Progress in Particle and Nuclear Physics 95 (2017) 245–278

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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

Review

Two-photon exchange in elastic electron–proton scattering

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ARTICLE INFO

Article history:
Available online 17 April 2017

Keywords:
Two-photon exchange
Radiative corrections
Form factors

ABSTRACT

We review recent theoretical and experimental progress on the role of two-photon exchange (TPE) in electron–proton scattering at low to moderate momentum transfers. We make a detailed comparison and analysis of the results of competing experiments on the ratio of e^+p to e^-p elastic scattering cross sections, and of the theoretical calculations describing them. A summary of the current experimental situation is provided, along with an outlook for future experiments.

Contents

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http://dx.doi.org/10.1016/j.ppnp.2017.03.004
0146-6410/

1. Introduction

Electron scattering has been a primary experimental tool in the study of hadron physics for many decades. The electromagnetic interaction is well understood, and the pointlike nature of electrons makes it an ideal tool to probe the internal structure of hadrons. Furthermore, the relatively small value of the electromagnetic coupling, $\alpha \sim 1/137$, makes the electromagnetic interaction amenable to a perturbative treatment in the context of quantum field theory.

Much of our information on the structure of the proton comes from unpolarized measurements of the inclusive electron–proton scattering cross section. These measurements determine the proton electric (G_E^p) and magnetic (G_M^p) form factors, which are fundamental observables characterizing the internal structure of the proton. Specifically, the quantities $(G_E^p)^2$ and $(G_M^p)^2$ can be extracted from the angular dependence of the unpolarized electron scattering cross section.

More recently, polarized beams, polarized targets, and measurements of the recoil polarization of the target proton have been used to provide additional information on the spin structure of the proton, and to improve our knowledge of proton form factors. Polarization measurements have proven to be a crucial ingredient in studies of proton form factors over the past two decades. These experiments access the ratio G_E^p/G_M^p directly from the ratio of transverse to longitudinal nuclear polarization measurements.

In what has become known colloquially as "the proton form factor puzzle", a comparison of the form factor ratio extracted from both types of experiments revealed a significant discrepancy in kinematic regions where both techniques provide precise measurements. Because these, and essentially all other electron scattering measurements, are analyzed in the framework of the one-photon exchange (OPE) or Born approximation, this discrepancy led to a reexamination of the possible role played by radiative corrections to the electron scattering cross sections. For electron scattering, radiative corrections must be applied to measured cross sections in order to extract an equivalent OPE form. Although these radiative corrections are large, they are generally model-independent and well understood. In particular, the standard radiative corrections are independent of hadronic structure.

Attempts to reconcile the unpolarized and polarized measurements have mostly focussed on improved treatments of these radiative corrections. Of particular interest, and the subject of this review, are considerations of two-photon exchange (TPE) effects beyond the minimal model-independent terms incorporated into the standard radiative corrections. The challenge in calculating these TPE contributions is that they are not independent of hadronic structure. The challenge in measuring them directly is that they are most prominent at high momentum transfer and backward scattering angles, where the cross section is suppressed. Early measurements and calculations suggested that TPE effects are a few percent correction to cross sections, consistent with the expectation that they are of order $\mathcal{O}(\alpha)$ compared to the OPE approximation. However, there is now convincing evidence that these corrections can nevertheless be extremely important in specific circumstances.

Over the past 15 years there has been a significant investment, on both the theoretical and experimental fronts, to studying TPE in electromagnetic processes. Many of these efforts have been the subject of previous reviews, such as the 2007 review by Carlson and Vanderhaeghen [1], and 2011 review by Arrington, Blunden and Melnitchouk [2]. Since the 2011 review [2] there has been significant progress in theoretical calculations, which we highlight here. In addition, results have recently been reported from the VEPP-3, CLAS, and OLYMPUS experiments, which were designed to directly measure TPE effects from the ratio of e^+p to e^-p elastic scattering cross sections.

Interest in TPE effects has been furthered by the so-called "proton radius problem" [3]. Briefly, the proton radius extracted from electron scattering and atomic hydrogen spectroscopy measurements disagrees by several standard deviations from the proton radius extracted by spectroscopy on muonic atoms. Two-photon exchange is one contributor to the energy shift in atomic systems. This is described in a recent review by Carlson [4], and we do not address it further in this review.

The outline of this review is as follows. Section 2 provides a theoretical overview. This includes the relevant electron scattering formalism in Sections 2.1 and 2.2. Section 2.3 describes the formalism and calculations of TPE corrections in unpolarized electron scattering, summarizing the older work but focussing on recent improvements in the past five years. Two-photon exchange for spin-polarization effects are described in Section 2.4.

Section 3 focusses on experimental measurements. In particular, the recent VEPP-3, CLAS, and OLYMPUS experiments, which look for direct evidence of TPE effects by measuring the ratio of e^+p to e^-p elastic cross sections, are each described in some detail. A comparison and analysis of the results of these experiments is made in Section 3.8. Conclusions and the outlook for both theory and experiment are given in Section 4.

2. Theoretical overview

2.1. Kinematics and definitions

In this section we define the general kinematics of elastic electron–nucleon scattering, and present amplitudes and cross sections in the OPE or Born approximation.