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Theory of the $n = 2$ levels in muonic deuterium

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ABSTRACT

The present knowledge of Lamb shift, fine- and hyperfine structure of the 2S and 2P states in muonic deuterium is reviewed in anticipation of the results of a first measurement of several 2S − 2P transition frequencies in muonic deuterium (μd). A term-by-term comparison of all available sources reveals reliable values and uncertainties of the QED and nuclear structure-dependent contributions to the Lamb shift, which are essential for a determination of the deuteron rms charge radius from μd. Apparent discrepancies between different sources are resolved, in particular for the difficult two-photon exchange contributions. Problematic single-sourced terms are identified which require independent recalculation.

Contents

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1. Introduction

Laser spectroscopy of 2S → 2P Lamb shift transitions in muonic atoms and ions promises a tenfold improvement in our knowledge of charge and magnetic radii of the lightest nuclei ($Z = 1, 2$ and higher). Our recent measurement [1,2] of the 2S Lamb shift and the 2S hyperfine splitting (HFS) in muonic hydrogen, μp, in combination with accurate theoretical calculations by many authors, summarized in Ref. [3], has revealed a proton root-mean-square (rms) charge radius of

$$r_{\rm p} = 0.84087\,(26)^{\rm exp}(29)^{\rm theo}\ {\rm fm} = 0.84087\,(39)\ {\rm fm}. \tag{1}$$

This is an order of magnitude more accurate than the value of $r_{\rm p} = 0.8775(51)$ fm evaluated in the CODATA least-squares adjustment [4] of elastic electron–proton scattering [5,6] and many precision measurements in electronic hydrogen [7].

Most strikingly, however, the two values differ by 7 combined standard deviations (7σ). Despite numerous attempts in recent years to explain this "proton radius puzzle", it remains a mystery [8,9]. Taken at face value, this 7σ discrepancy constitutes one of the biggest discrepancies in the Standard Model. Further data are clearly required to shed light on this puzzle.

Muonic deuterium, μd, has been measured in the same beam time as μp [1,2], and the data are now nearing publication [10]. We anticipate here that the experimental accuracy of the various 2S − 2P transitions is of the order of 1 GHz, or, equivalently, ∼0.004 meV.[1] Ideally, theory should be accurate on the level of 0.001 meV to exploit the experimental precision, and to determine the deuteron charge radius, $r_{\rm d}$, with tenfold better accuracy, compared to the CODATA value [4]

$$r_{\rm d}\,({\rm CODATA}) = 2.1424(21)\ {\rm fm}. \tag{2}$$

The CODATA value originates from a least-squares adjustment of a huge amount of input values, such as the deuteron charge radius from elastic electron scattering [11,12]

$$r_{\rm d}\,({\rm e-d\ scatt.}) = 2.130(10)\ {\rm fm}, \tag{3}$$

but also the proton radius from electron scattering [5,6]. These radii are connected because the CODATA adjustment includes many transition frequencies in hydrogen (H) and deuterium (D) [7,4]. In particular, the squared deuteron–proton charge radius difference,

$$r_{\rm d}^2 - r_{\rm p}^2 = 3.82007\,(65)\ {\rm fm}^2 \tag{4}$$

[1] 1 meV $\widehat{=}$ 241.799 GHz.