Abstract number: I3
Invited

QED tests in hydrogen molecules

Ubachs W.†[1]
[1] *Department of Physics and Astronomy, Vrije Universiteit Amsterdam, The Netherlands*
†w.m.g.ubachs@vu.nl

Precision measurements in H_2 and the hydrogen isotopologues HD and D_2 can be confronted with results of the most advanced theoretical calculations of its level structures. These calculations involve details of non-adiabatic, relativistic and quantum-electrodynamical (QED) effects.[1] By this means QED theory can be tested on molecular systems. Since the weak and strong interactions do not play a role in hydrogenic systems, at least not at the level currently in reach, such tests in fact interrogate the Standard Model of physics.[2] The dissociation energy of the H_2 molecule represents a typical benchmark and a test ground, while its precision has been improved by many orders of magnitude since the early days of spectroscopy and quantum mechanics. With the involvement of the Amsterdam-Zürich collaboration the precision on the experimental side has been improved by a factor of 1000.[3,4,5] Recently also a strongly improved value for the dissociaton energy of the D_2 molecule was obtained,[6] which was found to be in agreement with theory.[7] So far no significant deviations from theoretical calculations have been found, so the measurements stand as a test of molecular QED. At the same time the results can be used to rule out or constrain theories beyond the Standard Model, on fifth forces and extra dimensions.[1]

Alternatively, vibrational transitions in hydrogen are a testground for QED calculations, in particular now that Doppler-free measurements can be performed for the HD species that exhibits a small dipole moment.[8,9,10] The interpretation of the measurements relying on saturation spectroscopy has been halted, and the full potential of the accurate measurements cannot be exploited, because the line shapes of the HD resonances are not fully understood. Detailed studies have come up with models and explanations on the one hand pointing at underlying hyperfine structure and cross-over resonances as being at the origin of the line shape,[11] while on the other hand an interaction between bound and continuum resonances yielding a Fano line shape is postulated.[12]

Finally, measurements on tritium-containing isotopes T_2, DT and HT are currently being performed to broaden the test ground for QED calculations of hydrogenic systems.[13,14] These developments on the experimental side go hand in hand with activity on the theoretical side.[15]

[1] P. Czachorowski, M. Puchalski, J. Komasa, and K. Pachucki, *Phys. Rev. A* **98**, 052506 (2018).
[2] W. Ubachs, J.C.J. Koelemeij, K.S.E. Eikema, and E.J. Salumbides, *J. Mol. Spectr.* **320**, 1 (2016).
[3] J. Liu, E.J. Salumbides, U. Hollenstein, J.C.J. Koelemeij, K.S.E. Eikema, W. Ubachs, and F. Merkt, *J. Chem. Phys.* **130**, 174306 (2009).
[4] C. Cheng, J. Hussels, M. Niu, H.L. Bethlem, K.S.E. Eikema, E.J. Salumbides, W. Ubachs, M. Beyer, N. Hoelsch, J. A. Agner, F. Merkt, L.G. Tao, S.M. Hu, and C. Jungen, *Phys. Rev. Lett.* **121**, 013001 (2018).
[5] N. Hoelsch, M. Beyer, E.J. Salumbides, K.S.E. Eikema, W. Ubachs, C. Jungen, and F. Merkt, *Phys. Rev. Lett.* **122**, 103002 (2019).
[6] J. Hussels, N. Hoelsch, C.-F. Cheng, E. J. Salumbides, H. L. Bethlem, K. S. E. Eikema, Ch. Jungen, M. Beyer, F. Merkt, and W. Ubachs, *Phys. Rev. A.* **105**, 022820 (2022).
[7] M. Puchalski, J. Komasa, A. Spyszkiewicz, and K. Pachucki, *Phys. Rev. A.* **100**, 020503(R) (2019).
[8] F.M.J. Cozijn, P. Dupre, E.J. Salumbides, K.S.E. Eikema, and W. Ubachs, *Phys. Rev. Lett.* **120**, 153002 (2018).
[9] L.-G. Tao, A.-W. Liu, K. Pachucki, J. Komasa, Y.R. Sun, J. and Wang, and S.-M. Hu, *Phys. Rev. Lett.* **120**, 153001 (2018).
[10] A. Fast S.A. and Meek, *Phys. Rev. Lett.* **125**, 023001 (2020).
[11] M.L. Diouf, F.M.J. Cozijn, B. Darquie, E.J. Salumbides, and W. Ubachs, *Opt. Lett.* **44**, 4733 (2019).
[12] T.-P. Hua and Y. R. Sun and S.-M. Hu, *Opt. Lett.* **45**, 4863 (2020).
[13] M.T. Trivikram, M. Schloesser, W. Ubachs, and E.J. Salumbides, *Phys. Rev. Lett.* **120**, 163002 (2018).
[14] K.F. Lai, V. Hermann, T.M. Trivikram, M.L. Diouf, M. Schloesser, W. Ubachs, and E.J. Salumbides, *Phys. Chem. Chem. Phys.* **22**, 8973 (2020).
[15] K. Pachucki and J. Komasa, *Mol. Phys.* **x**, doi.org/10.1080/00268976.2022.2040627 (2022).