Progress in Particle and Nuclear Physics 88 (2016) 29–97

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Nucleon polarizabilities: From Compton scattering to hydrogen atom

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ARTICLE INFO

Article history:
Available online 19 December 2015

Keywords:
Proton
Neutron
Dispersion
Compton scattering
Structure functions
Muonic hydrogen
Chiral EFT
Lattice QCD

ABSTRACT

We review the current state of knowledge of the nucleon polarizabilities and of their role in nucleon Compton scattering and in hydrogen spectrum. We discuss the basic concepts, the recent lattice QCD calculations and advances in chiral effective-field theory. On the experimental side, we review the ongoing programs aimed to measure the nucleon (scalar and spin) polarizabilities via the Compton scattering processes, with real and virtual photons. A great part of the review is devoted to the general constraints based on unitarity, causality, discrete and continuous symmetries, which result in model-independent relations involving nucleon polarizabilities. We (re-)derive a variety of such relations and discuss their empirical value. The proton polarizability effects are presently the major sources of uncertainty in the assessment of the muonic hydrogen Lamb shift and hyperfine structure. Recent calculations of these effects are reviewed here in the context of the "proton-radius puzzle". We conclude with summary plots of the recent results and prospects for the near-future work.

Contents

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http://dx.doi.org/10.1016/j.ppnp.2015.12.001
0146-6410/

1. Introduction

The concept of *polarizabilities*, common in optics and classical electrodynamics, was extended to the nucleon in the 1950s [1,2], together with the first observations of Compton scattering (CS) on the proton [3–8]. Since then, the CS process, with real (RCS) or virtual (VCS) photons, became the main experimental tool in studying the nucleon polarizabilities, with dedicated experiments completed at: Lebedev Institute (Moscow) [8,9], MUSL (Illinois) [10], SAL (Saskatoon) [11,12], LEGS (Brookhaven) [13], Bates (MIT) [14], MaxLab (Lund) [15], MAMI (Mainz) [16–22], and Jefferson Laboratory (Virginia) [23].

In recent years, the nucleon polarizabilities have advanced to the avantgarde of hadron physics. They are a major source of uncertainty in the muonic-hydrogen determination of the proton charge radius [24] and Zemach radius [25], and hence are a prominent part of the "proton-radius puzzle" [26]. They play an important role in the controversy of the electromagnetic (e.m.) contribution to the proton–neutron mass difference [27–29]. Several issues involving the nucleon polarizabilities have emerged from the ongoing 'spin physics program' at the Jefferson Laboratory (JLab), which is mapping out the spin structure functions of the nucleon [30–32]. The various moments of these structure functions are related to the forward *spin polarizabilities*, with one of them, δ_{LT}, being notoriously difficult to understand within the chiral effective-field theory (χEFT) [33,34]. The currently operating photon beam facility MAMI has established a dedicated experimental program to disentangle the nucleon polarizabilities through the low-energy RCS with polarized beams [35,36] and targets [37,38]; a complementary program, at even lower energy, is planned at HIGS (Duke) [39,40]. A new experimental program is being