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Physics beyond the Standard Model from hydrogen spectroscopy ☆

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ABSTRACT

Spectroscopy of hydrogen can be used for a search into physics beyond the Standard Model. Differences between the absorption spectra of the Lyman and Werner bands of H_2 as observed at high redshift and those measured in the laboratory can be interpreted in terms of possible variations of the proton–electron mass ratio $\mu = m_p/m_e$ over cosmological history. Investigation of ten such absorbers in the redshift range $z = 2.0$–4.2 yields a constraint of $|\Delta\mu/\mu| < 5 \times 10^{-6}$ at 3σ. Observation of H_2 from the photospheres of white dwarf stars inside our Galaxy delivers a constraint of similar magnitude on a dependence of μ on a gravitational potential 10^4 times as strong as on the Earth's surface. While such astronomical studies aim at finding quintessence in an indirect manner, laboratory precision measurements target such additional quantum fields in a direct manner. Laser-based precision measurements of dissociation energies, vibrational splittings and rotational level energies in H_2 molecules and their deuterated isotopomers HD and D_2 produce values for the rovibrational binding energies fully consistent with quantum ab initio calculations including relativistic and quantum electrodynamical (QED) effects. Similarly, precision measurements of high-overtone vibrational transitions of HD^+ ions, captured in ion traps and sympathetically cooled to mK temperatures, also result in transition frequencies fully consistent with calculations including QED corrections. Precision measurements of inter-Rydberg transitions in H_2 can be extrapolated to yield accurate values for level splittings in the H_2^+-ion. These comprehensive results of laboratory precision measurements on neutral and ionic hydrogen molecules can be interpreted to set bounds on the existence of possible fifth forces and of higher dimensions, phenomena describing physics beyond the Standard Model.

1. Introduction

With the detection and first characterization of the Higgs particle [1,2] the Standard Model of physics has seemingly become complete. A full description in three families of fundamental material particles behaving as fermions, acting upon each other through three fundamental forces via bosonic force-carrying particles, has been formulated in a consistent framework. However, a number of physical phenomena are not contained in the Standard Model (SM): dark matter and dark energy are not explained; a connection of the three fundamental SM-forces to gravity cannot be made; and neither is it understood why gravity is such a feeble force. Deeper questions as to why the Universe is built in 3+1 dimensions, why there exist only 4 forces, and whether the constants of nature may depend on cosmological history or on local space–time conditions remain unanswered as of yet.

It is the paradigm of the present paper that molecular physics may contribute to finding answers to these questions. The recent searches for a dipole moment of the electron, setting tight constraints of $|d_e| < 8.7 \times 10^{-29}$ e cm, have already ruled out some supersymmetric extensions to the Standard Model. These studies take advantage of the very strong internal polarizing fields of $\sim 10^{11}$ V/cm in YbF [3] and ThO [4] molecules as well as of HfF^+ ions [5].

At the most fundamental level laser spectroscopic investigations of molecules can be applied for an experimental test of the symmetrization postulate of quantum mechanics. The fact that integer-spin species must exhibit a symmetric wave function upon interchange of identical particles makes that certain rotational quantum states in the $^{16}O_2$ [6–8] or in the $^{12}C^{16}O_2$ [9,10] molecule cannot exist. This provides an experimental platform for the investigation of the symmetrization postulate.

A search for varying constants implies a search for physics beyond the SM. The fact that the fundamental coupling strengths and other constants such as the mass ratios between particles are inserted as parameters in the fundamental theory suggests that these fundamental constants can be varied at will. However, a

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time-variation or a space–time dependence of these constants should be phrased in field theories, and in order for those to remain consistent, even in the simplest approaches, additional fields have to be invoked [11,12]. Such fields can also be associated with fifth forces or quintessence [13].

The hydrogen molecule is an experimental probe for detecting a possible variation of the proton–electron mass ratio $\mu = m_p/m_e$, a dimensionless constant of nature. The strong dipole-allowed spectrum of the Lyman and Werner bands in the vacuum ultraviolet spectral range provides a sensitive tool for detecting H_2. Observation of H_2 absorption spectra, redshifted into the atmospheric transmission window ($\lambda > 300$ nm) with ground-based telescopes constrain putative variations of μ over time. Since H_2 is the most abundant molecule in the Universe, it is readily observed even up to redshifts as high as $z = 4.2$ [14] providing look-back times of 12.5 billion years into cosmic history. Alternatively, H_2 absorption spectra as observed from photospheres of white dwarf stars can be employed to probe whether this constant μ depends on special local conditions, such as e.g. gravitational fields.

Another approach toward probing new physics from molecules is to carry out ultra-precise measurements on level energies of molecules under well-controlled laboratory conditions. A historical inspiration is drawn from the discovery of the Lamb shift in atomic hydrogen [15], where a measurement of a small shift in the relative energies between $2s_{1/2}$ and $2p_{1/2}$ levels led to the birth of quantum electrodynamics (QED), the modern theory describing the interaction between light and matter. In a similar fashion QED-calculations of small molecular systems can be tested in precision laser spectroscopic experiments to search for phenomena beyond QED. Any deviations from first principles calculations in the framework of QED can be interpreted in terms of physics beyond the Standard Model, in terms of fifth forces or quintessence, in terms of extra dimensions, or as any other phenomenon beyond the Standard Model. Here the status of such searches for new physics from spectroscopy of hydrogen molecules and molecular ions will be discussed. The focus is mainly on reviewing the work performed on H_2/HD^+ spectroscopy in the Amsterdam group and of the Amsterdam-Zürich collaboration, although some highlights of related activities of other groups are mentioned as well.

The remainder of the paper is structured as follows. In Sections 2 and 3 the use of the H_2 spectrum for a search for a varying proton–electron mass ratio is discussed, either on a cosmological time scale or as a local variability with dependence on a gravitational field. In Section 4 a number of recent precision measurements on the H_2 molecule, including its dissociation limit, its fundamental ground state vibrational splitting, as well as level energies of a sequence of rotational states and a high vibrational level, are presented. In Section 5 some recent precision measurements on the H_2^+/HD^+ molecular ions are discussed. These outcomes of experimental precision studies are compared with the most advanced QED-theoretical calculations for these benchmark molecules in Section 6. The agreement found between the experiments and theory is interpreted, in Section 7, in terms of setting bounds on a fifth force and on extra dimensions, both concepts beyond the Standard Model of physics. In the final Section 8 an outlook is presented on perspectives to perform more sensitive searches for new physics in these areas.

2. A cosmologically varying proton–electron mass ratio

Searches for temporal variations of the proton–electron mass ratio $\mu = m_p/m_e$ can be conducted by comparing absorption spectra of molecules observed astronomically from high redshift objects with the same spectra measured in the laboratory. Such comparisons can be made for many molecules [16], but molecular hydrogen is often a species of choice since it is the most abundant molecule in the Universe, and readily observed at medium to high redshifts. The relative variation of μ can be deduced by imposing the following relation to the obtained redshifted wavelengths λ_i^z and laboratory (zero redshift) wavelengths λ_i^0:

$$\frac{\lambda_i^z}{\lambda_i^0} = (1 + z_{\rm abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right) \qquad (1)$$

Here the redshift parameter $z_{\rm abs}$ relates to the overall redshift of the absorbing hydrogen cloud, and the parameters K_i represent the sensitivity coefficients expressing the induced wavelength shift upon a varying μ for each individual line in the absorption spectrum of H_2 [17]:

$$K_i = \frac{d \ln \lambda_i}{d \ln \mu} \qquad (2)$$

The laboratory wavelengths λ_i^0 are determined in laser-based experiments of the $B^1\Sigma_u^+ - X^1\Sigma_g^+$ Lyman and $C^1\Pi_u - X^1\Sigma_g^+$ Werner bands of H_2 via extreme ultraviolet laser spectroscopy [18–21] achieving accuracies of $\Delta\lambda/\lambda = 5 \times 10^{-7}$. Even better accuracies were obtained in a study measuring anchor level energies in two-photon Doppler-free excitation of the $EF^1\Sigma_g^+ - X^1\Sigma_g^+$ system [22], combined with results of a comprehensive Fourier-transform emission study delivering relative values for rovibrational levels in the $EF^1\Sigma_g^+, GK^1\Sigma_g^+, H^1\Sigma_g^+, B^1\Sigma_u^+, C^1\Pi_u, B'^1\Sigma_u^+, D^1\Pi_u, I^1\Pi_g$, and $J^1\Delta_g$ states [23]. This two-step process yielded accuracies of $\Delta\lambda/\lambda = 5 \times 10^{-8}$ [24] for a number of Lyman and Werner band lines. For the purpose of comparing with quasar absorption spectra the laboratory values for the absorption wavelengths may be considered exact.

The overall redshift $z_{\rm abs}$ is, within a good approximation, connected to a look-back time T into the cosmological history of the Universe

$$T = T_0\left[1 - \frac{1}{(1 + z_{\rm abs})^{3/2}}\right] \qquad (3)$$

where $T_0 = 13.8$ Gyrs is the age of the Universe.

A possible small differential effect on the absorption spectrum, due to a varying proton–electron mass ratio and represented by a relative change $\Delta\mu/\mu$, may be derived from the spectrum in a comprehensive fit. In such a fit the molecular physics information on the wavelengths λ_i^0, the oscillator strength f_i, and the natural lifetime broadening parameters Γ_i for each H_2 line is fixed, the values for the sensitivity coefficients K_i inserted, and the physical parameters describing the absorbing medium, such as the Doppler width b, the column densities for each J-level N_J and the redshift $z_{\rm abs}$ are fitted to model the spectrum. From the resulting values of N_J it is found that typical population temperatures of 50 K are found in most cases, although the populations do not exactly represent a Boltzmann distribution. In all cases only absorption from the lowest $v'' = 0$ vibrational level is observed for rotational states $J = 0$–5. Hence the dipole allowed absorption spectrum lies shortward of 1120 Å and extends to the Lyman cutoff of 912 Å, thus covering the $B^1\Sigma_u^+ - X^1\Sigma_g^+$ Lyman bands from (0,0) up to (17,0) and the $C^1\Pi_u - X^1\Sigma_g^+$ Werner bands up to (4,0). In several cases absorption lines of deuterated hydrogen HD are observed and included in the analysis, by comparing to accurate laboratory wavelengths [25] and invoking calculated sensitivity coefficients [26]. For HD only R(0) lines are observed. Due to the opacity of the Earth's atmosphere (transparency for $\lambda > 300$ nm) only for systems of redshift $z > 2$ can a significant number of absorption lines be observed with ground based telescopes.