyperfine structure, SHFS is the super hyperfine structure and SSHFS is the super super hyperfine structure.

<table>
<thead>
<tr>
<th>Term</th>
<th>Expression</th>
<th>$\text{He}^+$</th>
<th>$\text{He}^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFS</td>
<td>$F = L_\tau + S_e$</td>
<td>$F = L_\tau + S_e$</td>
<td></td>
</tr>
<tr>
<td>SHFS</td>
<td>$J = F + S_\tau = L_\tau + S_e + S_\tau$</td>
<td>$J = F + S_\tau = L_\tau + S_e + S_\tau$</td>
<td></td>
</tr>
<tr>
<td>SSHFS</td>
<td>$G = F + S_h = L_\tau + S_e + S_h$</td>
<td>$J = G + S_\tau = L_\tau + S_e + S_h$</td>
<td></td>
</tr>
</tbody>
</table>

1.2.3 2008 Results

In 2007 we measured $\Delta \nu_{HF}$ to a precision of 60 kHz at a pressure $p = 250$ mbar [21]. Our aim in 2008 was to reduce this error to the precision of theory (33 kHz) by performing a high statistic density dependence study. We measured microwave frequency profiles at $p = 150$ mbar and $p = 500$ mbar at a microwave power $P = 5$ W. We measured additional profiles at $p = 150$ mbar, at $P = 3$ W and 15 W to examine power effects. Figure 12 shows the averaged data for the highest statistics measurements.

Our preliminary results are shown in Fig. 13. At the measured precision there is no evidence of a density or power dependent shift [27]. Therefore it is possible to take the average of all the results, achieving a precision of 36 kHz, a factor of 10 improvement over our first measurement [20]. Other systematic effects that influence the measurement include shot-to-shot microwave power fluctuations and variances in the laser position and fluence from day to day. However these effects have been determined to be far smaller than the shot-to-shot fluctuations of the antiproton beam. This is reduced by normalising over the first peak (proportional to the number of antiprotons captured, see Section 1.2.1) but the error bars have also been increased by the squareroot of the reduced $\chi^2$ to account for this.

Further analysis, concerning the microwave power frequency dependence, has yet to be completed but a publication is planned for the beginning of next year. Table 4 shows the current results in comparison to our two previous publications and the most precise theory.

Table 4: Averaged data with most results at the top compared with the most precise theory, where $\nu_{HF}^+$ are the HF transition frequencies and $\Delta \nu_{HF}$ is the difference between $\nu_{HF}^+ - \nu_{HF}^-$. 

<table>
<thead>
<tr>
<th>Term</th>
<th>$\nu_{HF}^+$ (GHz)</th>
<th>$\nu_{HF}^-$ (GHz)</th>
<th>$\Delta \nu_{HF}$ (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt. 08</td>
<td>12.896 668(28)</td>
<td>12.924 494(23)</td>
<td>27.810(36)</td>
</tr>
<tr>
<td>Theory [19]</td>
<td>12.896 3(13)</td>
<td>12.924 2(13)</td>
<td>27.896(33)</td>
</tr>
</tbody>
</table>
Figure 13: (a) and (c) The difference between the most precise theory [19] and the measured transition frequencies as a function of pressure $p$. Measured with $T = 350$ns. (b) and (d) The difference between the most precise theory and the measured transition frequencies as a function of the square root of microwave power. Measured at $p = 150$ mbar. (a) and (b) show the difference between the individual points and theory = $0$ MHz. The experimental value of $\nu_{HF}^+$ is shown as ▼ and $\nu_{HF}^-$ as ▼. The theoretical error is $1.3$ MHz and therefore off the scale. The gradient of the theoretical line in (a) represents the predicted density shift [27]. (c) and (d) show the difference between $\Delta \nu_{HF}$ and theory = $0$ MHz. The experimental value is shown as ▣. The points shown at $x = 0$ and represented by ● on all four graphs represent the averaged data.
2 Antiproton-nuclei cross sections measurements at 5 MeV

The main difficulty in performing a measurement of antiproton $\sigma_{\text{ann}}$ at AD comes from the pulsed characteristic of the antiproton beam since even a small fraction of annihilations can saturate the acquisition system.

To overcome the problem the solution chosen by ASACUSA requires both accurate settings of the AD beam and a particular design of the experimental set-up.

Concerning the AD beam optimization, the so called "multiple extraction" option was used: the 100 MeV/c beam was divided into 6 bunches with lower intensity which were kicked out individually separated by 2.4 s.

In addition, for each bunch the time gate of the AD septum was reduced to remove the long tails (various hundreds of nanoseconds) of very low intensity (some thousands of antiprotons) that blinded our detector before the arrival of the signal. The final actual length of each bunch resulted to be 40-50 ns, as required. Moreover the radial halo of the beam was reduced to few mm, by moving the AD scrapers position, avoiding any annihilation on the lateral wall of the target vessel when the target was removed (see after).

The experimental set-up was designed with a particular care to avoid contaminations from the $\bar{p}$ annihilations not occurring on the target. A sketch of the experimental set-up is plotted in Fig. 14. It is quasi-axial symmetrical around the $\bar{p}$ beam and consists of a vessel containing a thin solid target surrounded by a vertex detector.

The vessel was directly connected with the AD beam line without any material along the $\bar{p}$ beam before the target. To reduce the Rutherford scattering background the radius of the target vessel was increased after the target in 2008. The target vessel was long enough to reduce contaminations from the beam annihilations on the end wall where a beam counter was placed to monitor the $\bar{p}$ beam intensity.

The selection of the annihilation events on the target was performed by means of a vertex detector that was able to reconstruct the tracks of the charged pions emitted in the $\bar{p}$ annihilation. Since the tracks coming from different annihilations can be disentangled only if few annihilations occur per bunch, the thickness of the target was very thin.

The targets were metallic disks (5 cm in diameter) sputtered on Mylar foils (12 cm in diameter and 0.9 micrometers in thickness). We used nickel, tin, platinum targets with suitable thickness (hundreds of nanometers) in order to have annihilation events numbers comparable with the ones from Mylar assuming an $A^{2/3}$ law for $\sigma_{\text{ann}}$. The Mylar in turn constitutes a target with $A$ similar to the carbon one.

In 2008 one target at a time was positioned along the $\bar{p}$ beam near the end of the smaller part (inner...
radius \( R = 7.5 \text{ cm} \) of the target vessel. The swap of target was done very quickly without opening the target vessel by means of a rotary-linear multi-motion system which moved the selected target on the \( \bar{p} \) beam from the parking inside the larger part (inner radius \( R = 30 \text{ cm} \)) of the target vessel (see Fig. 15).

We present here the preliminary analysis of a part of the data acquired in one week (8 hours per day) in July 2008 by means of the described apparatus. In 2006 and 2007 comparable acquisition times were used to understand and to improve the AD settings and to modify the experimental set-up to increase the background rejection.

In Fig. 16 we show typical time distributions of the measured hits in one layer of the detector for one spill with different targets. The signals from the \( \bar{p} \) annihilations in the targets are expected in the interval \( \Delta t \) between 760 and 830 ns.

This clearly appears if we compare in Fig. 16 the presence of few hits with Ni, Sn and Pt targets with the absence of any hit when no target is placed on the \( \bar{p} \) beam (the so called ”empty target”). It is confirmed further by the lot of hits in \( \Delta t \) when a dummy tick target is inserted.

After the aforementioned interval \( \Delta t \) a flux of pions coming from the end wall of the target vessel fires the whole detector.

The absence of events before 830 ns with the empty target also indicates that the radial halo of \( \bar{p} \) beam is well confined and that the annihilations from the end wall of the target vessel are well-separated in time from the annihilations in the target.

In Fig. 17 the z-coordinate of the vertices reconstructed in the \( \Delta t \) interval with the radius less than 2 cm are plotted for the different targets.

For each target the number of the reconstructed vertices has been counted and the contribution of the Mylar support has been subtracted by using the data acquired with a reference target made only by a Mylar foil. The antiproton annihilation cross sections can be determined by means of the following formula:

\[
\sigma_{\text{ann}} = \frac{N_{\text{ev}}}{N_e \cdot N_T \cdot \rho \cdot \frac{N_A}{A} \cdot l \cdot \varepsilon_{\text{ev}}} \tag{4}
\]
where $N_{ev}$ is the number of vertices reconstructed in the target, $N_p$ is the incident $\bar{p}$s on the target, $N_c$ is the number of scattering centers of the target molecule ($N_c=1$, apart for Mylar), $\rho$ is the target density, $N_A$ is the Avogadro’s number, $M$ is the molecular weight of the target, $l$ is the target thickness, $\varepsilon_{ev}$ is the vertex detection efficiency.

In the Mylar case the number of annihilations is determined by the weights of the H, C and O elements in the annihilation dynamics: the estimation of the average $\sigma_{ann}$ value has been related to the average mass number of Mylar. Due to the relatively large statistical error of the measured events number this assumption does not affect strongly the estimation of the annihilation cross section with A.

The function $\sigma_0 \ A^\alpha$ has been fitted to the $\sigma_{ann}$ data. In Fig. 18a the data and the best fit function are plotted. The resulting free parameters $\alpha = 0.51 \pm 0.24$ indicate that within uncertainties the $A^{2/3}$ dependence of the $\bar{p}$ annihilation cross section is compatible with the data. The statistical errors shown in Fig. 18a will be reduced in the final analysis by using all the available data. A further reduction can be done by adding the events with only one track. For the determination of a vertex at least 2 reconstructed tracks are needed. This represent a limit in the counting of the annihilation events since in the present measurement the target is axially near the edge of the detector where the efficiency in the vertex reconstruction is reduced. In Fig. 18b we present the data where the events with single track crossing the target are added to the reconstructed vertex events used in Fig. 18a. The behavior of the $\sigma_{ann}$ values is still in agreement with the $A^{2/3}$ law since the $\alpha$ free parameters result to be $0.61 \pm 0.09$.

In conclusion for the first time the relative $\bar{p}$ annihilation cross sections on not-light nuclei (Mylar, Ni, Sn, Pt) have been measured at low energy (5 MeV) by the ASACUSA Collaboration. This represents also the first measurements of antinucleon annihilation cross section at low energy performed at a pulsed beam.

Preliminary results indicate that $\sigma_{ann}(\bar{p} - A) \propto A^{2/3}$ is compatible with the data. This suggests that the saturation effect seen with light nuclei at lower energies (below 60 MeV/c) is not present for the measured target at 100 MeV/c. Data analysis is still in progress to confirm this preliminary result.

**Figure 18:** Antiproton $\sigma_{ann}$ data with the best fit function: in (a) with only the reconstructed vertices, in (b) also with the events with single track crossing the target (see text for the explanation).
3 Progress towards $\bar{H}$ ground-state hyperfine spectroscopy

3.1 MUSASHI operation status

The MUSASHI sub-group in ASACUSA collaboration operated ultraslow monoenergetic antiproton ($\bar{p}$) beam source (MUSASHI). The aim of MUSASHI is to provide ultraslow $\bar{p}$ beam with combination of the AD and the RFQD. Millions of $\bar{p}$ are confined in the trap of MUSASHI, and then cooled via collisions with preloaded $e^-$ [29]. Such prepared ultraslow $\bar{p}$ were transported as 250 eV DC like beam to a supersonic gas jet chamber for antiprotonic atom ($\bar{p}$A) collision experiments and as 150 eV pulse beam to a Cusp trap for antihydrogen ($\bar{H}$) experiment. This beam is also applicable for other atomic collision experiments such as AIA ionization experiment which will be resumed in 2009.

Unfortunately, there were several reasons for decreasing trapping number of MUSASHI during our 2008 run. One reason is the weaker beam intensity from the AD ($2.5 \times 10^7$) than the last year ($3.5 \times 10^7$ in the 2007). The second is that the AD beam optics and its steering did not match to the ASACUSA-RFQD line well. The AD operators took their efforts to improve it, however the trapping efficiency had not been improved so much because of the limitation of our usable beam time. The third one is our side problem, which is a creeping discharge problem on an electrode applying a high voltage (-13 kV) to capture decelerated $\bar{p}$ beams. Due to this discharge problem, only -7 to -10 kV was applied, and around 30–50% $\bar{p}$ was lost against -13 kV condition which was suitable for better trapping efficiency. This will be fixed with newly designed insulator during this winter shutdown period. Though the total trapped number of antiprotons in the MUSASHI resulted in only 50–80% of 2007 run and extracted number was also smaller, MUSASHI has been operated continuously to produce ultraslow $\bar{p}$ beams at 150–250 eV by routinely compressed trapped $\bar{p}$ clouds with rotating wall technique developed for last years [30].

In 2008 we performed two kinds of measurements, which energy spread estimation of further decelerated $\bar{p}$ beams for $\bar{p}$A experiments and plasma mode frequency measurements for non-destructive diagnosis of $\bar{p}$ cooling in the MUSASHI trap.

The energy width of extracted ultraslow $\bar{p}$ beam was roughly estimated by reflection of the beams. The preliminary analysis says an further decelerated 26.5 eV beam has about $\pm 1.5$ eV energy spread. It is noted that the beam energy spread became wider in apparent since the beam diverged at the reflection point far from the target point. Therefore the actual beam energy width is expected to be smaller than the above value as was expected.

The measurement of frequency shifts of $e^-$ plasma’s electrostatic oscillations was performed parasitically during the main run. We excited axially symmetric electrostatic oscillation of $(l,0)$ modes by applying a pulse train of a 5 $\mu$s with repetition rate of 1 Hz to one of the trap electrode. The frequency of excited mode was analyzed using FFT after the excitation pulse had over. This non-destructive measurements did not interrupt the main run.

The temperature variation by $\bar{p}$ beam injection to preloaded $e^-$ plasma causes the frequency shift of higher order ($l \geq 2$) modes [29]. The variation of the plasma frequencies during the cooling that followed heat transfer from the $\bar{p}s$ were consistently reproduced by solving rate equations [31] took into account the cyclotron (synchrotron) radiation cooling of $e^-$ with a measured time constant $\sim 9/B$ for MUSASHI trap and the energy transfer between $\bar{p}$ and $e^-$ plasma. From the temperature variation of $e^-$ plasma we can know non-destructively when $\bar{p}$ and $e^-$ were settled in a thermal equilibrium state.

On the other hand, the new result is the first systematic observation of the $(1,0)$ mode frequency shift. It is known that the $(1,0)$ mode corresponds to the center-of-mass motion of plasma and should have no dependence of plasma temperature and shape. This shift shows $\bar{p}$ cooling process in another way. As shown in Fig. 19, $\bar{p}$ beam just captured was held in “A” region between two catching walls, then $\bar{p}s$ lost their energy via collisions with $e^-$ only when $\bar{p}s$ passed through $e^-$ plasma. During this cooling process, $\bar{p}s$ have been fallen into the bottom of the harmonic potential well (HPW) one by one, where $e^-$ plasma was confined.
Thus stored $\bar{p}s$ formed a cloud. Since $\bar{p}$ is much heavier, the harmonic oscillation of $\bar{p}$ in the HPW shall be neglected, that is to say, $\bar{p}$ cloud was at rest for $e^-$. The cloud would distort the effective trapping potential, that is, the depth of harmonic potential well for $e^-$ effectively became shallow and then the (1,0) mode frequency red-shifted. Since this shift depend on the number of confined $\bar{p}$ as can be expected, we can roughly know the number of $\bar{p}$ trapped in HPW against the time. Since the ratio of $\bar{p}$ number against $e^-$ was almost two orders of magnitude greater than the other AD experiments, we were succeeded in observing an effect of presence of $\bar{p}s$ in $e^-$ plasma.

These observations of non-neutral $e^-$ plasma waves revealed the cooling process of $\bar{p}$ from two points of view. One is that higher order modes’ shift reflect on the $e^-$ plasma temperature variation, which indicates when they are in thermal equilibrium. The other is that (1,0) mode shift corresponds to the number of trapped antiproton in HPW via cooling process in real time.

### 3.1.1 Beam profile of the extracted $\bar{p}$ beam

Measurement of the profile of the extracted antiproton beam is essential for beam tuning as well as for diagnosis of the beam size and the emittance. The cross section image of the beam was measured at various distances $d$ from the end of the transport beam line, with a step of 5 mm for $10 \leq d \leq 60$ mm. Here, $d = 25$ mm corresponds to the position of the gas-jet target while $d = 60$ mm corresponds to the position of the downstream-MCP in the collision experiment. A translationally movable MCP was installed in a small chamber for this measurement. Figure 20 shows the profile of the beam at 250 eV and 27.5 eV, corresponding to a typical energy for ionization and atomic capture, respectively. Here, we demonstrated that the 250 eV beam was transported as a parallel beam while the 27.5 eV beam was strongly focused at the collision point, as was intended and predicted in our beam tracking simulation.

### 3.2 Cusp trap commissioning in 2008

We have accomplished the following in 2008:

- transport cooled antiprotons from the multi-ring trap of the antiproton trap (pbar-MRT) to the multi-ring trap of the cusp trap (cusp-MRT) with high efficiency, then trap and cool antiprotons both in the upstream and downstream spindle cusp regions
- construct an efficient positron accumulator
- trap and cool antiprotons and positrons simultaneously
- install and tune the 3D detector to monitor radial as well as axial annihilation positions of antiprotons in the cusp-MRT, which is essential to study antihydrogen production processes
The lifetime of cooled antiprotons in the spindle cusp region was still 100 s or so. After various trials to improve the lifetime, we eventually found a small low temperature vacuum leak in the bore tube, which is going to be repaired during the winter shutdown.

The AD beamtime spent for these cusp trap commissioning in 2008 was 16.5 8hrs AD shifts (including 3 shifts loss by our own problems and also small breaks and unstable beam period due to AD or PS problems), which was less than half the initially allocated 36 shifts at the beginning of 2008. What made things even worse was the fact that this large reduction of the beamtime was announced just several shifts before the end of our beamtime which resulted because of the SC magnet problem of LHC, i.e., no time was left to fit/correct the measurement schedule to the reduced beamtime. It is also noted that the number of pbars trapped was roughly a half of that in 2007 at least during the MUSASHI beamtime because the number of antiprotons delivered from the AD was roughly half.

Actually, our original plan was to use totally 42 8hrs shifts (6 weeks), which consisted of (1) 0.5 weeks for the tuning of the setup for transfer, trap, and cool antiprotons, (2) 2 weeks for alignment, compression, and cooling of antiprotons, (3) 0.5weeks for positron transfer, cooling, and compression, (4) 1.5 weeks for mixing of antiprotons and positrons, and (5) 1.5 weeks for antihydrogen detection (and antihydrogen cooling). Using the 16.5 shifts spent this year, we were quite successful in accomplishing item (1), a part of items (2) and (3). Items (4) and (5) were fully left for the coming beam time in 2009.

3.2.1 Transport of pulsed antiproton beam to the cusp trap and catching

The cusp trap for \( \bar{\text{H}} \) synthesis and its spectroscopy was installed at the AD in 2007. The cusp trap was designed to stably confine charged particles of both polarity and at the same time to trap neutral particles, which can be realized by combining a magnetic quadrupole (anti-Helmholz) and an electric multipole field.
Figure 21 shows a drawing of the main part of the setup in 2008 for the antihydrogen experiments. It consists of three superconducting (SC) magnets, one at the center provides a cusp magnetic field for antihydrogen trapping, and the left and the right magnets provide uniform solenoidal field to trap and cool antiprotons and positrons, respectively. Antiprotons of 60keV from the RFQD are transported from the left side, and are trapped and cooled by the antiproton trap. After cooling and compression [29] [30], antiprotons are accelerated to $\sim 150$eV and transported to the cusp trap with the help of magnetic coils ($B \sim 200$ G). Similarly positrons of $\sim 43$eV are transported from the positron trap (See Sect.3.2.4) to the cusp trap. Figure 22 is a photo of these three SC magnets with the new 3D detector (See Sect. 3.3) on both sides of the cusp magnet.

The temperature of the bore tube of the cusp magnet reached 4.0K [46]. Further, the thermal contact of the cusp-MRT to the bore tube was improved increasing contact surface area, and the temperature of the cusp-MRT in 2008 was 13K (it was 30K in 2007), comparable to that of the antiproton-MRT.

The annihilation position of the trapped $\bar{p} s$ was determined by the track detector consisting of two 2-m long scintillator bars as well as the 3D detectors (see Sect. 3.3). It is noted that the number of antiprotons accumulated in the cusp trap was 2 orders of magnitude larger than that usually used in other $\bar{H}$ experiments.

![Antiproton Trap, CuspTrap, Positron Trap](image)

**Figure 21**: A drawing of the MUSASHI antihydrogen setup with three superconducting magnets: From left to right, the antiproton trap, the cusp trap, and the positron trap.

Figure 23 shows the axial magnetic field along the axis of the three magnets together with a schematic drawing of the setup. The electric potential configuration in the case of the antiproton transport and the positron transport to the cusp trap is also shown at the bottom. An enlarged drawing of the multi-ring trap used for the cusp trap (cusp-MRT) is shown in the upper part of fig. 23. This year, antiprotons were trapped either around the electrodes U5 and U6 (upstream spindle region) or around the electrodes D4 and D5 (downstream spindle region). Antiprotons cooled in the multi-ring trap of the antiproton trap (pbar-MRT) were extracted as a pulsed beam by applying an 1 $\mu$s kick-off pulse to the pbar-MRT. The transport efficiency was improved this year and close to 90% in the best case.

### 3.2.2 Cooling antiprotons with electrons in the Cusp trap

The energy distribution of antiprotons trapped in the cusp-MRT was measured by shallowing the trap potential. The trapped $\bar{p} s$ were cooled via collisions with preloaded $e^-$s. The blue line in fig. 24 shows the energy spectrum of antiprotons trapped in the upstream spindle region for 10 s with $\sim 10^8$ cooling electrons (the extraction time was also 10 s). It is seen that the antiprotons were almost fully cooled. As a reference, the energy spectrum of antiprotons kept for 10s but without cooling electrons in the cusp-MRT is shown by the red line in fig. 24. It is seen that no cooling takes place in this case.
Figure 22: A photo of the MUSASHI setup, the positron trap, the cusp trap, and the antiproton trap from left to right. Four rectangular frames on both sides of the cusp trap are the frames supporting the 3D track detectors to monitor annihilation positions of antiprotons and antihydrogen atoms.

Figure 23: The magnetic field and the electric potential distributions along the system axis. Both spindle trap regions could be used to trap charged particles. The upper drawing shows the cusp trap electrodes. The center electrode “CENT” of the cusp-MRT was placed at B=0 of the cusp magnetic field.
To further study the cooling feature of antiprotons in the cusp trap (little has been studied yet), the energy spectra were measured for various cooling time. Figures 25(a), (b) and (c) show energy spectra for the cooling time of 5, 10 and 20 s, respectively. It is seen that (1) the energy spectra consisted of two peaks, one at $\sim 0$ eV and the other at $\sim 30$ eV when the cooling time was short, and (2) the higher energy peak disappeared with a time constant of 10s or so keeping the peak energy roughly the same. To study how this double structure resulted, the annihilation position distribution of antiprotons along the axis was observed continuously by shallowing the upstream trapping potential as shown in fig. 26(a). The continuous "belt" at around 1070 cm corresponds to annihilations of antiprotons trapped in the upstream spindle cusp region. At around 140 s, annihilation took place at 70-170 cm upstream from the trapping position. The corresponding trapping potential was $\sim 30$ eV, i.e., the higher energy components observed in figs. 25(a) and (b) travelled more than 1 m from the trapping position before annihilation. In other words, antiprotons of this group located very close to the axis when they were released from the cusp-MRT. As the trapping potential was further reduced, more intense annihilations started at around 145 s at $\sim 1$ m upstream of the trapping position, which lasted till 147 s with the annihilation position continuously moving closer to the trapping position, i.e., antiprotons located at larger radial position in the cusp-MRT were released later as is expected. As a reference, fig. 26(b) shows the result of a similar experiment but without cooling electrons in the spindle cusp.
3.2.3 Trapping antiprotons at various positions of the Cusp trap

It was a challenge to transport antiprotons across the B=0 region at the center of the cusp magnetic field and to stably trap in the downstream side of the spindle region. The dotted green line of the upper part of fig. 27 shows the result of such a study for 150eV pulsed antiprotons injected directly from the antiproton-MRT. The potential distribution used is again shown by the green curve of the lower part of fig. 27. The annihilation position distribution is shown by the green line of the upper part of fig. 27. As a reference, the annihilation distribution trapped in the upstream spindle cusp is shown by the dotted blue line of the the upper part of fig. 27 together with the corresponding potential distribution in the lower part. Although the position resolution of the track detector was not excellent, it is clearly seen that the trapping position moved according to the trap potential distribution. What is more, as is seen in fig. 27, the total number of antiprotons trapped in the downstream spindle region was as large as 70% of that in the upstream spindle region, i.e., the loss of antiprotons crossing the B=0 region was not very serious in the present condition. The same annihilation distributions from the upstream and downstream trapping were also monitored by the 3D detector, which are given by the solid green and blue lines in the upper part of fig. 27. It is seen that the resolution is better by a factor of 3.5-4 than the track detector.

3.2.4 Development of compact positron accumulator for cusp trap

The last essential piece for achieving $\bar{H}$ synthesis and their trapping with the cusp trap is a positron accumulator. We rapidly developed the compact positron accumulator, compatible to our cusp trap, based on the $N_2$ buffer-gas cooling scheme, established and reliable way [48].

All-in-one positron accumulation system is realized for the first time. Fig. 28 shows schematic drawing of the positron accumulator, which from left to right consists of the $^{22}$Na positrons source surrounded by a tungsten (heavy alloy) shield, the movable shield, the transmission moderator, the $N_2$ gas cell, the differential pumping aperture, the positron trap, and the movable reflection moderator.

A 50-mCi $^{22}$Na radioactive source ($Na_2CO_3$, $\phi=3.7$mm, $\tau_{1/2}=2.6$ yr) in a tungsten shield was directly
Figure 27: Upper part: Annihilation position distributions of antiprotons trapped in the upstream spindle cusp (blue lines) and the downstream spindle cusp (green lines). The dotted and the solid lines were obtained by the track detector and the 3D detector, respectively. Lower part: The corresponding electrostatic potential distributions.

Figure 28: Schematic view of the compact positron accumulator. It consists of a 50 mCi $^{22}$Na positron source, two moderators for making slow positrons, $N_2$ gas-buffer cell and multi-ring electrode trap for positrons. The whole system is placed in the strong magnetic field (2.5 T) of the superconducting solenoid.

placed in a superconducting solenoid. The positrons emitted from the source are automatically guided along the strong magnetic field (2.5 T) and introduced into the $N_2$-buffer cell passing through a transmission moderator. We used an annealed polycrystalline tungsten film moderator (4 $\mu$m in thickness) for reasons of availability. The inner pressure of the $N_2$ buffer cell is maintained to $10^{-3}$ torr while the trapping region is around $10^{-6}$ torr. An efficient differential pumping with the cylindrical aperture ($\phi=6$ mm, 100 mm in length, $\sim0.3$ l/s of conductance) is accomplished. The emitted slow positrons moderated in the tungsten moderator lose their energy via inelastic collisions with $N_2$ molecules and eventually trapped. The trapped positrons further collide with $N_2$ molecules in the multi-ring electrode trap for positrons (positron-MRT). The positron-MRT consists of 22 ring electrodes (gold-coated aluminum rings). Two of them are segmented into four for applying rotating electric fields. For the reasons of precision machining and heat resistance
(≤240°C), we adopted PEEK (poly-ether-ether-ketone) rings for the electrical insulation between the electrodes. One of the outstanding features of this positron-MRT is the excellent cylindricity, which is essential for stable trapping and manipulation of positrons. The cylindricity of 15 µm was achieved by utilizing several advanced processing techniques, wire-electrical discharge machining and horning.

Within the limited development time before the 2008 run, we successfully accumulated positrons of the order of 10^5 in 10 s with this accumulation system. The current accumulation rate is 1.2×10^4/s. Assuming a typical efficiency of the polycrystalline tungsten moderator (ε ∼ 10^{-4} [49]), an estimated trapping efficiency (ratio of the number of positrons entering in the trap to the accumulated ones) of this compact system is 17%, which is comparable with that for typical “large” accumulators in other experimental groups with N\textsubscript{2} gas-buffer scheme [48].

We also succeeded to transport positrons to the cusp trap. The accumulated positrons in the MRT were transported as a pulsed beam via three guiding coils. Most positrons were successfully caught in the cusp-MRT under ultra-high vacuum and inhomogeneous cusp magnetic field (1.5 T). We could confine them during ∼200 s even without compression.

Fine adjustment and optimizations of the positron accumulator is under development. The moderator, especially, leave much to be improved. We are continuing development works for improving the accumulation number and the manipulation techniques in the cusp trap towards the 2009 run.

### 3.2.5 Simultaneous trapping of antiprotons and positrons

We have succeeded to simultaneously trap antiprotons and positrons in the upper and lower spindle region of the cusp-MRT, respectively, i.e., we are ready to start the mixing experiment. Unfortunately, this was not realized this year due to the problem of LHC, and the expected extention of the beam time was cancelled in the last moment of our beamtime.

### 3.3 3D detector for the cusp trap

#### 3.3.1 The detector

The vertex detector consists of four different modules of scintillator rods aimed at detecting charged pions produced by \( \bar{p} \) annihilations. Two modules are placed on each side of the cusp trap, with respect to the antiproton beam from Musashi (see Fig.29; see also in Fig.22 a picture of the whole system, after the detector installation).

Each module is assembled by joining two layers of 64 rods of plastic scintillators (Polystyrene Dow Styron 663 W + 1% PPO + 0.03% POPOP, white capstocking TiO\textsubscript{2}) each 15 x 19 x 960 mm with a central hole of diameter 2 mm, Fig.30. The rods of the two layers are crossed by 90° to measure the coordinate of the pion intersection point along two perpendicular directions. A WLKS K uraray Y-11 green fiber 1 mm in diameter is plunged into each hole. The gap in each hole is filled with optical glue, which enables a particle detection efficiency > 90% on the full extent of the rod. In principle, each fiber could be read at both terminations, but actually in the 2008 setup this was done only for the horizontal fibers of the external modules. The signal coming form a fiber was read through a mechanical-optical connection with Hamamatsu 64-channel photomultipliers (PMT), whose slots where only partially filled (every second slot was connected to the fiber) to avoid cross-talk problems experienced in previous experiments (\( \bar{p} \)-nucleus annihilation cross-section measurement) with the same equipment.

Each module was self-triggered, as described in the next subsection.
3.3.2 Readout electronics

The readout electronics of the detector is a VME based system. It is organized in front end boards (one per two PMTs) and the so-called “repeater” boards that will be roughly described below.

The frontend boards (FEB) allow to obtain both an analog and digital information of every rod, the digital signal given by the time the signal from a PMT channel attached to a rod is above threshold and the analog one given by the amount of charge released from the same PMT channel. The system, during the 2008 acquisition period, has been operated in analog mode and in self triggering mode, with the trigger generated directly by the readout ASICs.

The frontend chain is based on the VA64TAP2.1 + LS64_2 ASICs (Gamma Medica - Ideas - Norway); the former is a 64 channel ASIC for the analog PMT signal handling (preamplification, shaping and discrimination), while the latter provides the level shifting of the VA64TAP2.1 output.

The readout electronics is composed of two blocks: the repeater boards, which are the interface between the FEBs and the DAQ, and the DAQ itself.
The FEBs are controlled by a repeater board to interface the frontend with the I/O VME readout system, each repeater acting as bias and voltage supplier, multiplexer for the ASICs and FPGAs control signals, demultiplexer for the analog and digital signals back from the frontend boards. The multiplexed signals are sent to Caen V550 ADCs (10 bits) that provide the digitization of the signals; they can also be operated in “zero suppression” mode but during the 2008 beam time this feature was not exploited because of the high noise conditions.

An ALTERA Cyclone II FPGA based VME programmable trigger board was used to operate with different triggers. In the final configuration the 4 modules have been operated with a “strong” AND due to the noisy conditions of the environment: in order to have a valid trigger, at least three modules out of four had to deliver a signal from at least one horizontal and one vertical rod above threshold.

After acquiring the data for each annihilation event, a deadtime of ~ 1.5 ms is expected, leading to a maximum acquisition rate of about 600 Hz.

### 3.3.3 Monte Carlo simulation

Simulations of the apparatus based on Geant 3 have been used to design the detector geometry and to test and subsequently improve the reconstruction program, which is based on a combinatorial algorithm similar to the one already used for the tracking detector in the $p$-nucleus annihilation cross-section measurement. This has proved to be effective in a wide central cusp trap region, where most of the annihilations are expected.

Here, two examples of reconstructed vertices distribution are reported (see Fig.31 and Fig.32). The two cases concerned are the most interesting for the foreseen experimentation: annihilations generated at the center of the trap ($x = y = z = 0$) and on the trap wall surface ($r = 4$ cm). In Fig.31 we report the distributions along the 3 directions ($z$ is along the trap axis, $y$ is the vertical direction, and $x$ is in consequence). In Fig.32, the associated $x-y$ scatter plot is shown.

The spatial resolution of the reconstructed vertices is mainly limited by the multiple scattering inside the material (especially in the cusp trap apparatus, rather than in the modules themselves) and by the strong, highly non-uniform, magnetic field of the cusp trap.

### 3.3.4 Experimental results

The detector was installed September 23 (see the picture in Fig.22; notice the asymmetrical placement of the modules on the two sides of the cusp trap, due to the tight space constraints on the right side). The first days were dedicated to tests and setting it up for the best working conditions. These operations were delayed because of the very high level of noise experienced by the modules, attaining even a level of tens of MHz for the counting rate from a single module. A very selective trigger (coincidence of three modules out of four) was used to reduce the effect of this noise. Considering that the beamtime dedicated to the cusp trap ended on September 29, only a few shifts of acquisition with this detector have been carried out.

In Fig.33 a typical annihilation event is reported. Usually, a single $\bar{p}$ bunch transferred from the MUSASHI trap to the cusp trap produced about $10^4$ trigger events on the detector, which led in turn to around $10^3$ reconstructed vertices.

A set of data acquired with the $\bar{p}s$ transferred into the cusp trap with similar conditions is presented here. In our reference system, the center of the cusp trap is situated at $x = 0$ cm, $y = -2$ cm, $z = 0$ cm, while the potential well where the $\bar{p}s$ were trapped is centered around $z = -13$ cm. The distribution of the reconstructed vertices (summed over 7 bunches) is presented in Fig.34, left.

In the same figure, on the right, the data taken in a single run with the $\bar{p}$ bunch transferred in a potential well situated downstream the cusp trap centre is presented (nominal position of the center of the potential well at $z = 10$ cm).
Figure 31: Relevant distributions of the reconstructed vertices for $\bar{p}$ annihilations generated at the centre (left) and uniformly on the trap wall, i.e. $r = 4$ cm (right); in both cases, the $z$-coordinate of the simulated annihilations is set to $z = 0$.

Figure 32: $x - y$ distribution for the reconstructed vertices for the same cases shown in Fig.31 (the spots aligned with the $y$ axis are produced by the discretization induced by the geometry of the detector).

In both cases, a sub-sample of vertices with higher quality is shown, being the selection criterion based on the fact that the vertex should have tracks crossing the modules on both sides of the cusp trap; this turned out to noticeably reduce the uncertainty on the vertex positions, probably because -if this condition is not fulfilled- the reconstruction error is increased by the combined effect of the small misalignment in the position of each module (of the order of 1 degree) and of the presence of the “ghost” crossing points.

The most important features are:

- the $x$ distribution is practically flat, even though in the upstream case the higher available statistics seem to reveal some asymmetry and some structure as well;
- the $y$ and $z$ distributions look very well defined, and both distributions look definitely narrower in the downstream case with respect to the upstream case;
Figure 33: Typical reconstruction event (for clarity, the figure has been rotated; $\bar{\psi}$s were coming from the top of the figure).

Figure 34: Relevant distributions of the reconstructed vertices for $\bar{\psi}$ annihilations produced by the bunches trapped in the cusp trap (the reference system is the same as for the simulated data reported in Fig.31).

- the mean value of the $z$ distributions corresponds very well (within the statistical uncertainty) to the center of the potential well where the $\bar{\psi}$s were trapped;

- for the downstream case, the distribution are not much wider than the Monte Carlo distribution in case of point-like annihilation, being the experimental ones only 20% wider that the simulated ones (see Fig.31, left); in the same case, the $y$ distribution is definitely incompatible with the expected distribution for uniformly distributed annihilations on the trap wall (see Fig.31, right), which is much wider, and probably the same thing holds also in the upstream case.

From those observations, it could be hypothesised that the different width of the distributions downstream and upstream is somehow correlated with the different physical conditions of the $\bar{\psi}$s when reaching the two wells.

In the downstream case, the source seems to be a point-like spot situated at $z = 10$ cm and $y = 2$ cm, far away from the trap axis ($x = 0$, $y = -2$, according the reference system), recalling what was indicated as “hot
spot” in the ATHENA experiment [50], that could be a universal feature of $\bar{p}s$ in multi-ring traps. Actually, because of the possible uncertainties in the trap position, it cannot be excluded that there is systematic offset in the measured positions; so, an alternative explanation, relying on the fact that the trapped $\bar{p}$ distribution along the trap axis is very narrow (a few mm), could ascribe this effect to the $\bar{p}$ annihilations on the residual gas (mainly $\text{H}_2$ or He, leading to the formation of protonium [51] or antiprotonic helium [2]). The data analysis is now going on to puzzle out the solution.

### 3.3.5 Future plans

Given the noisy environment of the AD experimental area, some changes are needed especially as far as the frontend electronics is concerned.

New frontend boards (FEB) will be designed: they will host the PMTs through a dedicated socket while the handling of the digital/analog outputs of the ASICs will be managed by the newer ALTEA CYCLONE III FPGA (Field Programmable Gate Array) instead of the CYCLONE II; and the boards will be located inside the detector box.

The same FEBs will host also:

- a memory unit to store the data collected during the MUSASHI cycles (this will improve dramatically the maximum acquisition rate; and this can be very useful for antihydrogen/antiproton detection, which can have a wide spread of rates);

- a 12-bit ADC which allows the acquisition of the analog information from every bar (the ADC digital outputs will be sent to the readout crate via a dedicated fast link);

- a dedicated calibration system is foreseen for the commissioning phase of the new FEBs. A scaler array will be implemented in the ALTERA CYCLONE III unit in order to manage threshold scans and map-checking by means of LEDs placed at one of the bar sides.

From the mechanical point of view an improvement in the supporting system is under study. A stricter alignment of the modules is required together with a more accurate knowledge of their positions to improve the accuracy of the vertex reconstruction to the level predicted by the Monte Carlo simulation.

### 3.4 Development of a superconducting radiofrequency Paul trap for antiprotons

In 2008, the ASACUSA collaboration, together with support from the CERN AB division, ECR group, CERN cryogenic laboratory, central workshop, and brazing workshop, completed the vacuum chamber and cryogenic systems of the radiofrequency Paul trap. Two traps will be used to confine and cool antiprotons, and produce the ground-state antihydrogen atoms needed to carry out microwave spectroscopy of their ground-state hyperfine structure. We also constructed a 1/2 superconducting test cavity made of pure niobium, with an eigen frequency of $\sim 30$ MHz. We cooled the device to temperature $T < 1.8$ K, and successfully demonstrated continuous operation with a zero-to-peak voltage amplitude of 27 kV. The cavity had a measured Q-value of $2.5 - 3 \times 10^6$. This verified that the high RF power needed to trap the antiprotons can be achieved. The cryostat of the Paul trap will be tested for the first time in early 2009, this will be followed by radiofrequency tests of the final superconducting trap structure. We will attempt the first trapping of protons in our new trap by end of 2009.

### 3.5 The asacusa positron beam line

The ASACUSA collaboration has jointly purchased a positron beam line from the company First Point Scientific, Inc. This apparatus is now assembled and tested and found to fulfil all specifications. It is...
therefore ready to become a part of the ASACUSA quest for the measurement of the hyperfine structure of antihydrogen.

The ASACUSA Positron Beam Line (APBL) consists of a positron source and a trap, as shown in figure 35. The source (RGM-1) presently holds a 10 mCi $^{22}\text{Na}$ source, but is designed to accommodate a source of up to 150 mCi. A beam of slow positrons is achieved by moderating the positrons in a solid neon moderator. The handling of the moderator is fully automated by the system computer, and a new moderator can be grown simply by pushing a button. RGM-1 also provides gas handling, magnetic beam transport and a magnetic momentum selector.

**Figure 35:** Illustration of the APBL, showing the source (RGM-1) and the trap.

The second part of the system is a modified Penning-Malmberg trap. The trap has three stages, operated at successively lower potentials, as shown in figure 9. The positrons lose energy by collisions with a nitrogen buffer gas and become trapped. Differential pumping ensures high trapping efficiency at the inlet and long positron lifetime near the end. The trapped positron plasma can be cooled by another buffer gas (CH$_4$ or SF$_6$) and compressed by applying a rotating electric field. In this way we obtain a plasma energy spread of $< 0.2$ eV and a radius of 1.5 mm. The trap is operated by going through three phases: First the trap is filled as shown in figure 36. After a few hundred milliseconds, the inlet and outlet electrodes are raised, and the positron plasma is stored for tenths of milliseconds. During this phase the rotating wall is spun up to compress the plasma. Finally the particles are ejected and a new cycle is ready to begin. Typical cycle repetition rate is 5 Hz.

To avoid contamination of the neon moderator, a cryogenic pump and a pumping restriction is placed between the two parts of the system. This provides a pressure difference of up to five decades.

The APBL was brought to Århus in October 2007. During the transport from California to Denmark, the system sustained damage to the vacuum chamber and gas handling systems. Fortunately none of these damages turned out to be expensive, although replacement and repairs proved very time consuming.

In light of these events, we are pleased to report, that the system is now fully operational and that it meets the expected specifications. The system has been tested with a 10 mCi $^{22}\text{Na}$ source, and the measured main parameters are given in table 1. Where applicable, the measured results have been scaled to the 50 mCi source intended for later ASACUSA experiments at the CERN AD.

Until needed at CERN, the system provides positrons for Positronium experiments in Århus. We plan to measure the positronium yield from different nano-porous silica films during the spring of 2009, and within the next year we hope to measure the cross section for N-photon ionization of positronium.

29
Figure 36: Electrode structure and layout of the trap. The potentials shown are for the “fill” phase.

Table 5: Specifications for the ASACUSA Positron Beam Line. Results are scaled from a 10 mCi to a 50 mCi source.

<table>
<thead>
<tr>
<th></th>
<th>FPSI specifications [45]</th>
<th>Århus measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RGM-1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of $e^+$ from source</td>
<td>$8 \times 10^6$</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td>Moderator decay rate</td>
<td>$&lt; 5%$ per day</td>
<td>1.2% per day</td>
</tr>
<tr>
<td>Source base pressure</td>
<td>$&lt; 10^{-9} \text{ mbar}$</td>
<td>$&lt; 10^{-9} \text{ mbar}$</td>
</tr>
</tbody>
</table>
Part II
Beamtime Plans for 2009

Table 6: Beam usage plan for 2008 (assuming $23 = 24 - 1$ (for AD4) available weeks)

<table>
<thead>
<tr>
<th>Topic</th>
<th>Mode</th>
<th>Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}$He Doppler-free saturation spectroscopy</td>
<td>with RFQD (100 keV $\bar{p}$)</td>
<td>7</td>
</tr>
<tr>
<td>Ultraslow $\bar{p}$ beam development</td>
<td>RFQD+MUSASHI</td>
<td>1</td>
</tr>
<tr>
<td>$\bar{p}$-D and $\bar{p}$-D$_2$ ionization down to 10 keV</td>
<td>RFQD+MUSASHI</td>
<td>2</td>
</tr>
<tr>
<td>Cusp trap - $H$ formation</td>
<td>RFQD+MUSASHI</td>
<td>6.5</td>
</tr>
<tr>
<td>$\bar{p}$-nucleus annihilation cross section</td>
<td>with RFQD</td>
<td>1.5</td>
</tr>
<tr>
<td>$\bar{p}^3$He hyperfine splitting</td>
<td>without RFQD (5 MeV $\bar{p}$)</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>23</td>
</tr>
</tbody>
</table>

1 Antiprotonic Helium Spectroscopy

1.1 Saturation spectroscopy of $\bar{p}$He$^+$ atoms

In 2009, we plan to continue experiments on the Doppler-free saturation laser spectroscopy of antiprotonic helium atoms. Data with higher statistics and better signal-to-noise ratio are needed to obtain publishable results involving with this new method. In principle, it should be possible to measure the transition frequencies of this atom to precisions of less than 1 part in $10^9$. This may then exceed the precision on the known electron-to-proton mass ratio. We are now carrying out extensive developmental work to accomplish this:

- The pilot experiments of 2008 indicate that the power stability of the laser must be improved if we are to improve the signal-to-noise ratio of this saturation spectroscopy method. All previous experiments carried out by ASACUSA used flashlamp-pumped lasers. Here the lasing material is pumped by light flashes produced by a discharge tube filled with xenon gas. We found the light output from these lamps can fluctuate by $\sim 10\%$. We intend to replace these lamps with semiconductor laser diodes, the output intensity of which can be precisely measured and controlled.

- For all of these experiments, it is crucial to construct laser resonators which can generate laser beams with a high degree of monochromaticity. We are now constructing two 3-m-long laser resonators suspended in vacuum, which should produce laser beams whose frequencies are controlled with a precision of 1 part in $10^{11}$.

- We are constructing a new experimental target, which would cool down the antiprotonic helium atoms to even lower temperature ($T < 1.8$ K) than before.

1.2 $\bar{p}^3$He hyperfine spectroscopy

The precision achieved for the (37, 35) state in $\bar{p}^4$He$^+$ cannot be improved further due to fluctuations of the $\bar{p}$ beam. Therefore a first measurement of $\bar{p}^3$He$^+$ is proposed which, in 2009, can be performed with the same experimental set up. We have recently received FWF$^5$ funding (proposal number I-198-N20) for this three year project.

$^5$Austrian Science Fund
Figure 37: Two laser stimulated annihilation peaks against the exponential decaying background of the other state populations. The peak-to-total of each is calculated by taking the ratio of the peak area ($I_p$) to the total area under the full spectrum.

The transitions between the SSHF octets of $\bar{p}^3\text{He}^+$ can be measured with the same method as those between the SHF quadruplets of $\bar{p}^1\text{He}^+$. Instead of two transitions, shown in Fig. 11a), there are now four as shown in Fig. 11b). The most appropriate candidate state is the $(n, l) = (36, 34)$ state, which has an unfavoured laser transition to $(37, 33)$ of $\sim 724$ nm, close to that of the previous measurement ($\sim 726$ nm). Korobov and Bakalov calculate the microwave transitions as the following [26],

16 GHz transitions:

\[ J^{++-} = L + \frac{1}{2} \quad \leftrightarrow \quad J^{--+} = L - \frac{1}{2} = 16.1107 \text{GHz} \]  

\[ J^{++-} = L + \frac{1}{2} \quad \leftrightarrow \quad J^{--} = L - \frac{1}{2} = 16.1434 \text{GHz} \]  

Difference = 32.72 MHz

11 GHz transitions:

\[ J^{++-} = L + \frac{1}{2} \quad \leftrightarrow \quad J^{--} = L - \frac{1}{2} = 11.1250 \text{GHz} \]  

\[ J^{++-} = L - \frac{1}{2} \quad \leftrightarrow \quad J^{--} = L - \frac{3}{2} = 11.1577 \text{GHz} \]  

Difference = 32.73 MHz

It is proposed to measure the 11 GHz transition in 2009 and the 16 GHz in 2010.
1.2.1 Experimental Method

The laser spectroscopy method takes advantage of the charged pions produced when the antiproton annihilates in the helium nucleus. An exponentially decaying background signal is ever present as the antiprotons, in various levels of the cascade, decay and eventually annihilate in the nucleus. This is referred to as an analog delayed annihilation time spectrum (ADATS), analog because a voltage proportional to the number of events is recorded. A measurement of a particular state can be made by laser stimulated transfer to a fast-decaying, Auger decay dominated, daughter state. The ratio of the peak area to the total background area (peak-to-total) indicates the size of the population transferred from the parent to the daughter state.

A microwave pulse can be used to transfer the populations between SSHFS octet states via an electron spin flip. Combined with the laser, to make a laser-microwave-laser technique, this method can be used to measure the transition frequencies.

Initially all the octet states are equally populated and so a population asymmetry must first be induced. A narrow band laser pulse, tuned to the \( f^+ \) transition, creates this asymmetry. The \( J^{+-}, J^{-+}, J^{++} \) and \( J^{++} \) octet states are depopulated through a laser induced transfer to the Auger dominated decay state, while the \( J^{+-}, J^{-+}, J^{++} \) and \( J^{-+} \) octet states remain relatively unaffected. This produces the first peak shown in Fig. 37. The microwave envelope follows which, if on resonance, results in partially inverting the asymmetry: refilling either the \( J^{+-} \) or \( J^{-+} \) from the \( J^{++} \) or \( J^{-+} \) octet state in the \( \sim 11 \) GHz region or the \( J^{++} \) or \( J^{-+} \) from the \( J^{++} \) or \( J^{-+} \) octet state in the \( \sim 16 \) GHz region respectively. After refilling, a second laser pulse, tuned to the same \( f^+ \) transition, is used to depopulate the doublet state again, producing the second peak shown in Fig. 37.

The first laser-induced annihilation peak remains constant, fluctuating only statistically or with the varying conditions of the target, and is therefore used to normalise the second. The second annihilation peak corresponds directly to the population transferred between the hyperfine substates by the microwave. The microwave frequency is scanned across the expected resonant frequency. A plot of the microwave frequency vs the normalised second annihilation peak, produces a peak at the resonant frequency.

1.2.2 Experimental Apparatus

The principle of the newly proposed experiment is the same as that of the \( ^3\text{He}^+ \) \((37, 35)\) state experiment. Therefore the apparatus required essentially remains the same, the microwave setup is described in detail by Sakaguchi et al. [28] while the laser system is described in Hori et al. [3] and summarised in Pask et al. [21]. The laser transition between the parent state \((n,l) = (36, 34)\) and the Auger decay dominated state \((37, 33)\) is \( \sim 724 \) nm so an identical laser system can be used. A new cavity and cryostat for the \( \sim 11 \) GHz transitions is under construction in Vienna, see Fig. 38. To produce a \( \sim 16 \) GHz microwave signal requires new waveguides, a new microwave signal generator and amplifier in addition to a new cavity. Therefore it is proposed only to measure the \( \sim 11 \) GHz transitions in 2009.

1.2.3 Numerical Simulations

The electric dipole moments of the \((36, 34) \to (37, 33)\) transition in \( ^3\text{He}^+ \) are of the same order as those of the \((37, 35) \to (38, 34)\) transition in \( ^3\text{He}^+ \) and it has been shown that the two hyperfine transitions can be well resolved [3]. However the presence of twice as many states increases the microwave resonant profile background and therefore has the potential to reduce the relative signal. An initial guess would be that the signal is reduced by a factor of two compared to the \((37, 35)\) state, reducing the signal to 10%.

The transitions were simulated by calculating the time evolution of the population transfer between the octets. This simplified model does not take into consideration the relaxation collisions. The results, shown in Fig. 39, indicate that the hypothesis is exaggerated and, although the background is twice as high, the signal is also increased. The overall signal height is over estimated because the collision induced
relaxations have not yet been included in the simulation. The ratio is however found to be larger than preliminary simulations on for the \((37, 35)\) \(\bar{\text{p}}^3\text{He}^+\) microwave resonance profile which also excluded the collision induced relaxations.

### 1.2.4 Antiprotonic helium-3 hyperfine structure

The density dependence of the laser experiments depended strongly on the state. Therefore a density dependent study should also be made of the new state. It is proposed that scans are measured at three different densities (150 mbar, 250 mbar and 500 mbar). At 7 shifts per density, 21 shifts would be required.

In addition, 14 shifts are required for setting up and optimising the experimental conditions. This process would include ranging, laser scans and microwave power dependant measurements, at each density.

This microwave transition has never been measured before so we anticipate that the same time will be required for these systematics that took 2 weeks to measure in 2006.
In total, the beamtime proposal in 2009 for the hyperfine splitting of antiprotonic helium is 35 shifts (~5 weeks). Table 7 summarises the requirements for this experiment.

Table 7: 2009 beamtime proposal summary

<table>
<thead>
<tr>
<th>Activity</th>
<th>No. Shifts</th>
</tr>
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<tbody>
<tr>
<td>Ranging and Timing</td>
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</tr>
<tr>
<td>150 mbar laser scans</td>
<td>2</td>
</tr>
<tr>
<td>250 mbar laser scans</td>
<td>2</td>
</tr>
<tr>
<td>500 mbar laser scans</td>
<td>2</td>
</tr>
<tr>
<td>150 mbar MW on off</td>
<td>2</td>
</tr>
<tr>
<td>250 mbar MW on off</td>
<td>2</td>
</tr>
<tr>
<td>500 mbar MW on off</td>
<td>2</td>
</tr>
<tr>
<td>150 mbar MW scans</td>
<td>7</td>
</tr>
<tr>
<td>250 mbar MW scans</td>
<td>7</td>
</tr>
<tr>
<td>500 mbar MW scans</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35</strong></td>
</tr>
</tbody>
</table>

2 \( \bar{p} \)-atom and \( \bar{p} \)-nucleus collisions

2.1 Antiproton-nuclei cross sections measurements at 100 keV.

In 2009 the measurement of antiproton-nuclei annihilation cross sections will be extended down to about 100 keV where no data exists. The lower energy ever reached is one order of magnitude higher with light nuclei (H, D, He) where the annihilation rates seem to be independent from the sizes of the targets (see Fig.40).

Figure 40: Antiproton annihilation cross sections for H, D, \( ^3 \text{He} \), \( ^4 \text{He} \) and Ne. Full stars and empty stars correspond respectively to antiproton-proton and antineutron-proton data
The foreseen experimental technique is based on the experience developed with the 5 MeV measurements performed in 2008.

We will use the same apparatus used at 5 MeV with the addition of the vertex detector used to monitor the antiproton annihilations in the cusp trap (see Fig. 41). The 5 MeV antiproton beam from AD will be decelerated down to 100-120 keV by the ASACUSA RFQD. The decelerated beam will be selected and focused on the target by the dog-leg and collimators placed far from the target in order to reject the background.

No material will be put along the antiproton beam before the target.

The very low energy (about 100 keV) requires very thin solid targets in order to have few annihilations per spill and to avoid too large spread of the antiproton energy along the target.

The targets thicknesses have been evaluated by taking into account an expected increase of the annihilations cross sections following a $E^{-1}$ proportionality with the antiproton energy.

The targets will be metallic disks sputtered on Formvar foils (12 cm in diameter and 50 nm in thickness) and will be realized at PSI by a well consolidated technique.

The metallic targets thicknesses (tens of nanometers) will satisfy the requirements to have annihilation events numbers comparable with the ones from Formvar assuming a $A^2$ law for $\sigma_{\text{ann}}$.

The antiproton energy lost is about 30 keV in the formvar support and few keV on the metallic targets.

The expected background will be due to antiprotons annihilations not occurring on the target. The antiproton low velocity (about 4 mm/s) will help separate in time the signal on the target from background.

**Figure 41:** Experimental set-up for 100 keV antiprotons

The target will be placed, as in 5 MeV measurements in 2008, along the antiproton beam not at the centre of the first detector but about 30 cm downstream where the target vessel has a larger radius (30 cm, instead of the 7.5 cm in the upstream part) in order to reduce the contaminations from the annihilations on the lateral wall of the target vessel due to the Coulomb scattering of the antiprotons on the target.
In this way for example a 100 keV antiproton scattered at 90 degrees needs about 70 ns to reach the lateral wall of the vessel and this time is more than the spill temporal length (50 ns).

The beam collimators placed at least 120 cm before the target will decrease the radial beam halo with a strong reduction of the annihilations number on the target vessel before the target. The collimators themselves will result to be sources of antiproton annihilations, but this background will not disturb the measurements. In fact the signals from the target will occur some hundreds of nanoseconds later when the electronics of the detector is again ready to acquire data (the detector dead time is 150-200 ns).

The antiproton beam not interacting with the target nuclei will annihilate on the end wall of the target vessel where a beam monitor will determine the beam intensity. The delay of these annihilations in respect to the signals on the target is of the order of some hundreds of nanoseconds which will guarantee a sharp separation between signal and end wall annihilations.

2.2 $\bar{p}$-D and $\bar{p}$-D$_2$ ionization

2.3 Introduction - progress up to 2008

Following the success of the MUSASHI group of the ASACUSA collaboration in capturing, storing, cooling and stacking a large number of antiprotons in their Penning trap and extracting these antiprotons at low energy, the AIA group, working together with the MUSASHI group, has achieved a long-time goal, namely to measure the cross section for single ionization of helium for impact of a few keV antiprotons [36]. This gives benchmark experimental data for the development of theoretical models of ionization, excitation and other processes in ion – atom collisions physics. Since the forces in these processes are precisely known (Coulomb), these data further support the development of theories for many-body interactions in other fields.

In our experiment, the antiprotons slowed down to 5.3 MeV by the CERN AD were further decelerated to 115 keV by a radio frequency quadrupole decelerator and then injected into a 2.5 T superconducting solenoid via a thin degrader foil to reduce their kinetic energy to around 10 keV. The antiprotons were then trapped, stored, cooled and the antiproton plasma was compressed in a multiring trap housed in the solenoid, as presented elsewhere in this report, as well as in [29]. The antiprotons were extracted as a 250 eV dc beam by slowly ramping up the trapping potential and transported to a magnetic-field-free region through x and y deflectors and electrostatic lenses with three differential pumping stages separated by apertures [38]. The number of antiprotons transported to the end of the differentially pumped beam line was typically $6 - 7 \times 10^5$ per AD shot.

In the apparatus sketched in Fig. 42, the antiprotons were focused and then accelerated to an energy between 3 and 25 keV. Subsequently they entered the collision chamber. The antiprotons were focused and steered into an interaction region where they passed through a gas jet consisting of 90% helium and 10% argon. Subsequently the antiprotons were detected by a 4 cm diameter microchannel plate detector (MCP), which supplied a timing signal and also an image of the antiproton beam shape on a phosphor screen. The ions created in the interaction region were extracted by a 333V cm$^{-1}$ electric field perpendicular to the antiproton beam and the gas jet and focused spatially and temporally onto another MCP detector, which gave a timing signal and information on the position of the impacting ions. The time difference between the detection of an antiproton and an ion created by it was recorded as a time-of-flight spectrum (TOF). The spectra show clear peaks at the expected positions for He$^+$, Ar$^{++}$, and Ar$^+$. The cross sections, $\sigma$, we need to measure $\epsilon nl$, which is the product of the efficiency for detecting the created ions and the integral of the gas density along the projectile path. For that, an electron gun was inserted in place of the last Einzel lens. An ion TOF spectrum was measured using a 3 keV pulsed electron

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6No beamtime was allocated to the ionization measurement in 2008. Results of the data taken in 2007 have recently been published in Refs. [36] and [44], and are briefly summarized in this section.
beam while accumulating the electron beam charge in a Faraday cup which replaced the antiproton detector in these measurements. From the known cross sections for ionization by 3 keV electrons, we then obtain the product $\varepsilon_{nl}$.

The present experimental data for the single ionization cross section of antiprotons colliding with helium atoms are shown in Fig. 43

Due to the challenges and the basic nature of the antiproton – helium single ionization process a large number of theorists have tried to calculate the cross section. Clearly, with the recent data we are now able to discern between the quality of the various theoretical models, and already a number of theorists are reconsidering their approaches. As an example, in figure 44 we show the development of calculations in one instance: the so-called Multielectron Forced Impulse Method (MFIM) of Ford and Reading [41], which takes into account the dynamic electron-electron correlation by introducing “cuts” in the temporal development of the collisions, in which the otherwise un-correlated wave functions are forced to collapse on fully correlated states. The more cuts, the better is the description of the dynamic correlation, and — as can be seen in figure 44— the better is the agreement with measurement. It can also be seen that the challenge is to extend this model to lower energies.

With respect to a comparison between our data and the many other calculations, the reader is kindly referred to [36].

An alternative outcome of the antiproton — helium collision is double ionization, resulting in a bare helium ion. Although the cross section for this process is much smaller than that for single ionization, we have extracted the cross section for some projectile energies, and upper limits for all energies treated here [42]. The result is shown in figure 45. As can be seen, the spread of the theoretical results is quite large. We can, based on the new data say that the BGM-RESP theories overestimate this cross section, while especially the MEHC theory fits our data well. This is surprising, since that theory underestimates the single
Figure 44: A comparison with the present data and one of the theoretical calculations: the Multielectron Forced Impulse Method of Ford and Reading.

Figure 45: The measured double ionization cross section for antiproton impact helium, compared with various calculations. References are found in [42].

Figure 46: The single and double ionization cross sections for antiproton impact on argon. The curves are the results of the calculations of Kirchner et al [43].

ionization cross section (see figure 43) antiproton impact on helium, compared with various calculations. References can be found in [42].

Helium is clearly the most important target for studies of dynamic electron correlation, but it is also interesting to see how good theory is when more complicated targets, with much more electrons, are in play. For this we measured the single and double ionization cross sections for antiproton impact on argon. The results are shown in figure [40].

As can be seen, the BGM-RESP calculations show the overall tendency of the experimental data, but serious discrepancies exist: The double ionization cross section is much underestimated at the lowest energies, and the single ionization cross section is underestimated at the highest energies (where a perturbation treatment should be valid).

2.3.1 $\bar{p}$-D and $\bar{p}$-D\textsubscript{2} ionization

Clearly, a breakthrough has been achieved with the new data obtained by the MUSASHI and AIA groups. We would, however like to extend the measurement in two directions: To measure the cross section for ionization of atomic hydrogen in 2009, and to perform differential measurement of the ionization process
on helium atoms in the future.

The first goal will be achieved if we succeed in reducing the noise caused by the AIA RF atomic hydrogen source. This is being worked on presently. The target density will be lower than the density of helium used in the last run, but this can be compensated for by a longer accumulation time, together with the fact that the cross section is larger for atomic hydrogen than that for helium. We also plan, of course, to measure the cross section for single ionization on molecular hydrogen in the same run.

2.3.2 Differential measurement of the ionization process on helium (> 2010)

The second goal seemed for a long time to be impossible due to the fact that differential measurements in a single pass experiment demand much more antiprotons than what can be achieved from the ASACUSA beam line. However, if the antiprotons can be “recycled” perhaps 100 times through the gas target, then such measurements should be possible. Therefore, together with the group of Joachim Ullrich and Carsten Welsch at University of Heidelberg, we are building a small “Coasting ring” which will recycle antiprotons through a so-called reaction microscope, which will record the differential cross section. A sketch is shown in figure 47.

![Figure 47: A simple electrostatic storage ring will “recycle” the antiprotons extracted from MUSASHI through a so-called reaction microscope.](image)

The design parameters of the Coasting ring are:

- **Design Maximum Energy**: 20 keV
- **Circumference**: 5.6 m
- **Assumed emittance**: $30\pi$ mm mrad
- **Lattice**: QQQ-90°-90°-QQQ × 2
- **Drift space to install Reaction Microscope**: 1.3 m
- **Vacuum**: $10^{-6}$ mBar

3 Towards antihydrogen ground-state hyperfine spectroscopy

3.1 MUSASHI beam development

MUSASHI will be operated for D and D$_2$ ionization experiments, and for CUSP trap experiment. To keep high intensity of ultraslow beams from MUSASHI, we still need some beam time for exclusive use for tuning. The actual performance in 2008 shows that it consumed five 8-hours shift at least, which includes AD beam steering and RFQD tuning. At the same time, we plan to improve trapping efficiency with modification of electrodes for catching to apply much higher potential.
3.2 Cusp trap Antihydrogen experiments in 2009

With the new bore tube and with more intense and well-controlled positrons, we plan to make the following studies with respect to the cusp trap:

- Optimize the transport and trap conditions of $\bar{p}$ from the antiproton trap to the cusp trap: 0.5 wks
- Tune the 3D detector with trapped antiprotons: 1 wk
- Optimize the cooling and compression conditions of $\bar{p}$ with and without electron plasma in the cusp trap: 2 wks
- Mixing antiprotons and positrons in the cusp trap: 1 wk
- Synthesis of (cold) antihydrogen atoms and detection with the 3D detector under various mixing conditions (mixing position, mixing scheme, radial distribution, trapping potential distribution): 2.5 wks
References

[38] K.Y. Franzen et al., Rev. Sci. Instrum. 74, 3305 (2003);