Hydrogen and Antihydrogen spectra in presence of external fields

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Motivation

Static electric field

- 2s-2p mixing:
  

- Rydberg states mixing.

- Level widths: \( \Gamma_{ns} = \sum_{k=1}^{n-1} W_{ns \gamma k} \) (to be published).

Magnetic field

- 21 cm emissin/absorption line
  

Conclusions


Motivation

- Experiments of highest order of accuracy for the hydrogen atom two-photon transitions 2s-1s and 3s-1s, 3d-1s

- Recent experimental successes on the synthesis of antihydrogen atoms
  The ALPHA Collaboration, Nature Physics 7, 558-564 (2011). \( \sim 1000 \text{ s of anti-} H \text{ atom} \)

- Signals for CPT and Lorentz violation may arise in hydrogen and antihydrogen spectroscopy


- CP invariance violation to explain baryon asymmetry in the universe
Static electric field: $2s-2p$ mixing


\[ |2s m_s\rangle = |2s m_s\rangle + \eta \sum_{m_p} \langle 2p m_p | e D r | 2s m_s \rangle | 2p m_p \rangle, \quad \eta = (\Delta E_L + i \Gamma_{2p}/2)^{-1}. \quad (1) \]

Then in Pauli approximation:

\[ U_{A' A}^P(k, e) = \left( (e \hat{p} + ie [k \times s]) e^{-ikr} \right)_{A' A}, \quad (2) \]

\[ W_{A' A}^{(1\gamma)} = \frac{e^2 \omega_{AA'}}{2\pi} \sum_{e} \int d{n_k} \left| U_{A' A}^P(k, e) \right|^2, \quad ns \rightarrow 1s + 1\gamma (M1). \quad (3) \]

In the presence of an external electric field $\bar{e} s \rightarrow 1s + 1\gamma (E1)$ decay channel:

\[ U_{2s m_s, 1s m'_s}^P(k, e) = U_{2s m_s, 1s m'_s}^P(k, e) + \eta \sum_{m_p} \langle 2s m_s | e D r | 2p m_p \rangle U_{2p m_p, 1s m'_s}^P(k, e). \quad (4) \]

\[ dW_{2s 1s}^{(1\gamma)}(n_k) = \frac{3}{8\pi} dW_{2s 1s}^{(1\gamma)}(n_k) \left[ 1 + e D(n_D n_k) \frac{\Gamma_{2p}}{W \Delta^2} + \frac{e^2 D^2}{W^2 \Delta^2} \right] d{n_k}. \quad (5) \]

\[ \Delta = \sqrt{\Delta E_L^2 + \frac{1}{4} \Gamma_{2p}^2}, \quad w = \sqrt{\frac{W_{2s 1s}^{(1\gamma)}}{W_{2p 1s}^{(1\gamma)}}}. \quad (6) \]
**Static electric field: 2s-2p mixing**

\[
dW_{2s1s} = W_0 \left[ 1 \mp \beta(D)n_D n_k \right], \quad W_0 = \frac{3}{8\pi} dW_{2s1s}^{(1\gamma)} \left( 1 + \frac{e^2 D^2}{(w\Delta)^2} \right),
\]

(7)

\[
\beta(D) = \frac{|e|D\Gamma_{2p} w}{(w\Delta)^2 + e^2 D^2}.
\]

(8)

The maximum value of \( \beta(D) \) is

\[
D_{\text{max}} = \frac{w\Delta}{|e|}, \quad \beta_{\text{max}} = \frac{\Gamma_{2p}}{2\Delta} \approx \frac{\Gamma_{2p}^2}{2\Delta E_L} \approx \frac{1}{20}.
\]

(9)

The relative difference for the \( H \) and \( \bar{H} \) atoms at \( D_{\text{max}} \)

\[
\frac{dW_{2s1s}^{(1\gamma)}(H)}{dW_{2s1s}^{(1\gamma)}} - \frac{dW_{2s1s}^{(1\gamma)}(\bar{H})}{dW_{2s1s}^{(1\gamma)}} = \frac{W_0(D_{\text{max}})2\beta(D_{\text{max}})}{\frac{3}{8\pi} dW_{2s1s}^{(1\gamma)} n_D n_k} \approx \frac{1}{5} n_D n_k.
\]

(10)

The formal T-noninvariance of the factor \( n_D n_k \) (\( n_k \) and \( n_D \) are T-odd and T-even vectors, respectively) is compensated by the dependence on \( \Gamma_{2p} \): Ya. B. Zeldovich, Sov. Phys. JETP 12, 1030 (1961) (Engl. Transl.).

However, theoretical analysis of the influence of an external electric field on the Rydberg states is also required: The ALPHA Collaboration, Nature Physics 7, 558-564 (2011).
Static electric field: Rydberg states mixing

The same procedure for the $ns$ states in hydrogen

$$|\overline{nsm_s}\rangle = |nsm_s\rangle + \eta_n \sum_{m_p} \langle npm_p|eDr|nsm_s\rangle|npm_p\rangle, \quad (11)$$

$$\eta_n = (\Delta E_L^{(n)} + i\Gamma_{np}/2)^{-1}, \quad \Delta E_L^{(n)}$$ is the Lamb shift (fine structure splitting) of the $ns$th state, $\Gamma_{np}$ is the level width.

$$U^P_{nsm_s, \overline{kpm'_s}(k, e)} = U^P_{nsm_s, ksm'_s(k, e)} + \eta_k \sum_{m_p} \langle kpm_p|eDr|ksm'_s\rangle U^P_{nsm_s, kpm_p(k, e)}. \quad (12)$$

$$dw^{(1\gamma)}_{nsm_s}(n_k) = \frac{3}{8\pi} dw^{(1\gamma)}_{nsm_s}(n_k) \left[ 1 - (-1)^{1/2+j_p} eD(n_Dn_k) \frac{n\sqrt{n^2-1}}{2\sqrt{3} \Gamma_{np}} \right] \frac{\Gamma_{np}}{w_1 \Delta_1^2} \quad (13)$$

$$\Delta_1 = \sqrt{\left(\Delta E_L^{(n)}\right)^2 + \frac{1}{4} \Gamma_{np}^2}, \quad \Delta_2 = \sqrt{\left(\Delta E_L^{(k)}\right)^2 + \frac{1}{4} \Gamma_{kp}^2}, \quad w_1 = \sqrt{\frac{w^{(1\gamma)}_{nsm_s}}{w^{(1\gamma)}_{nsm_s}}}, \quad w_2 = \sqrt{\frac{w^{(1\gamma)}_{nsm_s}}{w^{(1\gamma)}_{nsm_s}}} \quad (14)$$
Static electric field: Rydberg states mixing

Therefore,

\[ dW^{(1γ)}_{ns ks} = \frac{3}{8\pi} dW^{(1γ)}_{ns ks} \left( 1 + e^2 D^2 a^2 \right) \left[ 1 \pm (-1)\frac{3}{2} + jp \frac{eb_{(nDn_k)}}{1 + e^2 D^2 a^2} \right], \]  

(15)

where \( a \) and \( b \) are defined as

\[ a^2 = \frac{n^2(n^2 - 1)}{12w_1^2 \Delta_1^2} + \frac{k^2(k^2 - 1)}{36w_2^2 \Delta_2^2}, \quad b = \frac{n\sqrt{n^2 - 1}}{2\sqrt{3}} \frac{\Gamma_{np}}{w_1 \Delta_1^2} + \frac{k\sqrt{k^2 - 1}}{6} \frac{\Gamma_{kp}}{w_2 \Delta_2^2}. \]  

(16)

Then the relative difference for the \( H \) and \( \bar{H} \) atoms at \( eD_{\text{max}} = 1/a \)

\[ \delta(D_{\text{max}}) = \frac{dW^{(1γ)}_{ns ks} (H) - dW^{(1γ)}_{ns ks} (\bar{H})}{\frac{3}{8\pi} W^{(1γ)}_{ns ks} (1 + e^2 D^2 a)} = (-1)^\frac{3}{2} + jp (nDn_k) \frac{b}{a} \]  

(17)

with the account for \( \Gamma_{np} \ll \Delta E_L^{(n)} \ll \Delta E_f^{(n)}, \ \Delta_1(jp = 1/2) \ll \Delta_1(jp = 3/2) \).
Numerical results for the electric field magnitude $D_{\text{max}}$ and 500 V/m. The last magnitude of the electric field is associated with the experimental value.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$k$</th>
<th>$D_{\text{max}}^0$, V/m</th>
<th>$\delta(D_{\text{max}})$ V/m</th>
<th>$\delta(D)$ at $D = 500$ V/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>0.005</td>
<td>0.094</td>
<td>1.97 · 10^{-6}</td>
</tr>
<tr>
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<td>1</td>
<td>0.0009</td>
<td>0.087</td>
<td>3.14 · 10^{-7}</td>
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<tr>
<td>3</td>
<td>2</td>
<td>0.0001</td>
<td>0.094</td>
<td>3.77 · 10^{-8}</td>
</tr>
<tr>
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<td>1</td>
<td>0.0002</td>
<td>0.097</td>
<td>7.94 · 10^{-8}</td>
</tr>
<tr>
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<td>2</td>
<td>0.00003</td>
<td>0.098</td>
<td>1.18 · 10^{-7}</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>5.9 · 10^{-6}</td>
<td>0.11</td>
<td>2.60 · 10^{-9}</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>1.6 · 10^{-11}</td>
<td>0.099</td>
<td>6.33 · 10^{-15}</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>4.2 · 10^{-11}</td>
<td>0.099</td>
<td>1.65 · 10^{-14}</td>
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<tr>
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<td>3</td>
<td>7.2 · 10^{-11}</td>
<td>0.099</td>
<td>2.85 · 10^{-14}</td>
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</table>

The linear in the field term is proportional to the electron (positron) charge and, therefore, has the opposite sign for the $H$ and $\bar{H}$ atoms. Thus, the linear in the field summand produces the difference for the differential (depending on the photon emission directions, here $(nDn_k) = 1$) transition probabilities. The linear dependence vanishes in the total decay rate. However, the measurements of the differential quantities are closer to the experimental situation where the photon emission is detected in certain angles.
Static electric field: Level widths

The total transition probability of the partial decay channel $\overline{n}s \rightarrow \overline{k}s + 1\gamma$

\[ W^{(1\gamma)}_{\overline{n}s \overline{k}s} = W^{(1\gamma)}_{n s k s} + \frac{e^2 D^2 n^2 (n^2 - 1)}{\Delta_1^2} W^{(1\gamma)}_{n p k s} + \frac{e^2 D^2 k^2 (k^2 - 1)}{36 \Delta_2^2} W^{(1\gamma)}_{n s k p} \]  

(18)

\[ \Gamma_{\text{tot}} = \Gamma_{n s} + \Gamma_{\overline{n}s} = \sum_{k=1}^{n-1} W^{(1\gamma)}_{n s k p} + \sum_{k=1}^{n-1} W^{(1\gamma)}_{\overline{n}s k s}, \]  

(19)

\( \Gamma_{n s} \) is the natural width and \( \Gamma_{\overline{n}s} \) - the additional decay channels.

\( \Gamma_{\overline{n}s} \) as a function of \( n \) can be defined with \( W^{(1\gamma)}_{n p k s} \sim \frac{W^{(1\gamma)}_{2p 1s}}{k^3 n^3}, \ W^{(1\gamma)}_{n s k p} \sim \frac{W^{(1\gamma)}_{3s 2p}}{k^3 n^3}, \ \Delta E^{(n)}_{L(f)} \sim \frac{\Delta E^{(2)}_{L(f)}}{n^3}. \)

\[ \Gamma_{\overline{n}s} \sim \sum_{k=1}^{n-1} e^2 D^2 \frac{n^2 (n^2 - 1)}{12k^3} + \sum_{k=1}^{n-1} e^2 D^2 \frac{k^2 (k^2 - 1)}{36n^3}. \]  

(20)

Application of Eq. (11) should obey

\[ \left| \frac{\langle np | eDr | ns \rangle}{\Delta E^{(n)}_{L(f)} + i\Gamma_{np}/2} \right| < 1 \Rightarrow D^{(n)}_c \sim \frac{1}{n^5}. \]  

(21)

Static electric field: Level widths

Numerical results: the field strength $D_c^{(n)}$.

Table 2: the contribution of quadratic in the field terms Eq. (18) depending on the value of principal quantum numbers $n$ and $k$; $W_{ns}^{(1γ)}$, $W_{np}^{(1γ)}$, $W_{nk}^{(1γ)}$, $W_{np}^{(1})$, and $W_{ns}^{(1})$ in $s^{-1}$; the Lamb shift $ΔE_L^{(n)}$ in MHz.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$k$</th>
<th>$W_{ns}^{(1γ)}$</th>
<th>$W_{np}^{(1γ)}$</th>
<th>$W_{nk}^{(1γ)}$</th>
<th>$ΔE_L^{(n)}$</th>
<th>$Γ_{np}$</th>
<th>$Γ_{ns}$</th>
<th>$W_n$</th>
<th>$W_k$</th>
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</table>

The field strength is defined as $D_c \sim 475 \cdot 2^5 / n^5 \ V/cm$, where 475 $V/cm$ corresponds to the absolute mixing of 2s and 2p states. For the $n = 100$ $D_c \approx 3.8 \cdot 10^{-7}$ $V/cm$. The values of the one-photon decay rates:

**Static electric field: Level width \( n = 55 \)**

**Numerical results:** the field strength \( D_c = 3.02 \times 10^{-5} \text{ V/cm} \).

The induced transition probability as a function of \( k \). It is shown that mixing of the lower state becomes significant for the transitions between nearest atomic levels. In Table 3 notations are the same as in Table 2.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( k )</th>
<th>( W^{(1\gamma)}_{ns , ks} )</th>
<th>( W^{(1\gamma)}_{ns , kp} )</th>
<th>( W^{(1\gamma)}_{np , ks} )</th>
<th>( W_1 )</th>
<th>( W_2 )</th>
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<td>2.37202 ([-10])</td>
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<td>2.51584[4]</td>
<td>1.1044[4]</td>
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<tr>
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<td>2</td>
<td>1.21907 ([-12])</td>
<td>921.77</td>
<td>3.68593[3]</td>
<td>1.6173[3]</td>
<td>4.091[-13]</td>
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</table>

\( \Gamma_{55p} \approx 3.2 \times 10^4 \text{ s}^{-1} \), \( \Gamma_{55s} \approx 6.5 \times 10^3 \) and \( \Delta E_L^{(n=55)} \approx 50.9 \text{ kHz} \). Then \( \Gamma_{55s} \approx 1.4 \times 10^4 \text{ s}^{-1} \).

\[
\Gamma_{ns} \approx \sum_{k=1}^{n-1} \frac{e^2 D^2}{\Delta_1^2} \frac{n^2(n^2 - 1)}{12} W_{np \, ks}^{(1\gamma)} + \sum_{k=1}^{n-1} \frac{e^2 D^2}{\Delta_2^2} \frac{k^2(k^2 - 1)}{36} W_{ns \, kp}^{(1\gamma)}.
\]

Second term becomes important for the transitions between neighboring states.

The fields of the order of \( D_c^{(n)} \) can be attributed to the casual fields, the strict control of fields is required.
Circular polarizations of $H$ and $\tilde{H}$ atoms.
L. Labzowsky and V. Sharipov, Phys. Rev. A 71, 012501 (2005),

\[
\langle n F M_F | (\vec{e}[\vec{k} \times \vec{\mu}]) | n F' M_{F'} \rangle = \sum_q (-1)^q [\vec{e} \times \vec{k}]_{-q} \langle n F M_F | \mu_q | n F' M_{F'} \rangle.
\]

Associating the photon emission direction with the $z$-axis

\[
\langle n 1 M_F | (\vec{e}[\vec{k} \times \vec{\mu}]) | n 0 0 \rangle = \left( -i \sqrt{\frac{2}{3}} \right) (-1)^{M_F} \sum_r C_{1r 10}^{1-M_F} e_r k_0 \langle n \frac{1}{2} || \mu^1 || n \frac{1}{2} \rangle,
\]

\[
\vec{\mu} = \mu_0(\vec{l} + 2\vec{s}), \quad \mu_0 = \frac{e\hbar}{2c m_e}.
\]

$C_{1r 10}^{1-M_F} \neq 0$ for $r = -M_F$. Thus the circular polarization with $r = \pm 1$ (clockwise and anticlockwise) $\rightarrow M_F = \mp 1$ lower and upper hyperfine sublevels in hydrogen, respectively.

The Zeeman energy splitting is defined as $\mu_0 g M_F H$, $H$ is the magnetic field $\Rightarrow$ opposite signs at the fixed field direction.
Linear polarizations of $H$ and $\bar{H}$ atoms: Faraday rotation.

Faraday rotation: the rotation of the plane of linear polarization around the direction of the light propagation.

The linear polarization corresponds to the transition $n\,1\,0 \rightarrow n\,0\,0\,(M_F = 0)$.

$$\langle n\,1\,0|(\vec{e}[\vec{k} \times \vec{\mu}])|n\,0\,0\rangle \sim C^{1\,0}_{1\,1\,s} e_r k_s.$$ 

The polarization plane of the central component rotates around the direction of the light propagation in opposite directions in $H$ and $\bar{H}$ atoms. Thus the Faraday effect on this central line can be also used to distinguish between $H$ and $\bar{H}$ atoms provided that the direction of the external magnetic field is known.

The high-resolution observations of Zeeman absorption in HI region toward the radio sources:


The Faraday rotation of the plane of linear polarization for the 21 cm absorption line (not for the search of $\bar{H}$)


The magnetic fields can be measured also for the galaxies at high redshifts


Thus, in principle, observations of the 21 cm absorption line profile can be used as a tool for the search of anti-matter in universe.
Conclusions

The mixing of \( ns \) and \( np \) states in the electric field was described analytically.

Such mixing leads to the linear dependence on the field in differential transition probability.

The casual electric field can trigger significant changes in spectra of \( H \) and \( \bar{H} \) atoms.

Quadratic in the field terms lead to an essential increase of the level width.

Presence of a magnetic field leads to the opposite polarizations in the wings of the 21 cm line.

Faraday rotation of the linear polarized component in 21 cm line has opposite direction for the \( H \) and \( \bar{H} \) atoms.

In principle, observations of the 21 cm absorption line profile can be used as a tool for the search of anti-matter in universe.
Thank you for the attention

Hydrogen and Antihydrogen spectra in presence of external fields

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