In-beam HFS spectroscopy

- In-beam measurement of the ground-state hyperfine structure of antihydrogen to 1 ppm during run 3
  - Improve intensity & ground-state fraction of polarized slow (~50 K) $\bar{H}$ beam created by three-body recombination
  - Develop Ramsey method with $H$ and apply it to $\bar{H}$ during run 4, goal: factor 20

- 1 ppm precision gives insight into antiproton structure
- $\pi$ transition is sensitive to SME
- Method was verified with $H$ beam to ppb precision

Mixing studies with matter (2020+)

Positron Trap

B=0.6T

22Na

e+/−
e+/−

Cusp Trap

Field-ionizer

MCP
DLD40
Three-body mixing

• Rate is sensitive to $e^+$ temperature and density $\rho$:
  • cool $e^+$ to $T < 20$ K
• Simulations: rate, ground-state fraction increase with lower $T$, higher $\rho$

FIG. 6. Dependence of ground-state antihydrogen atoms on positron temperature (a) and density (b) for various positron density and temperature values (respectively) after 1 ms of flight. The $\alpha n_e^2 T_e^{-4.5}$ (solid line) and $\alpha n_e^{1.3} T^{-2.0}$ (dashed line) scaling behaviors are indicated for reference.

Possible deexcitation schemes

• Additional cold e− plasma, deexcitation by collisions

• Combination of THz radiation, microwave and laser deexcitation

https://arxiv.org/abs/1912.03163
Slow extraction plans

• Permanent installation of SE beam line possible
• Continuation of fragmentation studies (benchmark for MC codes)
• New ideas & proposals, also from other collaborations
  • Pontecorvo reaction
  • $\bar{p}$ annihilation cross sections
• To be explored
Spares
The H detector analysis of 2016 data

- Direct injection scheme
- 2D BGO & track fitting
- Machine learning optimization
  - Cosmics rejection 98.4%
  - False positive rate: 0.0077(15) s\(^{-1}\)
  - \(\bar{p}\) efficiency 80(1)%

\(n<14\) rate 0.16 → 0.395(96)/cycle
P-value significance 4.5σ → 6.8σ
17 evts/5 shifts: 4σ poisson
\(\tau(n=14 \rightarrow n=1) \sim 50 \mu s\)

Needed: 2000 \(\bar{H}(1S)/B_{\text{ext}}\) for 1 ppm

B. Kolbinger, Ph.D. thesis, 2019
Ground-State Hyperfine Splitting of H/$\bar{H}$

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

Hydrogen HFS and QED: finite size effects

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: deviation from Fermi contact term</td>
<td>$-92.77(1)$ ppm</td>
</tr>
<tr>
<td>finite electric &amp; magnetic radius (Zemach corrections):</td>
<td>$-41.43(44)$ ppm</td>
</tr>
<tr>
<td>polarizability of p/$\bar{p}$</td>
<td>$+1.88(64)$ ppm</td>
</tr>
<tr>
<td>remaining deviation theory-experiment:</td>
<td>$+0.86(78)$ ppm</td>
</tr>
</tbody>
</table>

C. E. Carlson et al., *PRA* 78, 022517 (2008)

Finite size effect of proton/antiproton important below $\sim 10$ ppm