High precision spectroscopy of antiprotonic helium atomcules - Hyperfine structure

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- Antiprotonic helium - short introduction
- „Hyperfine“ structure of pbar-He⁺
- Observation in laser transition at LEAR
- Planned 2-laser microwave triple resonance experiment at CERN-AD
Atomic Spectroscopy And Collisions Using Slow Antiprotons

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Structure and decay of pbar-He "atomcule"

Neutral pHe \_ +

Energy (a.u.)

\[ E = \frac{p^2}{2m} \]

Radiative transitions

Auger decay

Stark mixing

Nuclear absorption & Annihilation

Ionized pHe\_ ++

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

\[ n_0 = \sqrt{\frac{M^*}{m_e}} \sim 38 \]

Characteristics of both atom and molecule

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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: \( \vec{\mu}_p = \left[ g_s (\vec{p}) \vec{s}_p + g_l (\vec{p}) \vec{l} \right] \mu_N \)
  - "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:

\[
\begin{align*}
F_+ &= 1 + 1/2 & J &= 1 + 1 & \Delta \nu &= 50..150 \text{ MHz} \\
\quad & & J &= 1 & \Delta \nu &= 10..15 \text{ GHz} \\
F_- &= 1 - 1/2 & & J &= 1 - 1 \\

\vec{j} &= \vec{l}_p + \vec{s}_e & \vec{j} &= \vec{j} + \vec{s}_p = \vec{l}_p + \vec{s}_e + \vec{s}_p
\end{align*}
\]
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 scalar interaction

\[ E_1(L \cdot s_e) \]
\[ \text{sum} \]
\[ E_2(L \cdot s_p) \]
\[ E_3(s_p \cdot s_e) \]
\[ E_4(\text{tensor}) \]

spin-spin tensor interaction

\[ F = L + \frac{1}{2} \]
\[ \text{F = L} \]
\[ \text{J = L} \]
\[ \text{J = L + 1} \]
\[ \text{J = L} \]

Cancellation effect of spin-spin scalar and tensor interaction

\[ \rightarrow \text{level order determined by spin-orbit interaction pbar!} \]
“Hyperfine” splitting in a laser transition

- Laser transitions proceed along $\Delta F=0$, i.e. without changing the electron spin direction:

  $F_+ = l + \frac{1}{2}$

  $F_+ ' = l' + \frac{1}{2}$

  $F_- = l - \frac{1}{2}$

  $F_- ' = l' - \frac{1}{2}$

  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 ~ Doppler width

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


Peak to Total Ratio (%)

$\Delta = 2.98 \pm 0.09 \ pm$

$\Delta = 1.70 \pm 0.05 \ GHz$
2 Laser-microwave triple resonance exp. planned @ AD

(37,35): $\nu_{HF} = 12.91$ GHz
$\nu_{SHF^+} = 161$ MHz
$\nu_{SHF^-} = 133$ MHz

Laser pulse time structure

frequency domain

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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
Microwave system for pbar-He HFS measurement

- laser transition from (37,35)→(38,34)
- splittings of (37,35) state:
  - $\nu_{HF} = 12.91 \text{ GHz (theoretical precision } 10^{-4})$
  - $\nu_{SHF^+} = 161 \text{ MHz}$
  - $\nu_{SHF^-} = 133 \text{ MHz: difference } = 28 \text{ MHz}$

- 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
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
Prospects of HFS/SHFS measurement

- **significance**
  - HFS: test of 3-body theory incl QED corrections
  - achievable resolution:
    - lifetime ~\(\mu\)s: natural linewidth MHz
    - split 1/100: 10 kHz/13 GHz < 1 ppm
  - relaxation mechanisms?
    - in test @ LEAR, assymmetric depletion by laser could be observed only up to \(t_2-t_1 = 350\) ns
  - SHFS: antiproton magnetic moment
    - 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 \(\mu_{p\bar{a}r} : 3 \times 10^{-3}\)

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