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Time-like compton scattering and the Bethe–Heitler process

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Abstract. Arguments are presented for $p(\gamma, e^+e^-)p$ measurements to obtain new information about the off-shell time-like nucleon form factors, especially in the ϕ meson region governing the ϕN couplings $g^{V,T}_{\phi NN}$. Theoretical predictions based upon a Quantum Hadrodynamic model and vector meson dominance are highlighted for both the proton form factor and the time-like Compton scattering cross section. The Bethe-Heitler process is also calculated but is only important at low momentum transfer $|t|$ permitting a novel high $|t|$ ϕ enhancement in the Compton cross section related to nucleon strangeness to emerge.

PACS. 12.40.Nn Regge theory – 12.40.Vv Vector-meson dominance – 13.40.Gp Electromagnetic form factors – 13.40.Hq Electromagnetic decays

1 Introduction

While Compton scattering using real, $p(\gamma, \gamma)p$, and even virtual (space-like), $p(e, e'\gamma)p$, photons has been measured, the time-like virtual Compton scattering [TVCS] process, $p(\gamma, e^+e^-)p$, has received little attention. However such measurements can provide new information about the time-like proton form factor in the unobserved region $0 \leq q^2 \leq 4M_p^2$ (all measurements utilized $e^+e^- \leftrightarrow N\bar{N}$ where $q^2 \geq 4M_p^2$) since the three-body final state has an essentially unrestricted virtual photon mass $q^2 \geq 4M_e^2 \sim 0$. Previous theoretical studies using vector meson dominance [VMD] have predicted that the $p(\pi^-, e^+e^-)n$ [1,2] and $p(\gamma, e^+e^-)p$ [3] cross sections both exhibit a dramatic, dual peaked resonant signature for time-like virtual photon four-momentum spanning the vector meson masses ($q^2 \approx M_V^2$ for $V = \rho, \omega, \phi$). This paper extends the work of [3] by calculating the competing Bethe-Heitler [BH] process, $\gamma p \to \gamma\gamma_v p \to e^+e^-p$, and documenting that it is only important for small $|t|$, significantly below the interesting high $|t|$ region where the s and u channel processes embodying the VMD resonant signature dominate.

2 Hidden strangeness

In addition to mesons, other eigenstates of the QCD Hamiltonian also contain hidden strangeness. One clear example is the ground state vacuum with non-zero quark condensates $\langle O|\bar{s}s|O\rangle \simeq \langle O|\bar{u}u|O\rangle \simeq \Lambda^{QCD}$. Of current intense interest and debate is nucleon hidden strangeness which is completely specified by the $n = 1, 2 \ldots 16$ matrix elements, $\langle N|\bar{s}\Gamma_n s|N\rangle$, involving the Lorentz bilinear covariants. This study addresses the vector and tensor elements, γ_μ and $\sigma_{\mu\nu}$, corresponding to the coupling constants $g^V_{\phi NN}$ and $g^T_{\phi NN}$, respectively, since the ϕ is predominantly $s\bar{s}$. These ϕN coupling constants govern the Quantum Hadrodynamical [QHD] Lagrangian

$$\mathcal{L}_{\phi NN} = g^V_{\phi NN}\bar{N}\gamma_\mu N\phi^\mu + g^T_{\phi NN}\bar{N}\sigma_{\mu\nu}N[\nabla^\mu\phi^\nu - \nabla^\nu\phi^\mu]$$

used for both the VMD proton form factor and TVCS cross section predictions discussed below. If there is no or insignificant nucleon strangeness then ϕN coupling should be suppressed due to the dominant $s\bar{s}$ structure of the ϕ and the OZI rule. However, significant OZI violations have been observed in inelastic μp and elastic νp scattering, $p\bar{p}$ annihilation experiments and measurements of the πN sigma term, which collectively suggest appreciable strangeness in the proton. Evidence for nucleon strangeness is further discussed and reviewed in [4]. Related, a previous analysis [3] of space-like neutron electric form factor data and high $|t|$ ϕ photoproduction data yielded $g^V_{\phi NN} = 1.3$, $g^T_{\phi NN} = 2.3$. Accurate TVCS measurements at high $|t|$ will permit extraction of these couplings which quantify the degree of nucleon strangeness.

3 Predictions for TVCS

As detailed in [3] the nucleon form factors were calculated using a generalized VMD model. A good description of the baryon octet form factors was obtained, especially the sensitive space-like neutron electric form factor and the proton EM form factors in both the space-like and time-like regions as depicted in Fig. 1. Note the resonant peaks in the unmeasured time-like vector meson region, in particular the ϕ peak which scales with the ϕN coupling.

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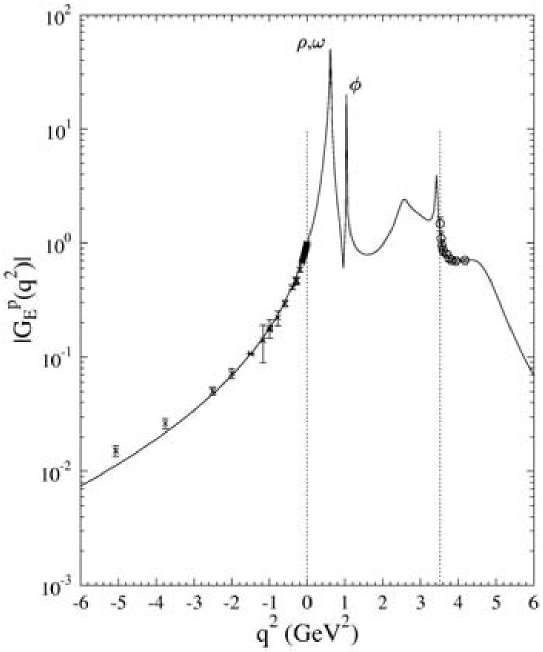

Fig. 1. Data and VMD (absolute value) for the proton electric form factor

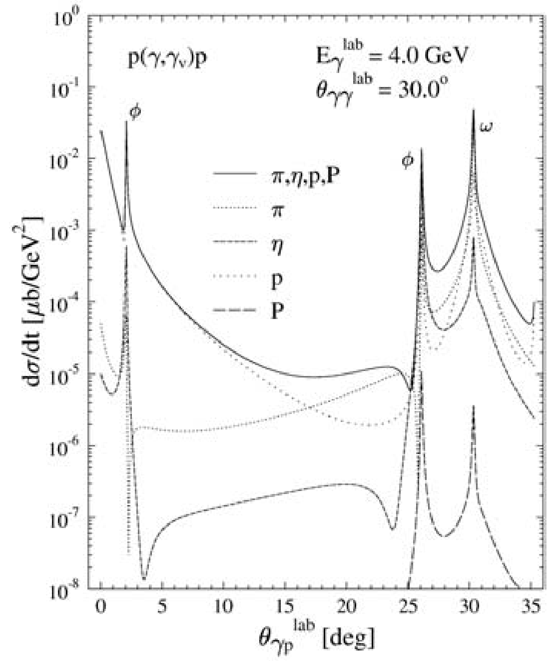

Fig. 2. VMD prediction for TVCS, $p(\gamma, \gamma_v)p$. The smaller angle ϕ peak quantifies the proton's strangeness

The form factor peaks are reflected in the TVCS cross section displayed in Fig. 2. A novel, dual peak profile arises from the quadratic relation between q^2 and the recoil proton lab angle. The smaller angle ϕ peak corresponds to high $|t|$ and is dominated by the u channel proton propagator with $g_{\phi NN}$ coupling (sparse dotted curve). The magnitude of this peak represents the degree of the proton's strangeness. The other two peaks near 30^o entail lower $|t|$ and involve ϕ and ω coupling, respectively, to π (dense dotted curve) and η (short dashed curve) t channel exchange. These two peaks represent the expected ϕ production background since they are based upon established results. This dual peak ϕ signature follows from only VMD and should occur in other dynamic models. Therefore VMD predicts that a measurement of the high $|t|$ TVCS cross section ratio $R = \sigma(q^2 = M_\phi^2)/\sigma(q^2 = M_\omega^2)$ is proportional to $g_{\phi NN}^2/g_{\omega NN}^2$. This has been numerically confirmed in this model giving $R = 0.14\ f$ (where f is a kinematic quantity of order unity) which is an order of magnitude larger than the OZI prediction [4], $R = tan^2\ \delta\ f = 0.0042\ f$, where $\delta = 3.7^o$ is the deviation from the ideal quark flavor mixing angle in the ϕ. TVCS measurements would therefore appear to be an excellent probe of the proton's strangeness content.

4 The Bethe–Heitler process

Because the BH and TVCS processes compete it is necessary to assess their relative magnitudes. Even if the amplitudes are comparable it is still possible to extract the TVCS amplitude by measuring the charge asymmetry $(\sigma(e^+e^-) - \sigma(e^-e^+))$ since in TVCS the e^+e^- pair has C-parity -1 (single photon production) while for the theoretically known BH process they have C = 1 (two photon production). For the kinematics listed in Fig. 2, the calculated BH cross section dominates the TVCS cross section for $|t| \leq 0.01$ GeV^2, is comparable for $|t|$ up to 0.04 GeV^2 and is an order of magnitude smaller for $|t| > 0.06$ GeV^2. Hence the charge asymmetry measurement will only be necessary for small $|t|$ where meson and pomeron (long dashed curve in Fig. 2) exchange dominate the TVCS process. To extract the ϕN couplings at high $|t|$, the TVCS cross section is sufficiently large for direct measurement without competition from the BH process.

5 Conclusion

With GeV electron facilities, such as Jlab, TVCS experiments appear quite feasible, providing an opportunity to obtain the unknown nucleon on and off-shell time-like form factors. If VMD is valid the ϕN couplings can then be extracted which in turn permits a direct assessment of nucleon hidden strangeness.

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