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The deuteron-radius puzzle is alive: A new analysis of nuclear structure uncertainties

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ABSTRACT

To shed light on the deuteron radius puzzle we analyze the theoretical uncertainties of the nuclear structure corrections to the Lamb shift in muonic deuterium. We find that the discrepancy between the calculated two-photon exchange correction and the corresponding experimentally inferred value by Pohl et al. [1] remain. The present result is consistent with our previous estimate, although the discrepancy is reduced from 2.6 σ to about 2 σ. The error analysis includes statistic as well as systematic uncertainties stemming from the use of nucleon–nucleon interactions derived from chiral effective field theory at various orders. We therefore conclude that nuclear theory uncertainty is more likely not the source of the discrepancy.

1. Introduction

The charge radius of the deuteron (d), the simplest nucleus consisting of one proton and one neutron, was recently determined to be $r_d = 2.12562(78)$ fm [1] using several Lamb shift (LS) transitions in muonic deuterium ($\mu - d$). This result provides three times the precision compared with previous measurements. Furthermore, the $\mu - d$ value is 7.5 σ or 5.6 σ smaller than the world averaged CODATA-2010 [2] or CODATA-2014 [3] values, respectively, and 3.5 σ smaller than the result from ordinary deuterium spectroscopy [4]. One can also combine the measured radius squared difference $r_d^2 - r_p^2$ obtained from isotope shift experiments on ordinary hydrogen and deuterium [5] with the absolute determination of the proton radius from muonic hydrogen experiments [6,7] (dubbed as "μp + iso") to obtain $r_d = 2.12771(22)$ fm, which is much closer to the $\mu - d$ result, but still differs from it by 2.6 σ (see Ref. [1] for details). Altogether, these significant discrepancies have been coined "the deuteron radius puzzle".

Unlike with the proton-radius puzzle [6], r_d from $\mu - d$ Lamb shift measurements is consistent with the electron–deuteron (e–d) scattering data due to the large uncertainty in the scattering experiments. Ongoing efforts to improve the precision in electron scattering will provide further information [8]. However, these discrepancies, compounded with the 7 σ (5.6 σ) discrepancy between the CODATA-2010 (CODATA-2014) and the muonic hydrogen proton radius [6,7], highlight the need to pinpoint the source of the differences. While the very recent $2S - 4P$ spectroscopy on ordinary hydrogen supports the small proton radius [9], the conundrum of the proton and deuteron radius puzzles is not yet fully solved and further experimental and theoretical investigations are clearly required.

The deuteron charge radius r_d is extracted from the LS measurement through

$$\Delta E_{\rm LS} = \delta_{\rm QED} + \delta_{\rm TPE} + \frac{m_r \alpha^4}{12} r_d^2, \quad (1)$$

which is valid in an α expansion up to 5th order, where α is the fine structure constant. The term m_r in Eq. (1) is the reduced mass of the $\mu - d$ system. The LS energy difference, $\Delta E_{\rm LS}$, is directly measured through pulsed laser spectroscopy experiments described in detail in [1,6,7,10]. The quantum electrodynamic (QED) corrections $\delta_{\rm QED}$ are obtained from highly accurate

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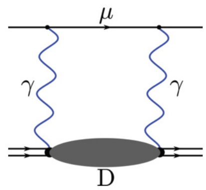

Fig. 1. Feynman diagram of the two-photon exchange between the muon and the deuteron.

theoretical calculations [11,12]. In the extraction of r_d from LS measurements the main source of uncertainty is due to nuclear structure corrections coming from a two-photon exchange (TPE) diagram, $\delta_{\rm TPE}$ depicted in Fig. 1. Because the latter is obtained from theoretical computations it is of paramount importance that all theoretical uncertainty contributions are thoroughly investigated.

Several groups have calculated $\delta_{\rm TPE}$ with different methods [13–18]. The two most recent and most precise computations, Ref. [17] and Ref. [18], are consistent within 0.6%. All theoretical calculations have been summarized by Krauth et al. [19] which resulted in a recommended value of $\delta_{\rm TPE} = -1.7096(200)$ meV. This value was also used by Pohl et al. [1] to extract r_d using Eq. (1).

On the other hand, measuring $\Delta E_{\rm LS}$ and knowing $\delta_{\rm QED}$, Eq. (1) enables the extraction of $\delta_{\rm TPE}$ from an experimentally determined radius. Using r_d from "μp + iso" leads to an experimental value $\delta_{\rm TPE} = -1.7638(68)$ meV [1], which differs from the theoretical one by 2.6 σ. This disagreement motivates a reassessment of the theoretical calculation, and in particular of its assigned uncertainties.

Finally, from the radii of light nuclei, such as hydrogen and deuterium, it is possible to determine the Rydberg constant R_∞ and consequently the radius puzzle can be turned into a "Rydberg constant puzzle". In Ref. [4] two values of R_∞ were calculated using the muonic hydrogen and muonic deuterium charge radii separately and the results were found to disagree by 2.2 σ. This difference was attributed to the $\delta_{\rm TPE}$ contribution used to extract r_d from the Lamb shift.

The purpose of this letter is to revisit our calculations of the nuclear structure corrections in $\mu - d$ and exploit chiral effective field theory and statistical regression analysis to systematically improve the theoretical uncertainty estimation in $\delta_{\rm TPE}$ and shed light on the deuteron radius puzzles.

State-of-the-art calculations of $\delta_{\rm TPE}$ in Refs. [16,18] as well as in this work, employ nucleon–nucleon (NN) potentials derived from a low-energy expansion of quantum chromodynamics called chiral effective field theory (chiral EFT). Within this approach, which also constitutes the modern paradigm of analyzing the nuclear interaction, the nuclear potential is built from a sum of pion-exchange contributions and nucleon contact terms, see, e.g., Refs. [20,21]. Power counting enables to determine the importance of individual terms in the low-energy expansion and thereby also facilitates a meaningful truncation of higher-order diagrams that build the potential. All potentials in this work employ Weinberg's dimensional power counting schemes [22,23], whereby the order $\nu \geq 0$ to which a diagram belongs is proportional to Q^ν, where

$$Q = \max\left\{\frac{p}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right\} \quad (2)$$

and p is a small external momentum, Λ_b is the chiral symmetry breaking scale of about the rho meson mass, and m_π is the pion mass. Given a power counting, contributions with a low power of ν are more important than terms at higher powers. Starting from the leading order (LO), i.e., $\nu = 0$, higher orders will be denoted as next-to-leading order (NLO), i.e., $\nu = 2$, next-to-next-to-leading order N^{2}LO, i.e., $\nu = 3$, and so on. It is worth noticing that, in chiral EFT, the contributions with $\nu = 1$ vanish due to time-reversal and parity. At each order ν of the chiral EFT potential, there will be a finite set of parameters, known as low energy constants (LECs), that determine the strength of various pion–nucleon and multi-nucleon operators. The LECs are not provided by the theory itself but can be obtained from fitting to selected experimental data, such as NN and πN scattering cross sections, and other few-body ground state observables, such as radii and binding energies. Different fitting procedures exist, and we will explore a variety of them as a way to probe both statistical and systematic uncertainties.

To avoid infinities upon iteration in the Lippmann–Schwinger equation all chiral potentials are regulated by exponentially suppressing contributions with momenta p greater than a chosen cutoff value Λ, see e.g. Refs. [20,21]. Non-perturbative ab initio calculations using momentum-space chiral EFT often employ NN interactions with $\Lambda \approx 400$–600 MeV.

Chiral EFT and effective field theories in general, unlike phenomenological models, furnish a systematic, i.e., order-by-order, description of low-energy processes at a chosen level of resolution. In this work, it provides us with an opportunity to estimate the uncertainty of $\delta_{\rm TPE}$ truncated up to different chiral orders. In our previous work [16,18], we probed the theoretical uncertainty stemming from the nuclear physics models by cutoff variation, i.e., varying Λ. Strictly speaking, this prescription to estimate the chiral EFT uncertainty also requires the excluded νth-order chiral contributions to be proportional to $1/\Lambda^{\nu+1}$ when Λ is approaching the breakdown scale Λ_b: a property that hinges on order-by-order renormalizability of the canonical chiral EFT formulation, which is not yet established. Also, cutoff-variation tend to either underestimate or overestimate the chiral EFT systematic uncertainty with respect to the variation range [24,25]. To this end, and to be as conservative as possible, we will augment the procedure of cutoff-variation by implementing the chiral EFT truncation-error to obtain solid systematic uncertainty estimates.

Any rigorous estimate of the theoretical uncertainty must also consider the effects of the statistical uncertainties of the LECs due to experimental uncertainties in the pool of fitted data. For example, in Ref. [26] it was found that a rigorous statistical analysis lead to a four-fold increase in the uncertainty estimates of the proton–proton fusion S-factor as compared to previous work which only probed the systematic uncertainty of the nuclear model by limited cutoff variations. Motivated by the possibility that the uncertainties were underestimated, we rigorously probe the statistical and systematic uncertainties in the nuclear structure corrections in the Lamb shift of $\mu - d$, by propagating the uncertainties of the LECs appearing in the NN potentials up to N^{2}LO [27,28].

Details on the observables associated with the LS in $\mu - d$ are explained in Section 2 and results of the statistical analysis will be shown in Section 3. In addition, we improve our estimates of the systematic uncertainty associated with the chiral EFT expansion by carrying out our calculations up to fifth-order in chiral EFT, namely N^{4}LO. We then use the method detailed in Refs. [24,25,29] to estimate the systematic uncertainty associated with the chiral truncation at each order. Results will be shown in Section 4. Finally, we will examine and combine all the relevant sources of uncertainty in Section 5, before drawing conclusions in Section 6.

2. Two-photon exchange contributions

For the calculation of $\delta_{\rm TPE}$ we separate terms that depend on the few-nucleon dynamics, denoted with A, from terms that exclusively depend on properties of the single-nucleon, denoted with N, as