Experimental Studies of Antiprotonic Helium

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- Discovery of antiprotonic helium “atomcules”
- pbar-He “atomcules” at LEAR - from curiosity-oriented to fundamental research
  - lifetime measurements in various phases of helium
  - laser spectroscopy of pbar levels
    - confirmation of structure
    - step-by-step improvement in theoretical and experimental precision
  - first observation of “Hyperfinestructure”
- pbar-He “atomcules” at CERN-AD
  - short description of AD machine
  - higher precision of pbar energy levels
  - direct determination of “hyperfine structure” by 2-laser microwave triple resonance experiment
PS205 collaboration (1991-1996): pbar-He atomcules @ LEAR

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Discovery of antiprotons (KEK, 1991)

- Prompt: \( \bar{p} \rightarrow \pi^+ \pi^- \rightarrow e^+ e^- \) in liquid helium
- Delayed annihilation of \( \bar{p} \) in liquid helium, KEK 1991
- Running time: 2 months
- Average lifetime: \( \approx 3 \mu s \)
- Trapping fraction: \( \approx 3 \% \)
- Protons: \( p = 600 \text{ MeV/c} \)
- Dublet momentum spread: \( \Delta p/p = 3 \% \)
- 28 \( \bar{p} \) per 4 s
- 10^4 more \( \pi^- , K^- \)
- Vertex reconstruction
- Nal calorimeter

\[ \begin{align*}
\text{counts / 200 ns} &= 10^5 \\
\text{Annihilation Time (\( \mu s \))} &\text{ delayed annihilation of } \bar{p} \\
\text{delayed annihilation of } \bar{p} &\text{ in liquid helium, KEK 1991}
\end{align*} \]
Structure and decay of pbar-He "atomcule"

- **Capture**
- Characteristics of both atom and molecule

Energy (a.u.)

- Neutral pHe\(^+\) → Neutral pHe\(^+\)
- Ionized pHe\(^{++}\) → Ionized pHe\(^{++}\)

- Radiative transitions
- Auger decay
- Nuclear absorption & Annihilation
- Stark mixing

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

\( n_0 = \sqrt{\frac{M^*}{m_e}} \approx 38 \)
Lifetime measurement in various phases of helium

Delayed Annihilation Time Spectra (DATS) of pbar stopped in dense helium gas, liquid, and solid helium and in helium gas with admixtures of noble gases and molecular gases

interesting atomic physics aspects:
- average lifetime changes little over huge range of density
- -> insensitivity to collisions with surrounding helium atoms
- insensitivity to collisions with noble gases
- large effect of admixture of molecular gases

(a) $^4\text{He}$ gas 4.5 K 405 mbar $T_{av}(1.0 \text{ s}) = 4.02 \pm 0.01$ s

(b) $^4\text{He}$ liquid $T_{av}(1.0 \text{ s}) = 2.89 \pm 0.03$ s

(c) $^4\text{He}$ solid $T_{av}(1.0 \text{ s}) = 2.05 \pm 0.03$ s

(d) $^3\text{He}$ gas 5.5 K 406 mbar $T_{av}(1.0 \text{ s}) = 3.42 \pm 0.01$ s

(e) $^4\text{He} + 10\% \text{Ne}$ RT 5 bar $T_{av}(1.0 \text{ s}) = 3.01 \pm 0.13$ s

(f) $^4\text{He} + 250 \text{ppm H}_2$ RT 3 bar $T_{av}(0.1 \text{ s}) = 0.44 \pm 0.02$ s
Principle of laser spectroscopy: forced annihilation

short-lived ($\tau \sim 10$ ns)

metastable ($\tau \sim 1$ µs)

first observed resonance (1993) $\lambda = 597.259$ nm
Detector setup for PS205

Setup of Counters

10^4 pbar/s
\( \Delta p/p \sim 10^{-4} \)

Beam counters

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Laser system for PS205

optimized for searching -> large bandwidth
- 2 commercial Excimer pumped dye laser systems
- trigger: one metastable pbar-He atomcule was formed!
- 10 mJ/ pulse, 30 ns length, 1.2 - 10 GHz BW
- typical trigger rate: 200 - 300 Hz
- delay trigger - light output: ~ 1.5 μs
- initial searching time: 5 days per transition

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Observed resonances

$\bar{p}^4\text{He}^+$

1996 new resonances found by HAIR method

Energy-level diagram

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Comparision to recent variational calculation by V.I. Korobov

more recently also calculations by Kino & Kamimura
Elander et al.

3-body calculation!

(\Delta \lambda_{\text{th}} - \Delta \lambda_{\text{exp}}) / \Delta \lambda_{\text{exp}} \ (\text{ppm})

Δv=0

“favoured”

Δv=2

“unfavoured”

Korobov (1995)
non-relativistic

Korobov (1996)
relativistic

data taken at 6 K, 600 mbar
error bars = experimental errors

difference experiment - theory : ≤ 10 ppm
BUT: density shift observed

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"Hyperfine" structure of pbar-He atomcules

- possible interactions of magnetic moments:
  - electron: $\vec{\mu}_e = g \mu_B \vec{s}_e$
  - pbar: $\vec{\mu}_p = [g_s(\vec{p}) \vec{s}_p + g_l(\vec{p}) \vec{l}] \mu_N$
  - "Finestructure": $\vec{l}_p \cdot \vec{s}_p$
    - magnitude $-10^{-7}$ eV (25 MHz) for l=37
    - negligible at current exp. precision
- "Hyperfinestructure": $\vec{\mu}_e \cdot \vec{\mu}_p$
  - sizeable because of large l of pbar.
- Level scheme:

\[ \Delta \nu = 10 \ldots 15 \text{ GHz} \]
\[ \Delta \nu = 50 \ldots 150 \text{ MHz} \]
\[ \vec{s}_p \text{ interaction with other moments "SHFS"} \]
"Hyperfine" splitting in a laser transition

- laser transitions proceed along ΔF=0, i.e. without changing the electron spin direction:

\[ F_- = l - 1/2 \]
\[ F_+ = l + 1/2 \]
\[ F_-' = l' - 1/2 \]
\[ F_+ = l' + 1/2 \]

unfavoured transition

First observation in an "unfavoured" transition

\[(n,l)=(37,35)\rightarrow(38,34)\]

laser BW: 1.2 GHz (quadruplet not resolved, only doublet)
remain: 0.4 GHz ~Dopplerwidth

theoretical prediction: 1.77 GHz (Korobov, Bakalov
PR A 57, 1662 (1998))

\[ \frac{\text{Peak to Total Ratio (\%)} \text{ vs } \lambda \text{ - 726 nm}} {E. Widmann et al, Phys. Lett. B404, 15 (1997)} \]

\[ \Delta = 2.98 \pm 0.09 \text{ pm} = 1.70 \pm 0.05 \text{ GHz} \]
AD (Antiproton Decelerator) @ CERN: an "all-in-one" machine

AD Antiproton Complex at CERN

- 5 x 10^{13} protons on prod. target
- Cooling and deceleration: (3.5 -> 2.0 -> 0.3 -> 0.1 GeV/c)
- fast extraction of 5x10^7 pbar, 0.2 μs pulse width
- Δp/p ~ 10^{-3}
- Cycle time: 1 pulse per minute
- cost ~ 7 MCHF (Japan, Germany, Italy)
- physics startup May/June 1999
Pulsed beam (ADATS) @ LEAR

10^7 to 10^9 pbar/pulse
100-200 ns pulse length

- suppression of prompt peak (97%) necessary
- pulsed PMT developed by HAMAMATSU
- ADATS same quality as DATS
- laser trigger can be applied at earlier times
2 Laser-microwave triple resonance exp. planned @ AD

(37,35): \( \nu_{HF} = 12.91 \text{ GHz} \)

\( \nu_{SHF^+} = 161 \text{ MHz} \)

\( \nu_{SHF^-} = 133 \text{ MHz} \)

**Annihilation time (\( \mu \text{s} \))**

**Resonance intensity (arb. units)**

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Details of SHFS splitting

Effective Hamiltonian:

\[ H_{\text{eff}} = E_1(L, S_e) + E_2(L, S_p) + E_3(s_e, s_p) \]
\[ + E_4 \{ 2L(L + 1)(s_e, s_p) - 3[(L, s_e)(L, s_p) + (L, s_p)(L, s_e)] \} \]

Spin-spin tensor interaction

Cancellation effect of spin-spin scalar and tensor interaction

-> Level order determined by spin-orbit interaction pbar!
test of selective depopulation of doublet @ LEAR

strong "crosstalk" between two sub-lines of doublet

\[
\frac{0}{(0)} = 0.8
\]

difference in depopulation efficiency visible for \( A^- A \) vs \( A^- B \) sequence up to \( t = 350 \text{ ns} \)

\[
\frac{0}{(0)} = 0.45
\]
Microwave system for pbar-He HFS measurement

- laser transition from (37,35)→(38,34)
- splittings of (37,35) state:
  - $\nu_{HF} = 12.91$ GHz (theoretical precision $10^{-4}$)
  - $\nu_{SHF^+} = 161$ MHz
  - $\nu_{SHF^-} = 133$ MHz: difference = 28 MHz
- Experimental setup
  - cavity for 13 GHz at < 10 K to reduce doppler broad.
  - low Q (~100) to avoid mechanical tuning
  - tuning via synthesizer and stub tuner
  - high-power pulsed TWTA amplifier (2 kW) to create magnetic filed up to 30 Gauss
- schematic circuit
Prospects of HFS/SHFS measurement

- significance
  - HFS: test of 3-body theory incl QED corrections
  - achievable resolution:
    - lifetime ~μs: natural linewidth MHz
    - split 1/100: 10 kHz/13 GHz < 1 ppm
  - relaxation mechanisms?
    - in test @ LEAR, asymmetric depletion by laser could be observed only up to \( t_2-t_1 = 350 \) ns
  - SHFS: antiproton magnetic monent
    - from 2-laser microwave experiment the difference \( \nu_{\text{SHF}^+} - \nu_{\text{SHF}^-} \) can be determined
    - direct determination would require additional RF field of ~100 MHz
    - current precision \( \mu_{\text{pbar}} \): \( 3 \times 10^{-3} \)

- experimental difficulties to be solved
  - separation of doublet by laser vs. depopulation efficiency
  - measurement of resonance intensity (peak-to-total) to a few %
Summary

- AD (successor of LEAR) will be built at CERN, experimental budget obtained in Japan
  -> program can continue
- achievements at LEAR:
  - first experimental proof of initial capture of exotic particle into \( n \sim \sqrt{M/m} \)
  - experimental accuracy for transition energies has reached a similar level of precision (0.5 ppm) as the best measurements of a 3-body system (He triplet FS)
  - theory is still 2-3 ppm off, higher order QED corrections need to be calculated
  - “hyperfine structure” observed experimentally with low precision (%)
- plans for the AD
  - higher resolution laser spectroscopy
    - high-precision studies of the antiproton
    - higher order QED corrections for energy levels
  - 2 laser-microwave triple resonance experiment
    - unusual HFS structure do to large orbital angular momentum of pbar
    - challenge to theoretical calculations
    - potential to determine pbar magnetic moment more accurately
  - continuation of atomic physics aspects (density dependence of lifetimes and energy levels, interaction with molecular impurities, etc.)
- antiprotonic helium still has a bright future at the AD