THE HYPERFINE STRUCTURE OF ANTIPROTONIC HELIUM AND THE ANTIPROTON MAGNETIC

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Atomic Spectroscopy And Collisions Using Slow Antiprotons

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- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen’s University of Belfast, Ireland

~ 44 members
$\bar{\text{pHe}}^+ \text{ “ATOMCULE” - A NATURALLY OCCURRING TRAP FOR ANTI PROTONS} \n
\text{Metastable states } \tau \sim \mu \text{s} \\
\text{short-lived states } (\text{Auger decay}) \quad \tau \leq 10 \text{ ns} \\

I_0 = 0.90 \text{ a.u. } \ (24.6 \text{ eV)}
"PHe+ "ATOMCULE" - A NATURALLY OCCURRING TRAP FOR ANTIPROTONS"

Metastable states
\( \tau \sim \mu s \)
short-lived states
(Auger decay)
\( \tau \leq 10 \text{ ns} \)

possibility of precision spectroscopy

Energy (a.u.)

0(s) 30 31 32 33 34 35 36 37 38 ... ~ 380

*\( M \)

\( m_e \)

0

Stark mixing

Nuclear absorption & Annihilation

Ionized \( \bar{\text{He}}^{++} \)

Auger decay

Radiative transitions

Neutral \( \bar{\text{He}}^{+} \)

delayed annihilation of \( \bar{p} \) in liquid helium, KEK 1991

prompt

trapping fraction: \(~ 3 \%\)
average lifetime: \(~ 3 \mu s\)

delayed

counts / 200 ns

0 5 10 15 20

Annihilation Time (\( \mu s \))

\( I_0 = 0.90 \text{ a.u.} \) (24.6 eV)

He

\( \bar{\text{He}}^{+} \)

He

\( \bar{\text{He}}^{0} \)

\( \bar{\text{He}}^{+} \)
Neutral $p\text{He}^+$

Ionized $p\text{He}^{++}$

$E_{\text{energy}} = 0.90 \text{ a.u.}$

$n_0 = \frac{\sqrt{M^*}}{m_e} \approx 38$
pairs of metastable - short-lived state
- laser spectroscopy
- forced annihilation
- determine mass, charge of antiproton

Neutral pHe^+

<table>
<thead>
<tr>
<th>Neutral pHe</th>
<th>Ionized pHe^{++}</th>
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\[ n_0 = \sqrt{\frac{M^*}{m_e}} = 38 \]
Precision spectroscopy

- pairs of metastable - short-lived state
- laser spectroscopy
- forced annihilation
- determine mass, charge of antiproton

Hyperfine structure
- magnetic moment of antiproton

$n_0 = \sqrt{\frac{m^*}{m_e}}$ 38
Tests of particle/antiparticle symmetry properties

- Inconsistent definition of figure of merit: comparison difficult
- Pattern of CPT violation unknown (P: weak interaction, CP: mesons)
Standard Model Extension: V.A. Kostelecky et al.

parameters of extended Dirac equ: dimension of energy

\[
(i\gamma^\mu D^\mu - M - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + i c_{\mu\nu} \gamma^\mu D^\nu + i d_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0
\]

absolute accuracy (GeV)

relative accuracy
Antiproton decelerator @ CERN

AD PROJECT

- AD
- Modification of the AC ring
- 1 ring for 3 tasks
  - Antiproton capture
  - deceleration
  - cooling
- start operation in 2000
**EXPERIMENTAL SETUP AT AD**

Analog Measurement of Delayed Annihilation using Cerenkov counters and digital oscilloscope

TOP VIEW

5.3 MeV antiprotons are stopped in ~ 6 K 0.5 – 3 bar He gas

Microwave cavity 12.91 GHz: 28.8 mm diameter, 24.5 mm length
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**HYPERFINE STRUCTURE OF $\bar{p}^4\text{He}^+$**

- **Interactions of magnetic moments:**
  - Electron: $\vec{\mu}_e = g\mu_B \vec{S}_e$
  - $p$-bar: $\vec{\mu}_{\bar{p}} = [g_s(\bar{p})\vec{S}_{\bar{p}} + g_l(\bar{p})\vec{L}_{\bar{p}}]\mu_N$

- "Hyperfine" splitting HFS:
  - $\vec{L}_{\bar{p}} \cdot \vec{S}_e$
  - Dominant because of large $L$

- "Superhyperfine" splitting

- HFS: 10 ... 15 GHz
- SHFS: 0.1 ... 0.3 GHz

$\nu_{\text{SHF}}$ sensitive to magnetic moment of $p$-bar

(known to $3 \times 10^{-3}$)

$\nu_{\text{HF}}$ tests **orbital** angular moment: $g_I$

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E. Widmann, Antiprotonic helium HFS
CURRENT KNOWLEDGE OF $\mu \bar{\nu}$

- fine structure of x-Rays of antiprotonic lead
- $^{208}$Pb to avoid HFS

- results (PDG):

$\bar{p}$ MAGNETIC MOMENT

A few early results have been omitted.

<table>
<thead>
<tr>
<th>VALUE ($\mu_N$)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
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<tbody>
<tr>
<td>$-2.800 \pm 0.008$</td>
<td>KREISSL</td>
<td>88</td>
<td>CNTR</td>
</tr>
<tr>
<td>$-2.8005 \pm 0.0090$</td>
<td>ROBERTS</td>
<td>78</td>
<td>CNTR</td>
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<tr>
<td>$-2.817 \pm 0.048$</td>
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<tr>
<td>$-2.791 \pm 0.021$</td>
<td>HU</td>
<td>75</td>
<td>CNTR</td>
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</table>

E. Widmann, Antiprotonic helium HFS

0.3%!!
1.75 GHz is difference of HF splitting of (37,35) and (38,34) state

SHFS transitions cannot be observed due to Doppler broadening & laser bandwidth
Laser-microwave-laser resonance experiment

Parameters of (37,35) state:
\[ \nu_{HF} = 12.91 \text{ GHz} \]
\[ \nu_{SHF^+} = 161 \text{ MHz} \]
\[ \nu_{SHF^-} = 133 \text{ MHz} \]

Step 1: depopulation of F^+ doublet with \( f_+ \) laser pulse

Step 2: equalization of populations of F^+ and F^- by microwave

Step 3: probing of population of F^+ doublet with 2nd \( f_+ \) laser pulse

Laser scan

Time spectrum with 2 laser pulses

\[ R^{++}(\nu_{MW}) = \frac{I_+(t_2)}{I_+(t_1)} \]

\( \Delta = 3.1 \pm 0.15 \) pm
\( = 1.8 \pm 0.1 \) GHz
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$$R^{++}(v_{MW}) = \frac{I_+(t_2)}{I_+(t_1)}$$

$(n,l) = (37,35) \rightarrow (36,34)$

$\Delta = 3.1 \pm 0.15 \text{ pm}$

$= 1.8 \pm 0.1 \text{ GHz}$

E. Widmann, Antiprotonic helium HFS
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Time spectrum with 2 laser pulses

$R^{++}(\nu_{MW}) = \frac{I_+(t_2)}{I_+(t_1)}$
**MICROWAVE CAVITY FOR HFS MEASUREMENT**

- Cavity for 13 GHz at < 10 K to reduce Doppler broadening
- Meshes to allow pbar and laser light to enter
- Low Q (~100) to avoid mechanical tuning
- Tuning via synthesizer and stub tuner

**Image Description**

- **He gas**
- **Waveguide**
- **25µm thick stainless steel window**
- **7.5µm thick superinsulation foils**
- **50µm thick Kapton window**
- **Antiprotons 100 MeV/c**
- **Cryogenic SMA cable**
- **Meshes**
- **Two laser beams**
- **Quartz windows**
- **Cavity**
- **Mumetal shield**
- **Cryostat wall temperature shields**

**Technical Details**

- Diameter: 28.8 mm
First observation of HFS transition

\[ \nu_{HF}^+ \quad \nu_{HF}^- \]

Experimental accuracy: \( \sim 3 \times 10^{-5} \)

| \( \nu_{HF}^+ \) | 12.895 96(34) GHz | 27 ppm |
| \( \nu_{HF}^- \) | 12.924 67(29) GHz | 23 ppm |

E.W. et al. PRL 89 (2002) 243402
FIRST OBSERVATION OF HFS TRANSITION

Experimental accuracy: $\sim 3 \times 10^{-5}$

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E. Widmann, Antiprotonic helium HFS
**First Observation of HFS Transition**

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<td>23 ppm</td>
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**Comparison to theory favours most recent results of both groups**

- Korobov & Bakalov JPB 34 L519 2001
- Kino et al. Proc. APAC 2001

- Difference $< 6 \times 10^{-5}$

- Corresponds to theoretical uncertainty
  - Omission of terms $O(\alpha^2)\sim 5\times10^{-5}$
Determination of $\mu\bar{p}$

- $\nu_{\text{SHF}}^{+}, \nu_{\text{SHF}}^{-}$ most sensitive, but impossible to measure (power requirement)
- $\Delta \nu_{\text{HF}} = \nu_{\text{HF}}^{-} - \nu_{\text{HF}}^{+} = \nu_{\text{SHF}}^{+} - \nu_{\text{SHF}}^{-}$: sensitive to $\mu\bar{p}$
- Sensitivity factors from theory (D. Bakalov and E.W., PRA in print)
  - $S(F,J) = \partial E_{nFLJ} / \partial \mu\bar{p} |_{\mu\bar{p} = -\mu_p}$
  - $S(\nu_{\text{HF}}^{+}) = S(F^{-J^{-}}) - S(F^{+J^{+}})$

$\nu_{\text{MW}}$ (GHz)

$R^{++}/R^{++}_{\text{off}}$

- $F^{+} = L + 1/2$
- $F^{-} = L - 1/2$
- $J^{++} = L + 1$
- $J^{+} = L$
- $J^{-} = L - 1$
- $J^{-+} = L - 1$

$\nu_{\text{SHF}}^{+}$
$\nu_{\text{SHF}}^{-}$
$\nu_{\text{HF}}^{+}$
$\nu_{\text{HF}}^{-}$
$\nu_{\text{HF}}$
**DETERMINATION OF $\mu\bar{p}$**

- $\nu_{SHF}^+$, $\nu_{SHF}^-$ most sensitive, but impossible to measure (power requirement)
- $\Delta \nu_{HF} = \nu_{HF}^- - \nu_{HF}^+ = \nu_{SHF}^+ - \nu_{SHF}^-$: sensitive to $\mu\bar{p}$
- sensitivity factors from theory (*D. Bakalov and E.W., PRA in print*)
  - $S(F,J) = \frac{\partial E_{nFLJ}}{\partial \mu\bar{p}} |_{\mu\bar{p} = -\mu_p}$
  - $S(\nu_{HF}^+) = S(F^-J^-) - S(F^+J^+)$

$\nu_{MW}$ (GHz)

<table>
<thead>
<tr>
<th>MW (GHz)</th>
<th>12.86</th>
<th>12.88</th>
<th>12.90</th>
<th>12.92</th>
<th>12.94</th>
<th>12.96</th>
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<tbody>
<tr>
<td>0.95</td>
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<td>1.00</td>
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<tr>
<td>1.05</td>
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<tr>
<td>1.10</td>
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<tr>
<td>1.15</td>
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$R_{++}/R_{++\text{off}}$

- Diagram illustrating transitions and labels $(n,L)$, $F^+=L+1/2$, $F^-=L-1/2$, $J^+=L$, $J^-=-L-1$, $J^{++}=L+1$, $J^{+-}=L$.
Improvements of $\mu\bar{\nu}$

- Error of known value of $\mu\bar{\nu}$: $\delta_\mu = 3 \times 10^{-3}$

- Limitation for $\bar{\nu}$He$^+$: theoretical accuracy
  - for $\Delta\nu_{HF}$: $\Delta_q \sim O(10^{-3})$ conservative!

- Max. improvement from ratio: factor $\Delta_q/\Delta_\mu = 3 - 9$

- $(37,35)$: factor 3 improvement in $\mu\bar{\nu}$: factor 10 in exp. accuracy

<table>
<thead>
<tr>
<th></th>
<th>(35,33)</th>
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<th>(33,32)</th>
<th>(36,34)</th>
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<th>(34,33)</th>
<th>(38,35)</th>
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<tbody>
<tr>
<td>$\Delta_q \times 10^4$</td>
<td>6</td>
<td>11</td>
<td>3</td>
<td>8</td>
<td>23</td>
<td>12</td>
<td>6</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>$\delta_\mu$ kHz</td>
<td>180</td>
<td>90</td>
<td>270</td>
<td>510</td>
<td>50</td>
<td>90</td>
<td>210</td>
<td>360</td>
<td>190</td>
</tr>
<tr>
<td>$\Delta_q/\Delta_\mu$</td>
<td>5.0</td>
<td>2.7</td>
<td>8.9</td>
<td>3.6</td>
<td>1.3</td>
<td>2.7</td>
<td>5.4</td>
<td>8.4</td>
<td>6.0</td>
</tr>
<tr>
<td>$\delta_{exp}$ kHz</td>
<td>36</td>
<td>33</td>
<td>30</td>
<td>142</td>
<td>38</td>
<td>33</td>
<td>39</td>
<td>43</td>
<td>32</td>
</tr>
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D. Bakalov & E.W., submitted
possible sources of line width: \( \sim 6 \text{ MHz} @ \Delta t=160 \text{ ns} \)
- collisional broadening
- Fourier limit

\[ \Delta f \approx \frac{1}{\Delta t} \]
- 160 ns: \( \Delta f \approx 6 \text{ MHz} \)
- 350 ns: \( \Delta f \approx 3 \text{ MHz} \)

MW pulse length:
- Red = 150 ns
- Blue = 350 ns
- Green = 700 ns
NEW MEASUREMENTS IN 2006: LASER SCANS

- improved laser system
- laser band width < Doppler broadening
- seeded by cw laser
- much higher frequency stability
- longer pulse length
- higher depletion efficiency
- higher signal-to-noise
- HF doublets completely separated
- no cross talk
- first test experiments
- factor ~5 improved accuracy
  (PRELIMINARY)
relaxation time constant: $\tau_{\text{exp}} \sim 660 \pm 69 \text{ ns}$

theory

$\tau_{\text{max}} \sim 325 \text{ ns}$

NEW MEASUREMENTS IN 2006: MICROWAVE SCANS

- ~ 3x narrower line width
- ~ 3x larger S/N
- ~ 5x better accuracy (PRELIMINARY)

- more systematic tests necessary (2007)
  - density dependence (very small according to theory)
  - MW power dependence
NEW MEASUREMENTS IN 2006: MICROWAVE SCANS

- ~ 3x narrower line width
- ~ 3x larger S/N
- ~ 5x better accuracy (PRELIMINARY)

For 2006 measurements:

- Microwave frequency (GHz) range: 12.86 to 12.96
- Normalized intensity range: 0.95 to 1.15
- Line width is ~3x narrower than in 2001.
- Signal-to-noise ratio is ~3x larger.
- Measurement accuracy is ~5x better.

Additional data points:

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<th>Normalized Intensity</th>
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<td>12.87</td>
<td>0.95</td>
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<td>1.10</td>
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These measurements were performed on June 16, 2007.
antiprotonic helium offers one of best CPT tests in the hadronic sector
big impact on development of 3-body bound-state QED
many results for atomic (collision) physics
further improvements expected
factor 3-9 possible over PDG for magnetic moment