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# Exploring Roper Structure via DVCS

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In the quark model the low-lying Roper resonance is considered to be a radially-excited three-quark state which rapidly decays to $N\pi$, a description that poorly describes its low mass. We discuss the possibility that the Roper is dynamically generated as an $N\pi$ state and present a method of using GPDs to calculate the size of the effect on the Roper's structure.

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## 1. Introduction

The Roper ($P_{11}(1440)$) resonance is an unstable low-lying nucleon resonance with a particularly wide Breit-Wigner width, traditionally considered as a nucleon with a radially excited $n = 2$ quark [1]. It is unusual that this positive-parity resonance should exist at a lower energy than the $S_{11}(1535)$ which has negative parity. Some Lattice QCD evidence suggests that the $\Lambda(1405)$, another unusually light baryon, exists as a molecule-like bound state of an antikaon and nucleon [2–4]. There is therefore some question as to whether the Roper resonance can, to some degree, also be considered a molecular bound state of a pion and nucleon. This idea has been supported by Lattice results of $N\pi$ scattering using Hamiltonian Effective Field Theory [5, 6].

We aim to extend this work using GPDs, the three-dimensional analogue of parton distribution functions, to examine the effect of an $N\pi$ component in the nucleon state vector on the cross section for Roper production in a Deeply Virtual Compton Scattering (DVCS) process. We will use a factorisation of the GPDs to calculate the scattering amplitude for the case where the Roper is created by momentum transfer into a bare nucleon and consider the qualitative effect of including the process where a momentum is injected into an $N\pi$ system.

This paper summarizes a contribution to the QCHSC Conference. We address the current and historical understanding of Roper structure in the next section. In Section 3 we explore a technique using GPDs to estimate the size of the effect of molecule-like behaviour on the overall structure. In Section 4 we present some preliminary findings and promote further work to be done in this area.

## 2. Historical understanding of Roper structure

Unlike most excited baryons, whose structures and masses can be well described within constituent quark models (CQMs), the Roper resonance presented significant challenges, particularly due to its lower-than-expected mass compared to the first negative-parity excitation. Theoretical and experimental advances suggest that the Roper resonance is not a simple radial excitation of the nucleon, but a more complex state involving strong meson-baryon interactions and possibly hybrid configurations.

Early interpretations of the Roper resonance were based on non-relativistic CQMs, which describe baryons as bound states of three valence quarks. Within this framework, the Roper resonance is assumed to be the first radial excitation of the nucleon. However, these models predict the Roper resonance to have a higher mass than is observed experimentally, making it an outlier in the baryon spectrum [7]. More refined approaches, including relativistic CQMs and algebraic models, attempted to address this discrepancy but struggled to fully reproduce the mass ordering of the lowest nucleon excitations [8].

A significant breakthrough in understanding the Roper resonance came with the realization that it is strongly influenced by meson-baryon interactions. Dynamical coupled-channel models incorporate the effects of virtual meson-baryon states, allowing for interactions between the nucleon and $N\pi$, $N\pi\pi$ and other decay channels [9]. These models suggest that the Roper resonance gains a large portion of its structure from dynamical meson-baryon components rather than a pure three-quark state. The inclusion of pion-induced effects and intermediate mesonic states leads to a lower effective mass, providing a natural explanation for the unexpectedly low mass of the Roper resonance. Some analyses propose that the Roper resonance may be interpreted entirely as a dynamically generated baryon-meson system, such as an $N\sigma$ or $N\pi$ resonance, rather than a simple quark model excitation [10].

Recent high-precision experiments have provided critical experimental insight into the nature of the Roper resonance. Electron scattering experiments have provided data on the transition form factors of the Roper resonance indicating significant meson-cloud contributions, reinforcing the dynamical coupled-channel picture [11]. Analysis of the photoproduction and further decay of resonances through channels such as $N\pi$, $N\pi\pi$, and $N\eta$ reveals that the Roper resonance exhibits unusually strong couplings to multipion channels, supporting the idea of a mixed structure involving both three-quark and meson-baryon components [12]. This hybrid interpretation is further supported by Lattice QCD calculations, which reveal that the Roper exhibits a broader and more complex radial structure than the nucleon [13].

## 3. GPD Techniques

Increasingly, Generalised Parton Distributions (GPDs) have proven to be a convenient way to study hard, exclusive reactions such as Deeply Virtual Compton Scattering (DVCS) and gain an insight into the interior dynamics of hadrons [14, 15]. This area presents opportunity for major growth in our understanding of strong interactions in terms of the fundamental degrees of freedom of Quantum Chromodynamics.

GPDs extend our current Parton Distribution Function (PDF) probe of hadron dynamics by encoding a femto-photographic 'image' in the plane transverse to that of PDFs. Additionally, taking Mellin moments of the GPDs or using Ji's sum rule allows us to obtain access to the hadron's Gravitational Form Factors and Energy-Momentum Tensor (EMT), and the relative angular momentum of the various quark flavors, respectively [14].

Since the formalism was first developed, the idea of accessing non-diagonal DVCS processes, where a nucleon-meson system is produced in the final state, has been of great interest. Firstly, the GPDs for $N \to N^*$ transitions can probe the transition matrix elements of the QCD EMT and provide access to the longitudinal momentum distributions of the active quarks in the production of such resonances [16, 17]. Furthermore, these reactions are methodologically very similar to the low-virtuality electro-excitation of nucleons, but involving explicitly gluonic degrees of freedom which are inaccessible with electroweak probes, particularly in the high-energy limit where gluon GPDs dominate [18, 19].

Following the formalism developed by Semenov-Tian-Shansky and Vanderhaeghen [20], we employ a GPD parametrisation for the $N \to P_{11}$ transition and use it to calculate the scattering amplitude for the off-diagonal $e^-N \to e^-\gamma P_{11} \to e^-\gamma N\pi$ DVCS process. We then recalculate the amplitude, including a term where the nucleon emits a pion that acts as a spectator in a diagonal $e^-N \to e^-\gamma N$ process resulting in $e^-N \to e^-N\pi \to e^-\gamma N\pi$ where the invariant mass of the $N\pi$ is fixed at the Roper mass. We then plot the amplitudes for a kinematic variable of interest and assess whether there is a qualitative effect of producing the Roper through this spectator method. We note that we have not yet included the Bethe-Heitler interference term, where the final-state photon is produced on the electron line, i.e. via bremsstrahlung. However, we expect that this term will not cancel the qualitative effect of adding the $\pi$-spectator term.

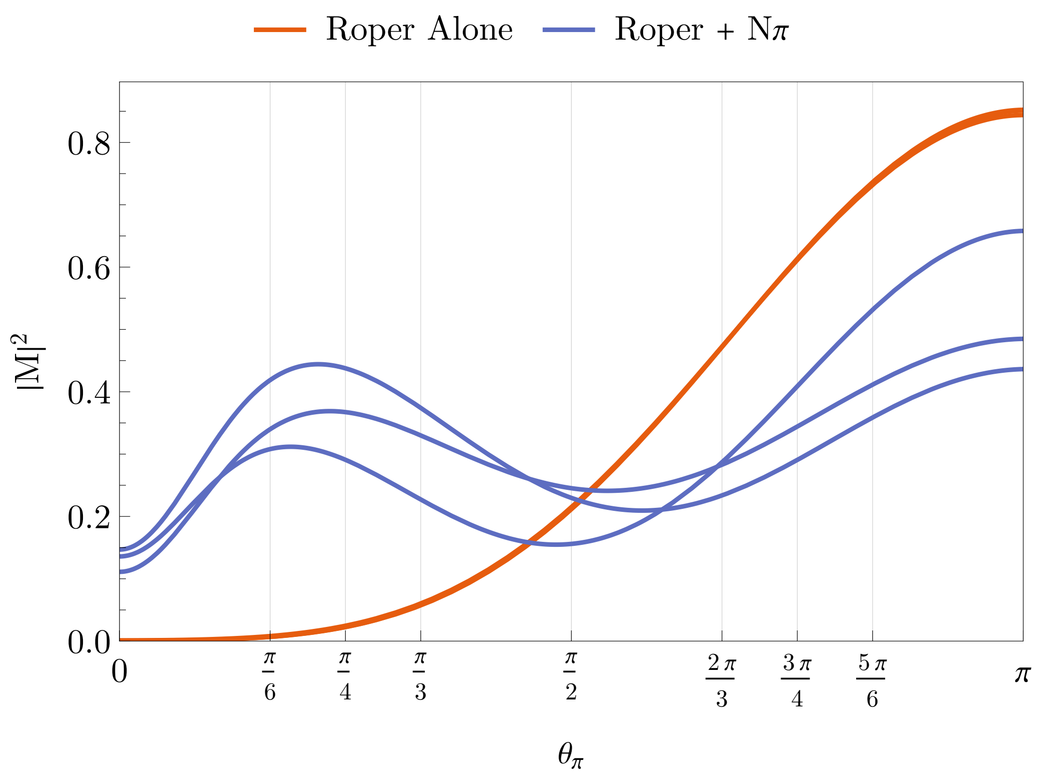


**Figure 1:** Angular distribution of the scattered pion in $e^-N \longrightarrow e^-\gamma N\pi$ process for a Roper produced through DVCS then decaying to $N\pi$ (red curves), and an emitted pion spectating a $N \longrightarrow \gamma N$ DVCS process (blue curves). Produced at fixed $E_e = 10.6\,\text{GeV}$, $Q^2 = 2.3\,\text{GeV}$, $x_B = 0.2$, $\phi = \frac{\pi}{2}$, $-t = 0.5\,\text{GeV}$, $M_{N\pi} = 1.440\,\text{GeV}$, and $\phi_\pi = \pi$ to produce a family of curves using $\theta_\pi = \frac{\pi}{4}, \frac{3\pi}{4}, \frac{\pi}{2}$ ordered top-to-bottom at $\pi$. N.B. the family of three red curves largely overlap.



## 4. Preliminary findings

Figure 1 shows the scattering amplitude for the two processes as a function of the final-state pion's polar angle. Both amplitudes have been normalised such that the area under each curve is equal to 1 so that they represent probability distribution curves. The red curves shows that, for the case where the Roper is produced via $N \longrightarrow N^*$ DVCS after which it decays into $N\pi$, there is a large central peak around $\theta_\pi = \pi$ tending to zero as $\theta_\pi$ tends to zero. Modifying the process to include the emission of a spectator pion before the DVCS transition results in the blue family of curves. This modification qualitatively changes the behaviour, producing an additional peak approximately at $\theta_\pi = \frac{\pi}{4}$ and not forbidding any angle. Figure 1 is produced at a fixed azimuthal angle, $\phi_\pi = \pi$, and photon emission angle, $\theta_\gamma$. The photon emission angle affects the relative heights of the central $\theta_\pi = \pi$ peak and the peak added by including the spectator pion subprocess, and slightly varies the location of the peak. Varying the azimuthal angle has no significant effect on either process. These preliminary results indicate that there is a significant impact on the theoretical scattering amplitude of the Roper if it has some meson-baryon molecular structure. The primary experimental observables then are the presence of an off-forward peak in the pion scattering, and a sensitivity to the photon emission angle not present in the family of red curves which overlap.

## 5. Conclusion and Outlook

These initial findings indicate that the scale of the effect of adding a $N\pi$ scattering term to the creation and decay of the Roper is non-negligible. This implies that the meson-baryon molecular term in the overall structure of the Roper is salient and supports at least a hybrid interpretation as per [12, 13]. Although the quantitative size of this effect is yet to be determined, this GPD technique presents a promising avenue to pursue the structure of low-lying nucleon resonances, including the Roper. The formalism is flexible enough to accommodate extensions to other excited states including the $S_{11}(1535)$ and the more complex spin–3/2 $\Delta(1600)$ to test the universality of this meson-baryon dominance hypothesis.


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