Testing fundamental interactions with the helium atom

Krzysztof Pachucki & QED Theory Group

University of Warsaw

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Testing fundamental interactions with light atoms and molecules

- H, µH, e⁺ e⁻, µ⁺ e⁻, ¯pHe, H₂⁺, H₂
- Garching 2010: ν(1S – 2S)₉ = 2 466 061 413 187 035(10) Hz
- What is the accuracy of theoretical predictions?

  \[ \nu = \nu(Ry, r_p, m/M, \alpha) \]

  \[ \Delta \nu_{fs} = \frac{7}{6} Ry c (Z \alpha)^4 \frac{r_p^2}{\chi^2} - 95.5 \text{ Hz}[\sim \alpha] - 929 \text{ Hz}[\sim \alpha^2] \]

  the ultimate theoretical predictions are limited by the proton polarizabilities

  the proton radius puzzle comes from the fact, that there is no any other narrow (optical) transition in H: \( \Gamma(2P) \approx 100 \text{ MHz} \)

  \[ \nu(1S – 2S)_{He^+} = ??? \]
(R_\infty - R_\infty, CODATA-18)/u(R_\infty, CODATA-18)

1-\sigma

CODATA-18

no \mu-H or \mu-D spectra

CODATA-18

courtesy of Eite Tiesinga, NIST (2019).
Helium

- has several very narrow transitions:
  - \( E(1^1 S_0 - 2^1 S_0) = 4984872315.48 \) MHz [Bergeson 98]
  - \( E(2^1 S_0 - 2^3 S_1) = 192510702.14872(20) \) MHz [Rengelink 2018]
  - \( E(2^3 S_1 - 2^3 P_0) = 276764094.6572(14) \) MHz [Zheng 2017]

- that can in principle be calculated as accurately as \( E(1S - 2S)_H \), but the electron correlation makes calculations more difficult

- at present \( \alpha^7 m \) is yet unknown...
### Table: $2^3S - 2^3P$ transition in $^4\text{He}$ in MHz

<table>
<thead>
<tr>
<th></th>
<th>$(m/M)^0$</th>
<th>$(m/M)^1$</th>
<th>$(m/M)^2$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha^2$</td>
<td>$-276,775,637.536$</td>
<td>$102,903.459$</td>
<td>$-4.781$</td>
<td>$-276,672,738.857$</td>
</tr>
<tr>
<td>$\alpha^4$</td>
<td>$-69,066.189$</td>
<td>$-6.769$</td>
<td>$-0.003$</td>
<td>$-69,072.961$</td>
</tr>
<tr>
<td>$\alpha^5$</td>
<td>$5,234.163$</td>
<td>$-0.186$</td>
<td>—</td>
<td>$5,233.978$</td>
</tr>
<tr>
<td>$\alpha^6$</td>
<td>$87.067$</td>
<td>$-0.029$</td>
<td>—</td>
<td>$87.039$</td>
</tr>
<tr>
<td>$\alpha^7$</td>
<td>$-8.0\ (1.0)$</td>
<td>—</td>
<td>—</td>
<td>$-8.0\ (1.0)$</td>
</tr>
<tr>
<td>FNS</td>
<td>$3.427$</td>
<td>—</td>
<td>—</td>
<td>$3.427$</td>
</tr>
<tr>
<td>NPOL</td>
<td>$-0.002$</td>
<td>—</td>
<td>—</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Theory</td>
<td></td>
<td></td>
<td></td>
<td>$-276,736,495.41\ (1.00)$</td>
</tr>
<tr>
<td>Exp.</td>
<td>[Florence.2004]</td>
<td></td>
<td></td>
<td>$-276,736,495.649\ 5\ (21)$</td>
</tr>
<tr>
<td>Exp.</td>
<td>[Zheng.2017]</td>
<td></td>
<td></td>
<td>$-276,736,495.600\ 0\ (14)$</td>
</tr>
</tbody>
</table>
the calculation of $\alpha^7 m$ correction will give possibility for the absolute charge radius determination of the helium nucleus and other nuclei from $2^3 S - 2^3 P$ in heliumlike ions but there is intriguing discrepancy for a similar transition:

$$E(3^3 D_1 - 2^3 P_0)_{\text{exp}} = 510 059 755.352(28) \text{ MHz}$$

$$E(3^3 D_1 - 2^3 P_0)_{\text{theo}} = 510 059 754.2(0.7) \text{ MHz}$$

and all the other transitions involving $3D$ state

Even more intriguing discrepancies are observed among the $^3\text{He} - ^4\text{He}$ isotope shifts
$^3\text{He} - ^4\text{He}$ isotope shift

- Rengelink ($^4\text{He}$, 2018)
- + van Rooij ($^3\text{He}$, 2011)
- Zheng ($^4\text{He}$, 2017)
- + CP ($^3\text{He}$, 2012)
- van Rooij (2011)
- Shiner (1995)
- Cancio Pastor (2012)
- CREMA (preliminary)

- $2^3S_1 \rightarrow 2^3P_J$
- $2^3S_1 \rightarrow 2^1S_0$
- $\mu$-He+ expected errorbar

picture by Youri van der Werf
QED theory group

- KP, University of Warsaw
- M. Puchalski, Poznań University
- J. Komasa, Poznań University
- V. A. Yerokhin, St. Petersburg Technical University
- V. Patkóš, Charles University, Praga
- P. Czachorowski, University of Warsaw (PhD student)
- M. Siłkowski, University of Warsaw (PhD student)