Weighing the antiproton: precision laser spectroscopy of antiprotonic helium atoms

Ryugo S. Hayano

ATOMIC SPECTROSCOPY AND COLLISIONS
USING SLOW ANTIPROTONS

ASACUSA Collaboration
antiproton  ↓  proton-electron mass ratio

electron  ↓  CPT theorem

↓  CPT test
pHe laser spectroscopy

Laser pulse changes the p orbit

Resonance detection via p annihilation

Frequency

\[ \nu_{n, \ell \rightarrow n', \ell'} = R_c \frac{m_p^*}{m_e} Z_{\text{eff}}^2 \left( \frac{1}{n'^2} - \frac{1}{n^2} \right) + QED \]

\( \bar{p} - e \) mass ratio

Theory

Korobov
Kino et al.

n~40
~1990
theory: Akaishi & Harada

KEK E167A (hayano et al.)

Search for $\Sigma$ hypernuclear ground state by kaon absorption on $^4$He
K^- beam

Liquid helium

K^- He

hypernucleus

Magnetic spectrometer

π^- etc.
Counts per MeV/c

Momentum (MeV/c)

Kaon weak decay!

All Negatively - Charged Particles from $K^-$ Stopped in Liquid Helium

$^4_\Lambda H \rightarrow \pi^- ^4\text{He}$

$\Sigma^- \rightarrow \pi^- n$

$K^- \rightarrow \pi^- \pi^0$

$K^- \rightarrow \bar{\mu} \bar{\nu}_\mu$

Delayed (3.5 - 50 nsec)

Counts per MeV/c

Momentum (MeV/c)

Kaon weak decay (12ns)
MUCH slower than capture (<<ns)
weak decay peaks SHOULD NOT BE THERE!
this is anomalous
what about $\bar{p}$ in liquid He?

KEK E215 (spokesperson: hayano)

Study of metastable states of $\bar{p}$ atom in liquid helium
Serendipitous discovery of $\bar{p}$ longevity in helium (KEK Japan)
Delayed Annihilation Time Spectra

“DATS”

Delayed Annihilation Time Spectra

T. Yamazaki et al., PS205
“DATS” measured at LEAR

Early days of LEAR PS205

Established $\bar{p}$ longevity in gas, liquid, solid helium-3 & helium-4

Lifetime 3~4$\mu$s, formation probability $\sim$3%
\[ \bar{p}^4\text{He}^{++} \text{ ion} \quad \bar{p}^4\text{He}^+ \text{ atom} \]

- \( n = 33 \)
- \( n = 32 \)
- \( n = 31 \)
- \( n = 30 \)
- \( n = 29 \)
- \( n = 28 \)

- **Level Energy (a.u.)**
  - \(-3.8\)
  - \(-3.6\)
  - \(-3.4\)
  - \(-3.2\)
  - \(-3.0\)

- **Stark Collisions Auger Decay**
- **Radiative Decay** (photon wavelength: 300-800 nm)
  - **Metastable state** (\( \tau \sim 1 \mu s \))
  - **Short-lived state** (\( \tau \sim 10\) ns to \( \sim 10\) ps)
  - **Ionized state** (\( \tau \sim \text{ps} \))

- **Capture** (\( \sim 38\))
Auger > Radiative short lived

Auger < Radiative metastable
Auger decay (<10 ns)

Stark Collisions Auger Decay

Radiative Decay
(photon wavelength: 300-800 nm)

Metastable state (τ ~ 1 µs)

Short-lived state (τ ~ 10 ns to ~ 10 ps)

Ionized state (τ ~ ps)

Capture (n~38)
Stark collisions induce s-wave ($L=0$) admixture.
**$\bar{p}$ annihilation on the He nucleus**

- Nuclear Absorption
- Ionized state ($\tau \sim \text{ps}$)
- Radiative Decay (photon wavelength: 300-800nm)
- Capture ($n \sim 38$)
- Metastable state ($\tau \sim 1 \mu\text{s}$)
- Short-lived state ($\tau \sim 10\text{ns to } 10\text{ ps}$)
- Stark Collisions Auger Decay
$\bar{p}^4\text{He}^{++}$ ion  $\bar{p}^4\text{He}^+$ atom

$\text{Level Energy (a.u.)}$

$\text{Stark Collisions Auger Decay}$

$\text{Radiative Decay}$

(photon wavelength: 300-800nm)

Capture ($n \sim 38$)

Metastable state ($\tau \sim 1 \mu s$)

Short-lived state ($\tau \sim 10\text{ns to } 10\text{ ps}$)

Ionized state ($\tau \sim \text{ps}$)

Nuclear Absorption

Ionized state ($\tau \sim \text{ps}$)

$\text{Ionized state}$
An example, \((n,l)=(39,35) \rightarrow (38,34)\)
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An example, \((n,l) = (39,35) \rightarrow (38,34)\)

Theory
Early days of PS205

Theory precision ~ 1000 ppm

~300 larger than the laser bandwidth of ~3GHz

Took weeks to hit the resonance

Variational calculation of energy levels in $p\,\text{He}^+$ molecular systems

V. I. Korobov

*Joint Institute for Nuclear Research, Dubna, Russia*

(Received 29 April 1996)

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**Theory precision ~ 50 ppm**

Shifted in a systematic way

< hour to find a new resonance
Theory - non-relativistic H

\[ H = T + V \]

\[
= -\frac{1}{2\mu_1} \nabla^2_R - \frac{1}{2\mu_2} \nabla^2_r - \frac{1}{M_{\text{He}}} \nabla_R \cdot \nabla_r - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R} - \mathbf{r}|},
\]

\[
\mu_1^{-1} = M_{\text{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\text{He}}^{-1} + m_e^{-1},
\]
Complex coordinate rotation (CCR) method

Careful treatment of Auger decay is needed

CCR calculates complex eigen values
add relativistic correction (∼100 ppm)


\[ H = T + V \]

\[ = -\frac{1}{2\mu_1} \nabla^2_R - \frac{1}{2\mu_2} \nabla^2_r - \frac{1}{M_{\text{He}}} \nabla_R \cdot \nabla_r - \frac{2}{R} - \frac{2}{r} + \frac{1}{|R - r|}, \]

\[ \mu_1^{-1} = M_{\text{He}}^{-1} + M_\chi^{-1}, \quad \mu_2^{-1} = M_{\text{He}}^{-1} + m_e^{-1}, \]

\[ E_{rC} = \alpha^2 \left( -\frac{p_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2} \left[ Z_{\text{He}} \delta(r_{\text{He}}) + Z_p \delta(r_p) \right] \right). \]
add self energy ($\sim$ 15 ppm)

$$H = T + V$$

$$= -\frac{1}{2\mu_1} \nabla_r^2 - \frac{1}{2\mu_2} \nabla_r^2 - \frac{1}{M_{\text{He}}} \nabla_r \cdot \nabla_r - \frac{2}{R} - \frac{2}{r} + \frac{1}{|R - r|},$$

$$\mu_1^{-1} = M_{\text{He}}^{-1} + M_{\chi}^{-1}, \quad \mu_2^{-1} = M_{\text{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left( -\frac{p_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2} [Z_{\text{He}} \delta (r_{\text{He}}) + Z_p \delta (r_p)] \right).$$

Bethe logarithm

$$E_{se} = \frac{4\alpha^3}{3m_e^2} \left[ \ln \frac{1}{\alpha^2} - \ln \frac{k_0}{R_{\infty}} + \frac{5}{6} - \frac{3}{8} \right] \langle Z_{\text{He}} \delta (r_{\text{He}}) + Z_p \delta (r_p) \rangle$$

$$+ \frac{4\alpha^4}{3m_e^2} \left[ 3\pi \left( \frac{139}{128} - \frac{1}{2} \ln 2 \right) \right] \langle Z_{\text{He}}^2 \delta (r_{\text{He}}) + Z_p^2 \delta (r_p) \rangle$$

$$- \frac{4\alpha^5}{3m_e^2} \left[ \frac{3}{4} \right] \langle Z_{\text{He}}^3 \ln^2 (Z_{\text{He}} \alpha)^{-2} \delta (r_{\text{He}}) \rangle$$

$$+ Z_p^3 \ln^2 (Z_p \alpha)^{-2} \delta (r_p) \rangle,$$
Relativistic & QED corrections

\( \bar{p}\text{He} \) first appeared in PDG everyone was ecstatic
end of LEAR PS205

\[(39,35) \rightarrow (38,34)\] Experimental value

Nonrelativistic calculations

Korobov

Kino et al.

Elander et al.

Relativistic correction

Lamb shift

\[597.220, 0.240, 0.260\] Vacuum wavelength [nm]

\[\frac{\lambda_{\text{th}} - \lambda_{\exp}}{\lambda_{\exp}} \text{ (ppm)}\]

\[(37,34) \rightarrow (36,33)\] Experimental value

Nonrelativistic calculations

Korobov

Kino et al.

Elander et al.

Relativistic correction

Lamb shift

\[470.700, 0.720, 0.740\] Vacuum wavelength [nm]

\[\frac{\lambda_{\text{th}} - \lambda_{\exp}}{\lambda_{\exp}} \text{ (ppm)}\]

note: wavelength comparison

Theory vs experiment

Figure 7. Comparison of measured and calculated transition frequencies for the \((39, 35) \rightarrow (38, 34)\) transition of \(\bar{p}^4\text{He}^+\).

The magnetic moment is much larger than the spin one, and the angular momentum coupling scheme proceeds as follows:

\[
F = L \bar{p} + S \bar{e},
\]

\[
J = F + S \bar{p} = L \bar{p} + S \bar{e} + S \bar{p}.
\]

(26)

Figure 8 (left) shows the resulting hyperfine splitting of \(\bar{p}^4\text{He}^+\). The dominant splitting arising from the interaction of the antiproton angular momentum and the electron spin leads to a splitting into a doublet \(F^+\) and \(F^-\) and is called a hyperfine (HF) splitting. The antiproton spin leads to a further, smaller splitting into a quadruplet \(J^{++}, J^{+-}, J^{-+}, J^{--}\) called superhyperfine (SHF) splitting.

In the case of \(\bar{p}^3\text{He}^+\), each level splits into an octet as shown in figure 8 (right), due to an additional coupling to the \(3\)\text{He} (helion) nuclear spin \(S_h\):

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F = L \bar{p} + S \bar{e},
\]

\[
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\]

\[
J = G + S \bar{p} = L \bar{p} + S \bar{e} + S_h + S \bar{p}.
\]

(27)

Although the helion magnetic moment is smaller than the antiproton one, its overlap with the electron cloud is larger and therefore the coupling scheme shown above is more stable.

The hyperfine structure has been first calculated by Bakalov and Korobov (BK) who showed that the HF splitting is in the order of \(\nu_{HF} = 10^{-15}\) GHz, while the SHF slitting is about two orders of magnitude smaller: \(\nu_{SHF} = 0.1-0.3\) GHz. Note that in laser transitions, it is the difference between the two hyperfine splittings which comes into play. In the case of \((n, \ell) \rightarrow (n+1, \ell-1)\) transitions (unfavored transitions), the splitting is of the order of 1.5 GHz and can be partially resolved in the laser resonance profiles, while in the case of \((n, \ell) \rightarrow (n-1, \ell-1)\) transitions (favored transitions) it is less than 0.5 GHz and hence cannot be easily resolved. In order to determine the hyperfine splittings, it is necessary to induce microwave transitions as indicated by wavy lines in figure 8, as discussed in detail in section 5.
反陽子減速器

ASACUSA at CERN AD
$3 \times 10^7 \bar{p}s @ 5 \text{ MeV}$

100ns-wide pulse every $\sim$90s
Basic AD Deceleration Cycle

- pbar injection
- Bunch rotation
- Stochastic cooling 17 s
- Stochastic cooling 6.6 s, Tune jump
- Electron cooling 8 s, Rebunching
- Fast Extraction

Actual Duration: 12(10) - 35(33) - 54(52) - 71(58)
Design Duration: 85(60) time [sec]

Beam bunched for deceleration (RF ON), debunched for cooling
How to work with pulsed $\overline{p}$?
Can’t use event-by-event counting

M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).
Can’t use event-by-event counting

M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).
Fist success at LEAR

LEAR final result

First ASACUSA result at AD


ASACUSA Phase 2 (RFQD)

ASACUSA new laser (goal for 2004)

proton mass precision ($4.6 \times 10^{-10}$)

Relative Precision

Year
reducing collision
more on collisions by Grigory Korenman
$\bar{p}$ He - He collisions do not destroy $\bar{p}$He but have consequences.
Density-dependent shift
RFQD

a decelerating linac
RFQD

Typical target density

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<table>
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<tbody>
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<td>10</td>
<td>10</td>
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Antiproton Decelerator (1% of c, ~25% efficiency)

Antiproton pulse from AD (10% of c)
With RFQD

Frequency measured to (6-19)×10⁻⁸

\[ \frac{\nu_{\text{th}} - \nu_{\text{exp}}}{\nu_{\text{exp}}} \] (ppb)

\[ \bar{p} \, ^{4}\text{He}^{+} \]

(40,35) \Rightarrow (39,34)
(39,35) \Rightarrow (38,34)
(37,35) \Rightarrow (38,34)
(37,34) \Rightarrow (36,33)
(35,33) \Rightarrow (34,32)
(33,32) \Rightarrow (32,31)
(32,31) \Rightarrow (31,30)

\[ \bar{p} \, ^{3}\text{He}^{+} \]

(38,34) \Rightarrow (37,33)
(36,34) \Rightarrow (37,33)
(36,33) \Rightarrow (35,32)
(34,33) \Rightarrow (35,32)
(34,32) \Rightarrow (33,31)
(32,31) \Rightarrow (31,30)


note: wavelength measurement
**Direct** measurement w RFQD

**Antiprotonic helium and CPT invariance 2013**

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Theory (Korobov)</th>
</tr>
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<td>1998</td>
<td>501949.2</td>
<td></td>
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<td>2000</td>
<td>501949.0</td>
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<td>2002</td>
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<td></td>
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<td>2004</td>
<td>501948.6</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>501948.4</td>
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</tbody>
</table>

**Figure 7.** Comparison of measured and calculated transition frequencies for the $\bar{p}^4\text{He}^+$ $(39,35) \rightarrow (38,34)$ transition of $\bar{p}^4\text{He}^+$. The magnetic moment is much larger than the spin one, and the angular momentum coupling scheme proceeds as follows:

$$ F = L_{\bar{p}} + S_{\bar{e}}, \quad J = F + S_{\bar{p}} = L_{\bar{p}} + S_{\bar{e}} + S_{\bar{p}}. \quad (26) $$

**Figure 8 (left)** shows the resulting hyperfine splitting of $\bar{p}^4\text{He}^+$. The dominant splitting arising from the interaction of the antiproton angular momentum and the electron spin leads to a splitting into a doublet $F^+$ and $F^-$ and is called a hyperfine (HF) splitting. The antiproton spin leads to a further, smaller splitting into a quadruplet $J^{++}$, $J^{+-}$, $J^{-+}$, and $J^{--}$ called superhyperfine (SHF) splitting.

In the case of $\bar{p}^3\text{He}^+$, each level splits into an octet as shown in figure 8 (right), due to an additional coupling to the $^3\text{He}$ (helion) nuclear spin $S_h$.

The hyperfine structure has been first calculated by Bakalov and Korobov (BK) who showed that the HF splitting is in the order of $\nu_{HF} = 10^{-15}$ GHz, while the SHF splitting is about two orders of magnitude smaller: $\nu_{SHF} = 0.1$–0.3 GHz. Note that in laser transitions, it is the difference between the two hyperfine splittings which comes into play. In the case of $(n, \ell) \rightarrow (n+1, \ell-1)$ transitions (unfavored transitions), the splitting is of the order of 1.5 Gz and can be partially resolved in the laser resonance profiles, while in the case of $(n, \ell) \rightarrow (n-1, \ell-1)$ transitions (favored transitions) it is less than 0.5 GHz and hence cannot be easily resolved. In order to determine the hyperfine splittings, it is necessary to induce microwave transitions as indicated by wavy lines in figure 8, as discussed in detail in section 5.
Frequency Comb
12 transitions were measured

- *p* $^4$He$^+$
- *p* $^3$He$^+$

Favored transitions
Unfavored transitions

Metastable states
Short-lived states
From the comparison of the measured transition frequencies, the mass and charge of the antiproton values are determined. They are compared with the two sets of theoretical and experimental data, including chirp (2–4 MHz), collisional shifts (0.1–2 MHz) and any possible shift due to the harmonic frequencies.

When deducing the p-to-electron mass ratio, we assume that the mass ratio (and then compare the value with the theoretically calculated values) is claimed by the authors to have been set to the fundamental constants. Indeed, unpublished data (1) to determine both the fundamental constants and the theoretically calculated values agree within the order of 2 standard deviations (figure 35).

On the other hand, in the older values of the mass ratio, we assume that the mass (and charge) of the antiproton can be deduced. This is done by varying the mass ratio (and then compare the value with the two previous experiments which imply that CPT invariance is not violated yet at the present experimental precision). We therefore set a new value of the fundamental constants, and let it vary relative to the previous experimental errors.

Let us first discuss the case 1, determination of the p-to-electron mass ratio (and then compare the value with the two previous experiments) within the order of 2 standard deviations.

The results from the authors have recently moved by 3–100 MHz from those of the previous theoretical calculations because of technical difficulties in evaluating their variational trial functions near the origin. Indeed, unpublished data (2) to test if there is any difference between the constituent particles approaches zero. In the present situation, the harmonic frequencies were lower than the 1–2 MHz. The RFQD+Comb used in the theory model, initially set to the 2002 CODATA recommended values for the fundamental constants, makes it possible to set a new value of the fundamental constants, and let it vary relative to the previous experimental errors.

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The important differences between the two sets of theoretical and experimental data are compared with the two theoretical data, including chirp (2–4 MHz), collisional shifts (0.1–2 MHz) and any possible shift due to the harmonic frequencies.

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with RFQD+Comb

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The magnetic moment is much larger than the spin one, and the angular momentum coupling scheme proceeds as follows:

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\nu_{SHF} = 0.1-0.3 \text{GHz}.
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Note that in laser transitions, it is the difference between the two hyperfine splittings which comes into play. In the case of \( (n, l) \rightarrow (n+1, l-1) \) transitions (unfavored transitions), the splitting is of the order of 1.5 GHz and can be partially resolved in the laser resonance profiles, while in the case of \( (n, l) \rightarrow (n-1, l-1) \) transitions (favored transitions) it is less than 0.5 GHz and hence cannot be easily resolved. In order to determine the hyperfine splittings, it is necessary to induce microwave transitions as indicated by wavy lines in figure 8, as discussed in detail in section 5.
\[
E_{nr} = 501972347.9 \quad \text{Non relativistic}
\]
\[
E_{rc} = -27525.3 \quad + \text{Relativistic & QED corrections}
\]
\[
E_{rc-qed} = 233.3
\]
\[
E_{se} = 3818.0
\]
\[
E_{vp} = -122.5
\]
\[
E_{kin} = 37.3
\]
\[
E_{exch} = -34.7
\]
\[
E_{\alpha^3-rec} = 0.8
\]
\[
E_{two-loop} = 0.9
\]
\[
E_{nuc} = 2.4
\]
\[
E_{\alpha^4} = -2.6
\]
\[
E_{total} = 501948755.6(1.3) \text{ MHz} \quad \text{Theory (Korobov)}
\]
\[
501948752.0(4.0) \text{ MHz} \quad \text{Exp.}
\]
\[12 \text{ such transitions CODATA 2006}\]
IV. ATOMIC TRANSITION FREQUENCIES

Atomic transition frequencies in hydrogen, deuterium, and antiprotonic helium yield information on the Rydberg constant, the proton and deuteron charge radii, and the relative atomic mass of the electron. The hyper-
2012
Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio

Masaki Hori, Anna Sótér, Daniel Barna, Andreas Dax, Ryugo Hayano, Susanne Friedreich, Bertalan Juhász, Thomas Pask, Eberhard Widmann, Dezső Horváth, Luca Venturelli & Nicola Zurlo

Nature 475, 484–488 (28 July 2011) doi:10.1038/nature10260
Received 12 April 2011  Accepted 26 May 2011  Published online 27 July 2011

Physical laws are believed to be invariant under the combined transformations of charge, parity and time reversal (CPT symmetry). This implies that an antimatter particle has exactly the same mass and absolute value of charge as its particle counterpart. Metastable antiprotonic helium (\( \bar{p}\) He\(^+\)) is a three-body atom consisting of a normal helium nucleus, an electron in its ground state and an antiproton (\( \bar{p}\)) occupying a Rydberg state with high principal and angular momentum quantum numbers, respectively \( n \) and \( l \), such that \( n \approx l + 1 \approx 38 \). These atoms are amenable to precision laser spectroscopy, the results of which can in principle be used to determine the antiproton-to-electron mass ratio and to constrain the equality between the antiproton and proton charges and masses. Here we report two-photon spectroscopy of antiprotonic helium, in which \( \bar{p}\)\(^3\)He\(^+\) and \( \bar{p}\)\(^4\)He\(^+\) isotopes are irradiated by two counter-propagating laser beams. This excites nonlinear, two-photon transitions of the antiproton of the type \((n, l) \rightarrow (n-2, l-2)\) at deep-ultraviolet wavelengths (\( \lambda = 139.8, 193.0 \) and 197.0 nm), which partly cancel the Doppler broadening of the laser resonance caused by the thermal motion of the atoms. The resulting narrow spectral lines allowed us to measure three transition frequencies with fractional precisions of 2.3–5 parts in \( 10^9 \). By comparing the results with three-body quantum electrodynamics calculations, we derived an antiproton-to-electron mass ratio of 1,836.1526736(23), where the parenthetical error represents one standard deviation. This agrees with the proton-to-electron value known to a similar precision.
After the resulting formation of a virtual intermediate state lay to the two-photon transition \((36, 34)\) such that the virtual state could inhibit the two-photon transition to remain small. This indicates that the background from any Doppler-broadened, \(0.5\) GHz; Fig. 1b, red line), the signal abruptly disappeared as expected. Single-photon transitions is very small. This was tuned off the two-photon resonance condition slightly (by \(\Delta v_d\)) and was measured using a heterodyne spectroscopy. CW, continuous wave; RF, radio frequency; SHG, second-harmonic generation; THG, third-harmonic generation; ULE, ultralow-expansion.

Identical laser systems were synthesized by decelerating a beam of antiprotons to \(200\) ns-long, pulsed beams of \(5.3\)-MeV antiprotons (Fig. 1c). Every laser beams. We used the CERN Antiproton Decelerator to produce in such targets within the volume irradiated by the 2-cm-diameter laser beams. The precision of this laser system was verified by measuring some two-photon transition frequencies \((35, 33)\) (Fig. 2a) measured under the same target and laser power conditions. This allows us to determine the atomic transition frequency with a correspondingly higher precision. The remaining width is caused by the Doppler- and power-broadening effects. The resonance profile measured by detuning the laser of frequency \(6\) GHz away from the real state \((35, 33)\) (Fig. 2b) measured under the same target and laser power conditions achieved so far for an antiprotonic atom, and is more than an \(\sim 6\) GHz and scanning the laser of frequency \(6\) GHz away from the real state (35, 33).

Figure 1

Figure 2

2-phonon spectroscopy of \(\bar{p}\) He

 elves.

\(He\) 2-phonon spectroscopy

Identical laser system

Achromatic beam transport

Virtual state

\(He^2+\)

\(p\)

\(\nu_1\) laser

\((n, l) = (36, 34)\)

\(\nu_2\) laser

\((35, 33)\)

\((34, 32)\)

\(\Delta v_d\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)

\(\nu_2\) laser

\(\nu_1\) laser

Virtual state

\(He^2+\)

\(p\)
The transition rates, power broadening effects, thermal motion of the atomic beam, and a.c. Stark effects limited experiments to probing the lowest magnetic quantum number states under our experimental conditions. The frequency chirp of each laser beam was estimated to be 3 MHz (all quoted errors are s.d.). We measured the spacing between the unresolved hyperfine lines (S = 2, 3) at 139.8 nm, from state (32, 31) to within 20%. Calculations show that the widths of the hyperfine lines and the smaller signal intensity.

The experimental transition frequencies, tabled in Table 2, were obtained as the quadratic sum of all these errors. The larger error for negative detunings, 

\[ \left( R_{\text{th}} - R_{\text{exp}} \right) / R_{\text{exp}} \text{ (p.p.b.)} \]

was changed by 2.3–2.8 MHz. By minimizing systematic errors on the states, the precision of obtaining the hyperfine structure function to be around 1 MHz.

The charge radii of the He nuclei give corrections to the states. The precision of the charge radii uncertainties required that higher laser intensities, (Fig. 2c). The small transition probability and antiproton population (ref. 16).

The total theoretical uncertainty (Table 2). When the antiproton-to-electron mass ratio, 

\[ \frac{m_{\text{p}}}{m_{\text{e}}} = \frac{1}{1.09738 \pm 0.00010} \]

was determined by numerically solving the nonlinear rate equations of the two-photon process. This included taking into account collisions.

Numerical uncertainty in calculation errors, statistical error,

<table>
<thead>
<tr>
<th>Transition</th>
<th>( \Delta \nu / \nu ) (p.p.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(36, 34) → (34, 32)</td>
<td>1</td>
</tr>
<tr>
<td>(33, 32) → (31, 30)</td>
<td>2</td>
</tr>
<tr>
<td>(35, 33) → (33, 31)</td>
<td>3</td>
</tr>
</tbody>
</table>

The agreement of the experimental values with theoretical values (ref. 3 and V. I. Korobov, personal communication) shows respective uncertainties from uncalculated QED terms. The charge radii uncertainties were obtained as the quadratic sum of all these errors.
Hyperfine structure of metastable states in antiprotonic helium including relativistic and radiative corrections of order $R$ was studied by laser spectroscopy. A chirp-compensated, injection-seeded alexandrite laser was used to maintain absolute precision for the duration of measurements. The result, with a frequency-doubled (second-harmonic generation) or frequency-tripled (third-harmonic generation) output, was recorded for each laser transition. The output beams were reduced to a few megahertz, and the remaining chirp was corrected for at the data analysis stage.

The transition frequency of cesium was measured 20 times over a two-week period. The result, with a relative uncertainty of $0.1 \text{ MHz}$, was obtained by combining X-ray spectroscopic data on antiprotonic helium (Ref. 19) with CODATA 2002 values (Ref. 16) and the GSI-Mainz measurements (Ref. 23).

The Cherenkov signals corresponding to the positronium transition were used as time markers for the injection-seeded laser. The laser frequency was recorded by counting the number of time spectra, with the area under the peak in each of these spectra plotted as a function of laser frequency to obtain the resonance profiles in Fig. 2.

The density shift and isotope shift were estimated by averaging over the three transitions.

Furthermore, the electron's atomic mass and the proton/electron mass ratio were measured by Penning trap mass spectroscopy and compared with CODATA values. This work reproduced the experimental data (Fig. 2). The validity of the method was also confirmed by using part of the light to measure the laser frequency offset.

Sub-ppm laser spectroscopy of antiprotonic helium and a CPT-violation limit on the antiprotonic charge and mass were also established. The measurements were verified by using part of the light to measure the frequency offset.
Table 2 | Errors for transition \((n, l) = (36, 34) \rightarrow (34, 32)\) of \(\bar{p}^4\text{He}^+\)

<table>
<thead>
<tr>
<th>Datum</th>
<th>Error (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error, (\sigma_{\text{stat}})</td>
<td>3</td>
</tr>
<tr>
<td>Collisional shift error</td>
<td>1</td>
</tr>
<tr>
<td>A.c. Stark shift error</td>
<td>0.5</td>
</tr>
<tr>
<td>Zeeman shift</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Frequency chirp error</td>
<td>0.8</td>
</tr>
<tr>
<td>Seed laser frequency calibration</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Hyperfine structure</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Line profile simulation</td>
<td>1</td>
</tr>
<tr>
<td>Total systematic error, (\sigma_{\text{sys}})</td>
<td>1.8</td>
</tr>
<tr>
<td>Total experimental error, (\sigma_{\text{exp}})</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Theoretical uncertainties

<table>
<thead>
<tr>
<th>Datum</th>
<th>Error (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainties from uncalculated QED terms*</td>
<td>2.1</td>
</tr>
<tr>
<td>Numerical uncertainty in calculation*</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass uncertainties*</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Charge radii uncertainties*</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total theoretical uncertainty*, (\sigma_{\text{th}})</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Experimental errors and theoretical uncertainties are 1 s.d.

* Ref. 3 and V. I. Korobov, personal communication.
LEAR experiments
AD construction
RFQD beam
Frequency comb, laser chirp correction
Two-photon spectroscopy
Relativistic corrections
Complex-coordinate rotation
Two-loop QED
CODATA98
CODATA2010
Two-loop QED
QED order $\alpha^6$
QED $\alpha^7$, improved
Bethe logarithm, Finite nuclear size

Precision on (anti)proton-to-electron mass ratio

Years
超微細構造

Hyperfine
pHe hyperfine

\[ J = L - \frac{1}{2} \]

\[ J = L + \frac{1}{2} \]
New Value for the $\bar{p}$ Magnetic Moment

Published in Physics Letters B in 2009:
summary
20 years of $\bar{\Lambda}$He

Serendipitous discovery

Precision now at $\sim 10^{-9}$ (RFQ, Comb, 2-photon, ...)

Contribute to fundamental constant ($m_p/m_e$)

Further improvements possible (takes exp/theory efforts), esp. with the ELENA
ELENA
In the original rectangular ring circumference of 26.2m (1/7 of AD ring), apart from the challenge of fitting all the ring elements, it was not possible to insert the necessary equipment for an additional (optional) ejection line. The new circumference is 30.4m (1/6 of AD ring) and has a hexagonal layout of the ring.

The benefits of the new design are:

- More flexibility for injection and extraction.
- The total length of bending magnets is shorter, leaving more space for other equipment.
- The minimum magnetic field in the bending magnets (at 100 keV) is increased from 399 Gauss to 493 Gauss.
- The new 6 fold ring with its circumference increased to 30.4m has a wider choice of tunes compared to the former design.
- Smaller beta function values resulting in a much reduced aperture required by the beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range, MeV</td>
<td>5.3 - 0.1</td>
</tr>
<tr>
<td>Circumference, m</td>
<td>30.4</td>
</tr>
<tr>
<td>Intensity of injected beam</td>
<td>3 × 10</td>
</tr>
<tr>
<td>Intensity of ejected beam</td>
<td>2.5 × 10</td>
</tr>
<tr>
<td>Number of extracted bunches</td>
<td>4</td>
</tr>
<tr>
<td>Emittance at 100 KeV, π.mm.mrad, [95%]</td>
<td>4</td>
</tr>
<tr>
<td>Δp/p after cooling, [95%]</td>
<td>10</td>
</tr>
<tr>
<td>Bunch length at 100 keV, m / ns</td>
<td>1.3/300</td>
</tr>
<tr>
<td>Required vacuum, Torr</td>
<td>3 × 10</td>
</tr>
</tbody>
</table>
ELENA:

Installation and integration committee meeting

17/11/2011

- Relocation of ATRAP/ASACUSA control room (it is still problematic, users are not "motivated")
- Relocate kicker platform (2 options, one inside, the other outside 193).

Figure 3: Ad possible modifications FB presents a possible solution with kickers, storage room and a workshop at the exterior in a 530m² building. FB mentions that this building will be equipped with a crane and also electricity, heating… FB insists on that there are still lots of technical difficulties to face before starting the construction due to the presence of the TT2 line underneath. For example, this building will have a 1m thick shielded floor but it will stay at the same level than the AD-hall.

Luc Sermes reminds that with ELENA coming we will need a new generator (kicker part) so we need more room that the one already calculated on FB drawing. FB reminds that it would be really difficult (or impossible) to make the new building bigger because we can not excavate the hills that are used as a shielding for the underneath transfer lines, and possible future neutrino line.

A. Lopez indicates that, to gain some space, we can remove the TT2 line access (not needed in this shape) in this case the crane should be able to go down into the TT2 access pit. FB says that it is also possible to locate the kicker under the crane (inside the hall, lifting the actual structure, keeping a safety margin below the crane).

T. Eriksson insists in the importance of having available room inside the AD hall for the other (new & old) experiments like G-barr. Also S. Maury reminds that at these low energy levels we cannot afford to have electrical/magnetic perturbation nearby. Both comments go toward the solution of putting kickers outside.

A. Lopez says that to build a 500 m² building we need at least 8 months just for the civil engineering. FB says that this building in this configuration will cost at least 50% or 100% more.