In-beam measurement of the hydrogen hyperfine splitting: towards antihydrogen spectroscopy

Martin Diermaier
LEAP 2016 Kanazawa Japan
• Charge
  particle - antiparticle
• Parity
  spatial mirror
• Time reversal

• CPT symmetry
  Combined symmetry
  of charge parity and time
  reversal – same properties for
  particles and antiparticles

No violation observed to date
GS-HFS of Hydrogen / Antihydrogen offers best test of CPT on absolute scale
1s-2s 2 photon transition
\[ \lambda = 243 \text{ nm} \]
\[ \Delta \nu/\nu = 10^{-14} \]

Ground state HFS
\[ \nu = 1.42 \text{ GHz} \]
\[ \Delta \nu/\nu = 10^{-12} \]
GROUND STATE HYPERFINE SPLITTING OF ANTIIHYDROGEN

Breit-Rabi diagram

- Coupling of angular momentum of proton and electron - spin spin interaction
- Splits into
  - Singlet state
  - Triplet state
Ground State Hyperfine Splitting of Antihydrogen

Breit-Rabi diagram

- Zeeman effect: energy levels shifted in external field
- In an inhomogeneous magnetic field states can be classified into
  - $\vec{F} = \nabla(\vec{\mu} \cdot \vec{B}) \propto \text{grad}|\vec{B}|$
  - Low field seekers – move in direction lower magn. Field
  - High field seekers – move in direction higher magn. field

Achievable resolution:

$10^{-6}$ for $T < 100 \text{ K}$
scan in reasonable time:
100 Hbar/s in 1s state into $4\pi$ needed event rate 1/min
GROUND STATE HYPERFINE SPLITTING OF ANTIHYDROGEN

• two transitions possible with cavity
  • $\sigma_1$ transition

Achievable resolution:

$10^{-6}$ for $T < 100$ K
scan in reasonable time:
100 Hbar/s in 1s state into $4\pi$ needed event rate 1/min
GROUND STATE HYPERFINE SPLITTING OF ANTIHYDROGEN

• two transitions possible with cavity
  • $\sigma_1$ transition
  • $\pi_1$ transition

Achievable resolution:

$10^{-6}$ for $T < 100$ K
scan in reasonable time:
100 Hbar/s in 1s state into $4\pi$ needed event rate 1/min
• in minimal SME HFS shows CPT violation
• HFS: Splitting of triplet even in zero field
• no effect on $\sigma_1$
• 1s-2s no effect

HISTORY OF HYDROGEN GS-HFS

- 1936: Simple atomic beams ~5%
- 1946: Atomic beams plus microwave resonance $4 \times 10^{-6}$
- 1955: $4 \times 10^{-8}$
- 1969-70: Hydrogen maser $6 \times 10^{-13}$

Not possible for antimatter

Molecular Beam Resonance Setup I.I.Rabi et al., Phys. Rev. 55, 526 (1939)
ASACUSA´S APPROACH
RABI BEAM EXPERIMENT

production region

spin flip
analyser
cavity
sextupole
double cusp
detector

same for hydrogen

already reported by Y. Nagata (Monday)
HYDROGEN BEAM LINE

- Source
- Cryogenics
- Permanent sextupoles
- Tuning fork chopper
- Cavity
- Superconducting sextupole
- HFS spectrometer (same as for Hbar)
- Quadrupole mass spectrometer
- Detector
- Atomic hydrogen source
### Differences \( \text{H/\text{Hbar}} \)

<table>
<thead>
<tr>
<th></th>
<th>\text{Hbar}</th>
<th>\text{H}</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam production rate</td>
<td>low ( \sim 10 ) per min</td>
<td>very high ( 10^{19} ) per minute</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>approximately ( \sim 0.9 )</td>
<td>detector ( 10^{-8} \ldots -9 ) + solid angle</td>
</tr>
<tr>
<td></td>
<td>\textit{B. Kolbinger (Poster)}</td>
<td></td>
</tr>
<tr>
<td>detection method</td>
<td>annihilation products, tracking</td>
<td>electron impact ionization and single ion counting</td>
</tr>
<tr>
<td>background</td>
<td>cosmic radiation supressed by tracking</td>
<td>residual gas background &gt;&gt; signal</td>
</tr>
</tbody>
</table>
ATOMIC HYDROGEN SOURCE

- Plasma induced by microwaves with $f = 2.45$ GHz
- H cooled with coldhead

$H - \alpha (n: 3\rightarrow 2)$

$H - \beta (n: 4\rightarrow 2)$

$H - \gamma (n: 5\rightarrow 2)$

NIM B79, 708-710 (1993)
polarization gained with a set of perm. sextupole magnets in Halbach array
\( B_{\text{max}} = 1.3 \text{ T}, 6 \text{ cm long, 1 cm inner diameter each} \)

- high field seekers defocused
- low field seekers focused
- changing the distance to each other selects velocity

V too high
V accepted
V too low
CAVITY – SPIN FLIP RESONATOR

- $\nu = 1.42$ GHz, $\Delta \nu = \text{few MHz}$
- homogeneity over $10 \times 10 \times 10$ $\text{cm}^3$ at $\lambda = 21$ cm
- spin flip resonator – strip line design
- $Q \sim 100$
superconducting sextupole magnet
400 A with max field strength of 3.5 T

analyser of the spin state
high field seekers defocused
• QMS – crossed beam configuration – no recombination of the atoms before detection
• single particle detection with channeltron
• tuning fork chopper – modulation of the beam, velocity cross checks
SEXTUPOLE FOCUSING - DEFOCUSING

- when the sextupole magnet is turned off a beam with low intensity can be seen
- sexutpole turned on beam intensity increases due to focusing
- TOF (phase) shows that slower part of the beam is focused on the detector
CAVITY – RESONANCE SHAPE

- W-shape of resonance curves: consequence of MW field in cavity
- Fit routine derived from numerical calculation of the Bloch equations for strip line cavity
• \( \sigma_1 \) transition
• get \( \nu_c, \nu, \sigma_v, B_{osc} \)
• measure \( \sigma_1 \) transitions (\( \nu_c \)) at different magn. fields

\[
\begin{align*}
F(\nu; B_{osc}, \nu_c, \nu, \sigma_v, A, b) \\
\chi^2/d.o.f. & = 32.9/34
\end{align*}
\]

Fit parameters | results
--- | ---
Microwave amplitude (mG) | 5.8 \pm 0.4
\( \nu_c \) (Hz) | 1 420 417 482 \pm 30
Velocity (m/s) | 839 \pm 6
\( \sigma_v \) (m/s) | 130 \pm 7
\chi^2/d.o.f. | 32.9/34

shift of resonances in magn. field
(a) 100 mA (b) 300 mA (c) 500 mA
ZERO FIELD EXTRAPOLATION

- Best beam value up to date

\[ \nu = 1420.40573(5) \text{ MHz} \]

\[ \frac{\Delta \nu}{\nu} = 3.5 \times 10^{-8} \]

\[ P. \text{ Kusch, Phys. Rev. 100, 4, (1955)} \]

- One extrapolation – this work
Other method to obtain zero field HFS

- Up to now $\sigma_1$ measured at different magn. fields and then zero field extrapolated with Breit-Rabi formula
- Measure $\pi_1 + \sigma_1$
- $\pi_1$ linear dependence on magn. Field
- $\sigma_1$ second order dependence
- Measurements depend on angle between oscillating and static magnetic field
  - for $\sigma_1$ transition B-field parallel
  - for $\pi_1$ transition B-field orthogonal

Magnetic field from Rabi eq. + meas.:

$\sigma_1$: $B = 34.9 \pm 5.8 \, \mu T$
$\pi_1$: $B = 33.78 \pm 0.01 \, \mu T$
Measured: $B = 37 \pm 4.2 \, \mu T$

Extrapolation:
$v_0 = 1\,420\,405\,776(88) \, Hz \rightarrow 6 \times 10^{-8}$
PRECISION LIMITS

- **Rabi method:**
  line width $\sim 1/T \propto v$ in RF field
  $H_{bar} \rightarrow \Delta \nu/\nu \sim 10^{-7}$

- **Ramsey – separated oscillatory fields:**
  line width reduced by $D/L$

- **Atomic fountain - trapped Hbar**
  - needs trapping and laser cooling outside of formation magnet
  - slow beam & capture in measurement trap
  - **Ramsey method:**
    with $d=1m \rightarrow \Delta \nu \sim 3$ Hz,
    $\Delta \nu/\nu \sim 2 \times 10^{-9}$

SUMMARY & CONCLUSION

- cold atomic hydrogen beam line has been developed and constructed
- showed that the sextupole magnet works and focuses atomic hydrogen
- spin flip resonator has been characterised
- we could observe $\sigma_1$ and $\pi_1$ transitions for atomic hydrogen
• measurement of $\pi_1$ transitions with modified H-setup → need more homogeneous B field for Zeeman splitting
• different Helmholtz coils (poster M.C. Simon)
• $\pi_1$ → sidereal variations: first measurements of many SME parameters (direction dependent)


• simulations: $10^{-7}$ precision with 1000 Hbar


• looking forward to measure zero field GS-HFS with antihydrogen
Thank you for your attention