Two-photon exchange measurements with positrons and electrons

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Abstract.

Two-photon exchange contributions have potentially broad ranging impact on several charged lepton scattering measurements. Previously believed to be extremely small, based in part on comparisons of positron scattering and electron scattering in the 1950s and 1960s, recent data suggest that the corrections may be larger than expected, in particular in kinematic regions that were inaccessible in these early positron scattering measurements. Additional measurements using positron beams at Jefferson Lab would allow for a detailed investigation of these contributions in a range of reactions and observables.

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INTRODUCTION

The nucleon electromagnetic form factors are fundamental quantities that relate to the charge and magnetization distributions in the nucleon [1, 2, 3, 4]. Thus, they are important quantities when examining the spatial distribution and dynamics of quarks in the nucleon [5, 6, 7]. Unpolarized elastic scattering has been used since the 1950s to obtain the proton electric and magnetic form factors, $G_E$ and $G_M$, using the Rosenbluth separation technique [8]. In certain kinematic regions, it is difficult to separate the electric and magnetic contributions to the cross section, and in particular it is difficult to extract $G_E$ from the cross sections at high $Q^2$ values [9, 10, 11]. Polarization measurements have an important role in overcoming this limitation, as they are sensitive to the ratio $G_E/G_M$ [12, 13]. The $Q^2$ measurements at Jefferson Lab [14, 15] showed a striking disagreement with previous measurements [16], as well as a new, high precision extraction using a modified Rosenbluth separation technique [17].

Early speculation was that the discrepancy could be the result of two-photon exchange (TPE) contributions, which are neglected (except for IR-divergent contributions) in standard radiative correction procedures based on the formalism of Mo and Tsai [18]. Estimates of contributions beyond the IR divergent terms suggested that any additional effects were small [19], and this was supported by comparisons of positron and electron scattering [20] where the TPE contributions change sign. More recently, the TPE contributions to the unpolarized cross section were reexamined [21], and it was also shown that these contributions could potentially have a large impact on the Rosenbluth extractions while having little impact on the polarization observables [22].

Since then, several approaches have been used to calculate the TPE contributions [23, 24, 25, 26, 27, 28, 29], for both cross section and polarization observables, as well as
examination of other reactions or observables [30, 31, 32, 33, 34, 35]. The cross section calculations have significant model dependence, but generally agree on the qualitative features [36, 37, 38]: a small contribution at small scattering angles, corresponding to the virtual photon polarization parameter $\varepsilon = 1$, and a larger contribution for small $\varepsilon$ values, and that the contributions become larger at large $Q^2$ values. This is consistent with the fact that the positron comparisons, which were used to set upper limits on TPE effect, were typically focussed on large $\varepsilon$ or low $Q^2$ values [39]. The calculations typically induce some non-linearity in the $\varepsilon$ dependence of the reduced cross section [24, 23, 40], which is linear in the Born approximation, but the limits on nonlinearities in the data [41], while significantly improved by the recent JLab measurements [17], are not yet tight enough to be at odds with the calculations.

It has been shown that the hadronic calculations of TPE [23] can resolve the discrepancy up to 2–3 GeV$^2$, allowing for extraction of the proton form factors [42] that includes an estimate of the uncertainties for additional TPE effects at high $Q^2$. However, this assumes that TPE corrections fully explain the discrepancy. If the discrepancy is related to something else, such as higher order contributions to the radiative corrections [37, 43], then the constraints applied, based on the assumption that only TPE corrections are missing, could be incorrect. It is therefore critical to verify that TPE corrections fully explain the discrepancy between Rosenbluth and polarization extractions of the proton form factors.

In addition, it is important to remember that TPE contributions contribute to all electromagnetic scattering processes. It is generally assumed that these corrections are small in almost all cases, and typically within the assumed uncertainties applied for radiative corrections. At the moment, we have no way to verify this other than to make theoretical estimates of the TPE contributions to other processes, and thus it is important to constrain these calculations as well as possible in the case of elastic electron–proton scattering, where there are multiple measurements that can be used to quantitatively test the calculations. While the focus has been on high $Q^2$, it is also important to keep in mind that the TPE corrections do not appear to be negligible at low $Q^2$, and thus the next generation of extremely high precision measurements made at low $Q^2$ will also need better knowledge of TPE corrections.

**FUTURE POSITRON-ELECTRON COMPARISONS**

It is clear from the recent activity that obtaining a more complete understanding of two-photon exchange effects is a matter of great interest and importance (see Refs. [36, 37, 38] for details on the theoretical and experimental activities). There are still quantitative differences between different calculations, and it is crucial to determine the reliability of the different approaches in their kinematic regions of applicability, both to have complete confidence in our knowledge of the form factors, but also to have reliable approaches that can be used to evaluate TPE corrections for other reactions.

While recent experiments are attempting to examine TPE through more detailed comparisons of the angular dependence of polarization and cross section measurements, these can only constrain the effects of TPE, they cannot isolate TPE contributions. Other measurements, specifically of polarization observables that are identically zero in the
Born approximation, can isolate TPE contributions. However, these observables relate to the imaginary part of the TPE amplitude, while the extractions of the form factors are modified by the real part. Thus, these are important in evaluating calculations of TPE corrections, but do not directly measure the effect on the form factor extractions.

Comparisons of $e^+\text{–proton}$ and $e^-\text{–proton}$ scattering (as well as $\mu^+\text{–p}$ and $\mu^-\text{–p}$) have been used to set limits on TPE effects. These contributions come through the interference of the one-photon and the two-photon exchange amplitudes, and while the Born cross section is independent of lepton charge, the interference term changes sign for positrons. Thus, the comparison of $e^+\text{–p}$ and $e^-\text{–p}$ scattering isolates the TPE contribution (after correcting for the interference between electron and proton bremsstrahlung, which also changes sign). Previous comparisons were interpreted as limiting the TPE contributions to the $e^-\text{–p}$ cross section at or below the 1% level except at large $Q^2$ [20]. However, due the the low luminosity of the secondary positron beams, the only measurements above 2 GeV$^2$ were at small scattering angles, corresponding to large $\varepsilon$ values. A reexamination of the positron measurements, in light of the form factor discrepancy between cross section and polarization measurements showed that there was evidence for a $\varepsilon$ dependent TPE correction [39]. While the data were qualitatively consistent with the TPE corrections necessary to explain the discrepancy, the observed effect was only three sigma from zero, and the data at low $\varepsilon$, where the TPE contributions were visible, was at low $Q^2$ ($< 1 \text{ GeV}^2$), where the TPE effects are expected to be smaller.

Further measurements are required to adequately understand the impact of TPE effects. To be confident in our extraction of the form factors, high $Q^2$ data are necessary to verify that TPE effects can fully explain the discrepancy. Mapping out the TPE contributions in detail will allow for precise corrections in the low $Q^2$ region, where many high-precision measurements are performed, and will also allow for detailed evaluations of the TPE calculations. Finally, with a high quality positron beams, direct measurements of TPE effects in reactions beyond elastic $e^-\text{–p}$ scattering will become possible.

In the short term, there are three experiments planned to examine TPE effects using positron beams. A measurement at Novosibirsk [44] will make a single high precision comparison of electron and positron scattering at $Q^2 = 1.6 \text{ GeV}^2$, $\varepsilon = 0.4$. The OLYMPUS experiment [45] will relocate the BLAST detector from MIT-BATES to the DORIS electron/positron storage ring at DESY. The experiment will be able to map out the epsilon dependence in more detail using 2 GeV lepton beams, reaching a maximum $Q^2$ of 2.3 GeV$^2$ at $\varepsilon = 0.35$ (and lower $Q^2$ for higher $\varepsilon$ values). Both of these experiments have clean lepton beams but are limited by the total luminosity, even with large solid angle detectors. Nonetheless, they provide a dramatic improvement over the previous measurements that included large scattering angle. The last experiment uses a mixed beam of positrons and electrons with a wide energy range, and the large acceptance CLAS detector in Hall B at JLab is then used to detect both the scattered lepton and struck proton, thus allowing for reconstruction of the charge and energy of the incoming lepton [46]. This will allow for extraction of the TPE contributions over a range in $Q^2$, covering approximately 0.5–2.0 GeV$^2$. In this case, the luminosity is limited by background rates in the detectors, and the $Q^2$ coverage may be increased if modified shielding configurations are sufficient to reduce these rates. This experiment (JLab E07-005) provides broad kinematic coverage and is the only one planned that can map out the TPE con-
tributions at low $Q^2$. However, it requires the large acceptance and moderate resolution of the CLAS spectrometer to fully reconstruct the events and to allow for control of the systematics, and due to the rate limitations, it is difficult to know exactly how high in $Q^2$ the data will extend.

These planned experiments will go a long way in verifying that TPE contributions are responsible for the form factor discrepancy. They will also provide the first quantitative measure of TPE effects in the elastic $e^{-}p$ cross section at low $\epsilon$ and $Q^2 > 1$ GeV$^2$, were the effects are believed to be most important. However, further measurements will be important in fully understanding TPE effects. The TPE calculations at higher $Q^2$ are significantly less well constrained, and information on both the scale and the $\epsilon$-dependence at larger $Q^2$ values will be very important. In addition, a well defined positron beam of high luminosity would allow for a survey of TPE contributions on a range of exclusive reactions. Depending on the luminosity available, such measurements may be limited to low $Q^2$, but this is the region where the majority of high precision measurements are performed, and constraints on TPE contributions will be most important.

A high quality positron beam at Jefferson Lab would allow for significant extensions to the program of TPE studies, as well as related effects such as Coulomb distortion \cite{47}. The main limitations of the planned measurements are the luminosity, combined with the fact that the experiments need to detect both the scattered lepton and struck proton in order to fully reconstruct the event and sufficiently eliminate backgrounds. A positron beam with a small energy spread ($10^{-3}$ or better), coupled with a high resolution spectrometer, would allow for a clean separation of the elastic events detecting only the lepton or proton. Proton-only detection, as used by the “Super-Rosenbluth” experiment in Hall A \cite{17} has several advantages in this case. Since only the proton is detected, the spectrometer does not need to change polarity when the beam charge changes. In addition, low $\epsilon$ values correspond to small scattering angles for the proton, making it easier to access small $\epsilon$ values and providing a factor of 10–20 increase in the effective solid angle at low $\epsilon$ compared to lepton detection. High $Q^2$ Rosenbluth separations at SLAC \cite{9} used beam currents up to 10 µA on a 15 cm liquid hydrogen target to extract the form factors up to 7 GeV$^2$. A measurement using the HRS or HMS/SHMS spectrometers in Hall A or C would gain a factor of 5–10 in solid angle and 10–20 in cross section when detecting protons at low $\epsilon$, and thus could perform similar measurements using positrons with a 100 nA positron beam, and even with 10 nA could make measurements up to 5 GeV$^2$.

For a direct comparison of $e^+$ and $e^-$ scattering, it would be beneficial to be able to change the beam fairly quickly. However, in this case, one can make precision Rosenbluth separations independently for positrons and electrons, using the proton detection technique which minimizes the uncertainties on the $\epsilon$ dependence of the reduced cross section. Therefore, one can make a direct comparison of the $\epsilon$ dependence extracted from electron and positron scattering, rather than a direct comparison of individual cross sections. In addition, the TPE contributions go to zero for $\epsilon \rightarrow 1$ ($\theta_e \rightarrow 0$), and this can be used for a relative normalization if the data extend close enough to $\epsilon = 1$ and the TPE corrections are sufficiently well behaved in this region.

A beam of 10–100 nA would also allow for significant measurements using CLAS in Hall B. After the 12 GeV upgrade, the acceptance (and electron identification) are limited at large scattering angles. Thus, it is not as well suited to looking for the large
angle TPE expected in elastic e–p scattering. However, as 10–100 nA are typical operating currents in Hall B, and the acceptance is very large, one could make a comparison of electron and positron scattering simultaneously for a large number of exclusive reactions, or use more specific trigger configurations to pick out specific reactions with a lower cross section if models suggest that particular reactions will be more sensitive to TPE contributions. Again, it will be necessary to carefully normalize the electron data to the positron data, taking multiple configurations, e.g., positron data with same polarity as electron data and with opposite polarity, to help minimize the systematics in the comparisons of the results. A quick change between positrons and electrons would again be useful, but use of elastic scattering, after TPE corrections are mapped out in detail, can be used as a check on differences in efficiency between periods of positron and electron running.

In all of this, it will be important to include low $Q^2$ measurements. Calculations looking at the low $Q^2$ region $[23,25]$ suggest that the TPE correction goes to zero somewhere in the vicinity of $Q^2 = 0.3$ GeV$^2$, and then changes sign and grows with decreasing $Q^2$. As the low $Q^2$ region is where high precision extractions of the cross section impact other observables, e.g. the extraction of the strangeness contribution to the nucleon form factors $[35,34]$, and the low $Q^2$ form factors that go into corrections of atomic hyperfine splitting $[48]$, precise limits are especially important in this region. If higher currents are available, one could also consider making measurements of polarization observables in elastic e–p scattering. The best extractions of the form factors come from combining Rosenbluth and polarization data, and at low $Q^2$, the TPE corrections on polarization observables are small but not necessarily negligible. With a polarized positron beam, it would be able to make such measurements using a polarized targets even for relatively low currents. Such measurements would likely be limited to larger $\varepsilon$ values, where one expects the TPE contributions to be smaller. This would suffice for extracting the corrections to polarization observables, as a high-precision measure of the asymmetries can be performed. To use this as a more detailed test of the TPE calculations, high polarization and higher beam currents, probably at least 100 nA, would be required.

In summary, a great deal could be done to improve our understanding of the two-photon exchange contributions, and thus the precision with which we can extract the proton form factors with a positron beam at Jefferson Lab. An unpolarized beam of 10 nA would allow for significant progress over the existing and planned measurements of electron-positron comparisons, and provide a first direct way to study TPE contributions in other reactions. If currents of 50–100 nA are available, these studies could be dramatically expanded: high $Q^2$ measurements on the proton, first measurements on the neutron, and better kinematic coverage for other exclusive reactions on the proton. These would dramatically improve our tests of the TPE calculations that are necessary if we want significantly improved precision on the next generation of electron-scattering experiments. Finally, polarized beams would allow much independent tests of the details of the TPE calculations, as well as providing direct measurements or significant constraints on the impact of TPE on polarization measurements.

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