Polarization Transfer Measurement in $\vec{\gamma} p \rightarrow \phi \vec{p}$ Reaction

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Abstract

The ϕ meson is important in the study of quantum chromodynamics (QCD) being an almost pure $s\bar{s}$ state. Double polarization asymmetries in the photoproduction of the ϕ meson have been proposed as an alternative way to probe the strangeness content of the nucleon, and to study additional OZI evading processes by probing the effective ϕNN coupling constant. We propose a first measurement of the proton recoil polarization from photoproduction of ϕ mesons from protons using a circularly polarized untagged bremsstrahlung photon beam. The proposed experiment will be carried out in Hall C using the combination of the SOS spectrometer with a focal plane polarimeter for the proton recoil polarization measurement and the HKS spectrometer for tagging the K^- particle from the ϕ meson decay. A longitudinally polarized electron beam of energy of 2.0 (2.5) GeV, corresponding to an invariant mass of 2.2 (2.4) GeV for the photon-proton system, with a maximum beam current of 50 μA will be employed. Three kinematic settings are proposed corresponding to ϕ mesons produced at forward angles in the center-of-mass frame, and the maximum $-t$ value is 0.6 $(\mathrm{GeV/c})^2$. We request a total number of 25 days for this experiment. The proposed measurement is expected to have great sensitivity to the strangeness content of the proton.

I. INTRODUCTION

Quantum Chromodynamics (QCD) is the accepted theory of the strong interaction in terms of quark and gluon degrees of freedom. QCD is experimentally well tested in the extremely high energy regime. The perturbative QCD (pQCD) approach, which works successfully in the high energy regime, is not applicable in the relatively low energy, or confinement region. As such our knowledge of confinement and the structure of matter in terms of the underlying QCD degrees of freedom is rather poor because of our inability to solve QCD analytically. While lattice QCD is promising, its predictive power at the present time is still limited by computer performance and other technical issues, and this situation will likely remain in the foreseeable future. Therefore, experiments which test various QCD inspired models are essential in improving our knowledge of QCD in the confinement region. In the very low energy region, chiral perturbation theory, an effective theory based on the chiral symmetry (up and down quark masses very close to zero) of QCD is extremely important and productive. Heavy quark symmetry [1] in the strong interaction, discovered by Isgur and Wise, has important implications for describing the spectrum of particles containing a single heavy quark and their decays. The strange quark is rather unique in QCD being neither as light as the up/down quark nor as heavy as the charm quark, which makes the treatment of it rather difficult in various approaches. But the importance of the strange quark in the structure of nucleon, i.e. in the structure of matter is undebatable.

In the naive constituent quark model, which has been quite successful in its description of the low lying states of the baryon [2], the nucleon ground state is composed of three quarks, two with flavor up and one with flavor down in the proton, and *vice-versa* in the neutron. However, in a more realistic description of the nucleon, the three valence quarks are surrounded by quark-antiquark pairs which fluctuate out of the vacuum, the so-called "sea" quarks. The sea is often assumed to be symmetric in the three light quark flavors. However, because the s quark is heavier, this symmetry may be broken. Since the up and down quarks are the lightest and, hence, have the longest fluctuation lifetimes, most of the sea is likely to consist of $u\overline{u}$ and $d\overline{d}$ pairs. Nevertheless, although strange quarks are heavier and thus $s\overline{s}$ pairs would have a lower probability of being in the sea at a given time, they are expected to be there at some level. The fixed target neutrino experiments [3] at Fermi Lab indicate that the $s\bar{s}$ is suppressed with respect to the $u\bar{u}$ and $d\bar{d}$ sea by a factor of about two.

This picture of $s\overline{s}$ pairs in the quark sea has been used to explain a number of experimental observations. These include (1) an anomalous value for the σ term observed in πN scattering, (2) deviations of the nucleon spin structure functions integrated over Bjorken x from earlier theoretical predictions, as observed in the deep inelastic scattering (DIS) of polarized leptons from polarized nucleons, (3) a larger than expected value of the proton axial-vector form factor observed in νp scattering, (4) the production of $\mu^+\mu^-$ pairs in DIS ν_μ scattering and (5) a much larger than expected cross section ratio $\mathrm{p\overline{p}} \to \phi\pi^+\pi^-/\mathrm{p\overline{p}} \to \omega\pi^+\pi^-$.

The ϕ meson being close to a pure $|s\overline{s}>$ state has its unique role in the study of the strange quark contribution to the structure of the nucleon, in gaining access to the quark correlation function in the proton, and in determining the ϕNN coupling constant, the knowledge of which has important implications in relativistic heavy ion collisions in the search for the quark-gluon plasma. The ϕ meson photoproduction on the nucleon is an effective way to address these important and fundamental questions. However, the extraction of the relevant information is only possible with detailed knowledge of the reaction mechanisms over a wide kinematic region.

Polarization degrees of freedom have been proven to be extremely useful in isolating small amplitudes otherwise impossible to be separated from large amplitudes from unpolarized cross-section measurements. Double polarization observables from photoproduction of the ϕ meson from the proton near threshold at small $-t$ values are sensitive to diagrams corresponding to the exhange of an object with unnatural parity between the nucleon and the photon. They are also extremely sensitive to the direct knockout of $|s\bar{s}>$ from the nucleon, which allows an effective probe of the strangeness content of the nucleon. While the proposed measurements are near the ϕ meson production threshold at forward angles, these results will have an important impact on other unique physics questions which one may probe with ϕ meson photoproduction with double polarizations in other kinematic regions. The proposed experiment is the first beam-recoil double polarization measurement of its kind. It opens a window for future exciting physics program of polarized ϕ meson production with the Jefferson Lab 12 GeV energy upgrade and the proposed upgraded detection systems.

II. PHYSICS MOTIVATIONS

A. Strangeness Content of the Nucleon

Low energy theorems relate the isospin even π-N scattering amplitude $\Sigma_{\pi N}$ [4] to $\sigma = \langle p|(m_u + m_d)(u\overline{u} + d\overline{d})|p\rangle/4M_N$. Naive estimates based on the baryon mass spectrum give $\sigma \approx 35$ MeV with SU(3) corrections. In the absence of $s\overline{s}$ contributions, it is expected that $\Sigma_{\pi N} = \sigma$. However, analysis of the πN scattering experiments gives $\Sigma \approx 60$ MeV [5]). This discrepancy and its possible interpretation in terms of strange quarks in the nucleon was first addressed by Cheng and Dashen [6]. Subsequently, the results have been analyzed and interpreted as evidence for $s\overline{s}$ in the nucleon quark sea; Gasser *et al.* [7] have concluded, after a detailed analysis, that $s\overline{s}$ pairs contribute ~ 130 MeV to the nucleon mass indicating about a 10% admixture of strange quarks. However, more recent studies have suggested that the $s\overline{s}$ contribution may be twice as large [8] or consistent with zero [9] after using input from lattic QCD to refine the hyperon mass relations. Moreover, Olsson [10] and Pavan [11] have questioned the accuracy of the π-N data and the extrapolation to obtain $\Sigma_{\pi N}$ and have suggested that $\Sigma_{\pi N}$ may be significantly larger than the accepted value. Thus, any conclusions from these analyses is very uncertain.

Most of the focus on the issue of strange quarks in the proton has arisen from the results of a series of experiments on the Deep Inelastic Scattering (DIS) of polarized leptons on nucleons, pioneered at SLAC and CERN, to obtain the spin structure function of the proton $g_1^p(x)$ [12,13]. By extrapolating to $x = 0$, EMC obtained $\int_0^1 dx g_1^p = \Gamma_1^p = 0.114 \pm 0.012 \pm 0.026$ (where the errors are, in order, statistical and systematic as is usually quoted) in disagreement with the sum rule of Ellis and Jaffe [14], in which the strange quark contribution to the nucleon spin was assumed $\Delta s = 0$. If the discrepancy is assumed to be due to $s\overline{s}$ pairs in the quark sea, then $\Delta s \approx -0.1$.

This prompted further experiments by SMC [15] and SLAC E142 [16] and E143 [17]. These efforts, together with later measurements on the neutron by the SLAC E154 [18] and HERMES collaborations [19], which gave $\Gamma_1^n = -0.036 \pm 0.004 \pm 0.005$, confirmed the agreement with the Bjorken sum rule and the discrepancy with that of Ellis and Jaffe. The most recent analyses now give the net valence quark contribution to the proton spin as [20–23] $\Delta q \approx 0.20 \pm 0.10$ and the strange sea quark contribution as $\Delta s \approx -0.10$. Thus, the extracted value of the strange quark contribution to the proton spin has remained remarkably robust through these measurements. However, the method of determining this value, which has also been consistent, is rather model dependent.

Measurement of the cross section for νp elastic scattering was used by Ahrens *et al.* [24] to extract the proton axial vector form factor $G_A(Q^2)$. These measurements yielded an excess of 0.12 ± 0.07 which was interpreted to be due to either heavy quark currents (such as $s\overline{s}$) or a "nonstandard" axial-vector isoscalar current. If the former interpretation is adopted with the accepted value of the axial mass $M_A = 1.032 \pm 0.036$ GeV, this leads to a value of $\Delta s = -0.15 \pm 0.09$ in remarkable agreement with the DIS analysis [25]. More recent DIS ν_μ scattering [26] has measured the production of $\mu^+\mu^-$ pairs which arise from the absorption of the neutrinos on s ($\overline{s}$) quarks resulting in the emission of μ^- (μ^+) and c ($\overline{c}$), the latter of which decay semileptonically to yield μ^+ (μ^-). The results indicate that the s and $\overline{s}$ each account for about 2% of the nucleon's momentum.

Finally, measurements of p$\overline{\text{p}}$ annihilation [27] at rest leading to $\phi\pi^+\pi^-$ and $\omega\pi^+\pi^-$ final states indicate that the ratio $\sigma(\phi\pi^+\pi^-)/\sigma(\omega\pi^+\pi^-) \sim 2-3\%$ in contrast to the expectation from the Okubo-Zweig-Iizuka (OZI) rule [28] of about 0.4%. Ellis *et al.* [29] have explained this in terms of "shake-out" and "rearrangement" diagrams by including $s\overline{s}$ pairs in the initial p and $\overline{\text{p}}$ states, thus avoiding the discrimination against disconnected $q\overline{q}$ pairs in the OZI rule.

On the other hand, these experimental observations might be explained without relying on any $s\overline{s}$ pairs in the quark sea. In particular, Lipkin has been able to account for the DIS results by assuming a *non* flavor symmetric sea [30]. Anselmino and Scadron [31] have used a modified $SU(6)$ valence quark model that allows for additional gluons and orbital angular momentum. Stern and Clement [32] incorporate $SU(3)$ symmetry breaking to analyze the DIS results and find good agreement with experiment, while imposing $\Delta s = 0$. Anselmino and Scadron have also used their model to obtain $\Sigma_{\pi N} \approx 60$ MeV without strange quarks. McGovern and Birse [33] have carried out an RPA calculation of the energy of the strange baryons and obtain $\sigma_{\pi N} \approx 92$ MeV and an expectation value of ≤ 0.05 for the $s\overline{s}$ content of the nucleon. While Close has argued that there is consistency in the $s\overline{s}$ content from DIS and νp, he also shows that if it is assumed instead that $\Delta s = 0$, then the νp data can be used to determine $M_A = 1.06 \pm 0.05$ GeV which is not in disagreement with the accepted value [25]. Lipkin (along with Zou) [34] has also demonstrated a possible breakdown of the OZI rule in the p$\overline{\text{p}}$ experiments. Thus it is not completely clear from the earlier measurements that there is convincing evidence for $s\overline{s}$ as constituents of the quark sea.

Parity-violating (PV) electron scattering can be used to probe the possible strangeness content of the proton by measuring the strange form factors of the nucleon from the interference of the γ-exchange and the Z^0-exchange amplitudes [35]. However, there are other contributions to parity violating electron scattering than those that arise from the interaction with strange quarks, and the quantitative extraction of the strange electric and magnetic form factor of the proton depends sensitively on knowledge of both the proton and neutron electromagnetic form factors, the latter of which is still poorly known at present. Recently, parity-violating experiments have been carried out at JLab, Mainz and MIT-Bates and others are planned. Results from both the SAMPLE [36–38] experiment at MIT-Bates and the JLab Hall A experiment HAPPEX [39,40] have been reported, and the extracted strange electromagnetic form factors are consistent with zero within the experimental uncertainties. However, it should be pointed out that a vanishing strangeness charge radius or magnetic moment does not necessarily mean an absence of strange quarks. The strange form factors probed from PV electron scattering experiments are sensitive to the details of the strange quark wave function.

The measurement of double polarization asymmetries in ϕ photoproduction from a nucleon target has been proposed as an alternative way of probing the strangeness content of the nucleon. [61,51] Such a proposal is based on the fact that a ϕ meson is an almost pure $s\bar{s}$ pair and direct knockout of an $s\bar{s}$ pair from the nucleon ground state is expected to contribute to ϕ meson production from a nucleon. However, because the ϕ possesses the same quantum numbers as the photon, *i.e.* is a vector meson with $J^P = 1^-$, there is a large (dominant) amplitude for ϕ production through vector-meson-dominance (VMD) via which the photon (real or virtual) fluctuates into a vector meson such as the ϕ and interacts hadronically with the nucleon, scattering diffractively through Pomeron exchange. At small $-t$ this is expected to be the dominant amplitude for ϕ photoproduction. Thus the observation of direct $s\bar{s}$ knockout must be observed through interference with the VMD amplitude employing double polarization asymmetries.

B. The OZI Rule and the ϕNN Coupling Constant

The Okubo-Zweig-Iizuka or OZI rule asserts that disconnected quark-line diagrams are highly suppressed relative to connected ones. Therefore, it predicts a small ϕNN coupling constant. While direct knockout of an $s\bar{s}$ from the nucleon contributes to OZI-evading production of the ϕ from the nucleon if there exists a non-vanishing $s\bar{s}$ content, the direct ϕNN coupling can induce OZI evading processes as well. The direct ϕNN effective coupling constant through kaon loops and hyperon excitations is predicted to be $g_{\phi NN} = -0.24$ [41], which is consistent with the OZI prediction. On the other hand, analyses of the nucleon electromagnetic form factor [42–44] based on the vector meson dominance model, and baryon-baryon scattering [45–47] favor a large ϕNN coupling constant ($g_{\phi NN} = -2.3$ to -4.7) that strongly violates the OZI rule. The extracted ϕNN coupling constant from these analyses is indirect and rather model dependent. Observables directly sensitive to the ϕNN coupling are therefore essential to the study of OZI violating processes.

The recent JLab CLAS ϕ photoproduction data [48] at large momentum transfers, allow a new promising way to constrain the ϕNN coupling constant. The data exhibit an increasing differential cross-section at large $\mid t \mid$, which has been interpreted as due to contributions from the u-channel nucleon exchange. The data have also been reanalyzed [49,50] to probe the nucleon resonances that couple to the ϕN channel of the SU(3) quark model. Recently, Oh and Bhang [51] re-analyzed the CLAS data taking into account contributions from Pomeron exchange, pseudo-scalar meson (π, η) exchange, the nucleon pole term and $s\bar{s}$

direct knockout diagrams. With $\mid g_{\phi NN} \mid = 3.0$, their model can reproduce the CLAS differential cross-section data (Fig. 3a). This result is consistent with results based on the Regge trajectory [52], and is also consistent with the ϕNN coupling constant obtained from the analyses of nucleon form factors and baryon-baryon scattering data described above. However, the VMD based electromagnetic form factor study only determines that the relative phase between the $\phi\gamma$ coupling and the ϕNN coupling is negative. One may further constrain the ϕNN coupling in ϕ photoproduction. Oh and Bhang [51] found that double polarization observables from ϕ meson photoproduction can also determine the phase of the ϕNN coupling. A well constrained ϕNN coupling constant is not only crucial to the study of OZI violating processes, it is also important as a test of VMD models in the description of nucleon electromagnetic form factor data.

However, the results by Oh and Bhang are different from predictions by Zhao *et al.* [50], which include nucleon resonances decaying into the ϕN channel within an SU(3) quark model. Therefore, double polarization asymmetry measurements in ϕ meson photoproduction can be used to test models for the nucleon pole terms and nucleon resonances, which has important impact on the search of the so-called "missing nucleon resonances". While double polarization asymmetry measurements from elastic ϕ meson photoproduction at large values of $-t$ are most sensitive as a probe of the ϕNN coupling as shown clearly in Figs. 5-7, and to differentiate different afore mentioned models, measurements at forward angles (small $-t$) are important to extract the ϕNN coupling constant reliably because they provide stringent tests of models. The proposed double polarization measurements of this experiment focus on forward angles.

C. Quark Correlation Function in the Nucleon

The CLAS collaboration reported the first measurement [48] of elastic ϕ photoproduction cross-section from the proton up to a $\mid t \mid$ value of 4.0 (GeV/c)^2. The ϕ photoproduction data can be well described at small values of $-t$ by the diffractive process through the VMD model, or the exchange of a Pomeron trajectory in the t-channel in a more modern description. However, at larger $-t$, the small impact parameter makes it possible for a quark in the vector meson and a quark in the proton to become close enough to exchange two gluons. The two gluons exchanged may not have enough time to re-interact to form a Pomeron because of the short distance involved. A diffractive model of Pomeron exchange by Donnachie and Landshoff [53] can describe the elastic ϕ photoproduction data well only up to a $-t$ value of 1.0 (GeV/c)^2, treating the Pomeron as two nonperturbative gluons.

Large momentum transfer may also select out configurations in which the transverse distances between the two quarks in the vector meson and the three quarks in the proton are small. As such, each gluon can couple to different quarks in the vector meson [54], as well as to two different quarks in the proton [55]. The exchange of quarks is suppressed because of the dominance of the $s\bar{s}$ component of the ϕ meson, and the assumed smallness of the strangeness component of the nucleon. Therefore, elastic ϕ photoproduction at large momentum transfer might be used to resolve the Pomeron as being composed of two-gluons and to study the quark correlation function inside the proton [52,56,57].

The CLAS data [48] at large $-t$ values rule out the diffractive Pomeron and strongly favor its two-gluon component, thus opening a window to the study of the quark correlation function inside the proton. The constraint of the ϕNN coupling constant is also crucial for this endeavor because of the contribution of the exchange of the nucleon pole in the u-channel at large $-t$ values, which is believed to contribute to the rise of the differential cross-section at large $-t$ [48,52]. Furthermore, the confirmation or refutation of the assumption that the strangeness content of the nucleon is small is important to the access of the quark correlation function. Such an assumption will be tested by the proposed measurements of double polarization asymmetries in elastic ϕ photoproduction from the proton at small $-t$ values, which is the region most sensitive to the strangeness content of the nucleon.

III. DOUBLE POLARIZATION OBSERVABLES IN ϕ MESON PHOTOPRODUCTION ON THE PROTON

A. The effect due to the strangeness content of the quark sea

The idea of looking for hidden strangeness in the nucleon, *i.e.* for $s\bar{s}$ pairs in the quark sea directly, originally proposed by Henley *et al.* [58], is to measure the amplitude for the direct knockout of such a pair in the form of a ϕ meson which is known to be nearly pure $s\bar{s}$. The difficulty with such a measurement is that other mechanisms contribute to ϕ production as well. Thus the problem (and the solution) is to attempt to find an experimental observable which is sensitive to the probability of finding the $s\bar{s}$ *in* the nucleon, rather than from some other mechanism(s). As is usual when searching for small reaction amplitudes in the presence of a larger one, the knockout amplitude is determined by measuring its interference with the larger amplitude. Polarization observables are one of the standard tools for measuring such interferences. As we will show, the prediction based on the conventional mechanisms for dynamical production of the ϕ gives a negligible contribution to these polarization observables, while that due to pre-existing $s\bar{s}$ pairs contributes significantly.

The primary contribution to electromagnetic production of the ϕ is for the incoming photon (real or virtual) to fluctuate into a virtual vector meson (such as the ϕ) and then diffractively scatter from the nucleon by Pomeron exchange, thereby putting the vector meson on the mass shell, a mechanism known as vector meson dominance (VMD) [69] (see Fig. 1a). Other contributions come from processes such as one pion exchange (OPE) (see Fig. 1b) wherein either the photon fluctuates into the vector meson which then exchanges a pion with the nucleon target (Fig. 2(a)), or the photon fluctuates into a virtual ϕ-π state and the pion is absorbed by the target nucleon (Fig. 2(b)). Such processes have been interpreted as corrections to the primary VMD mechanism [66]. Other diagrams such as those with a $\phi\phi\pi$ vertex are possible but are not found to be important in successful VMD calculations. [62,70] These calculations have fit data well. Other diagrams, such as ρ or ω exchange are forbidden by C-parity conservation. Hence, there is no vector meson exchange. The success of VMD models has been investigated in recent years within the framework of QCD. It was shown [71] that the interpretation of Pomeron-exchange in terms of gluon-exchange is consistent with the quark-substructure of vector mesons. At the low $-t$ considered in this proposal, the usual VMD parameterization of the diffractive amplitude is valid.

The cross sections and polarization observables for ϕ photo- and electroproduction have recently been calculated by Titov *et al.* and Oh *et al.* [61,65,51]. The results of these calculations are (1) both the VMD and $s\bar{s}$ knockout contributions are strongly forward peaked, *i.e.* are largest at small momentum transfer, $-t$; (2) with an assumed 1-2% admixture of $s\bar{s}$ quarks in the nucleon, the knockout cross section is $\sim 10\%$ of that for VMD; (3) the OPE contribution to the cross section is approximately equal to that for $s\bar{s}$ knockout; and (4) the uud knockout process, in which the $s\bar{s}$ quarks are spectators, becomes large, and perhaps dominant, at large momentum transfer (very backward angles for the ϕ), where the cross section is still smaller than that at forward angles by about two orders of magnitude. The diagrams for $s\bar{s}$ and uud knockouts are shown in Fig. 1 (e), and (f).

Before presenting the calculated polarization observables in detail, we discuss here a few general considerations regarding them. First of all, the single photon polarization asymmetries are not sensitive to the strangeness content of the nucleon [61]. For real photons, the single transverse photon polarization must vanish in the limit as the reaction angle goes to zero. For large angles the cross section rapidly decreases. Single polarization observables for circularly polarized photons are zero from parity conservation. Thus, the conclusion is that double polarization observables offer the highest sensitivity to the knockout process. The possible double polarization asymmetries observable with polarized photons are beam/vector meson where the cross section is determined for polarized incident photons and measured vector meson polarizations, beam/target in which the beam and target polarizations are controlled, and beam/recoil in which the photon polarization is controlled and the recoil proton polarization is measured.

Since in the diffractive VMD process, the outgoing vector meson ϕ must have the same polarization as the incoming photon, there will be a large asymmetry in the beam/vector meson double polarization asymmetry just due to this process, *i.e.* the cross section will be large for parallel polarizations and small for the antiparallel case. Any effects due to small reaction amplitudes will be dwarfed. This leaves the beam/target or beam/recoil double polarization asymmetries. Since the VMD process does not flip the target spin, the pure VMD contribution to either of these asymmetries is expected to be small, making them the most likely to have sensitivity to the knockout amplitude.

On the other hand, for the knockout mechanism, reversing the target polarization is equivalent to reversing the spectator uud polarization in the $|uud\rangle \otimes |s\bar{s}\rangle$ target. The $s\bar{s}$ in the target proton can couple to either $J^P = 1^-$ or 0^-. This pair then couples to the uud $J^P = 1/2^+$ core configuration in a state of orbital angular momentum $L = 1$ so that the $|uud\rangle \otimes |s\bar{s}\rangle$ total wave function is $1/2^+$. The largest contribution to the electromagnetic excitation of the target $s\bar{s}$ pair to a ϕ ($J^P = 1^-$) arises from the $0^- \rightarrow 1^-$ transition. Hence the largest contribution to the knockout mechanism is from a 0^- $s\bar{s}$ pair coupled to the $1/2^+$ uud valence quark configuration in a relative $L = 1$ state (P-wave). Thus, the projection of the orbital angular momentum along the proton spin axis must be $M = 0$. Reversing the orientation of the target spin reverses the orientation of the uud valence quark configuration in the target proton and flips the sign of the coupling coefficient and, hence, also the sign of the knockout amplitude relative to the sign of the VMD amplitude giving a large asymmetry in the beam/target asymmetry. Similar arguments also apply to the beam/recoil asymmetry.

The calculations by Titov *et al.* and Oh and Bang [61,65,51] of the various double polarization asymmetries confirm the naive arguments given here. The beam/vector meson polarization asymmetry is almost entirely due to the VMD mechanism with extremely little sensitivity to the knockout mechanism. Both the beam/target and beam/recoil polarization asymmetries exhibit large effects due to including $s\bar{s}$ quarks in the proton provided the incoming photon is circularly polarized. For the beam/recoil asymmetry, the largest sensitivity to the percentage of strange quarks in the target occurs for a recoil polarization transverse to the proton momentum direction and in the reaction plane, for ϕ CM angles of $45° - 60°$. This observable was referred to as $L^{BR}_{zx'}$ in the earlier work [61] (see Fig. 4) and as $C^{BR}_{zx'}$ or just $C_{x'}$ in the more recent calculations [65,51]. The $C^{BR}_{zz'} = C_{z'}$ polarization asymmetries (with recoil polarization along the recoil proton momentum direction) are largest for ϕ CM angles near 180° (Fig. 10), where the cross sections are smallest, indicating they are primarily due to the *uud* knockout with an $s\overline{s}$ spectator.

These calculations also include contributions from both 0^- and 1^- $s\overline{s}$ pairs (in contrast to the naive arguments given earlier). Separate amplitudes are calculated for (1) $s\overline{s}$ knockout with a *uud* spectator, and (2) *uud* knockout with an $s\overline{s}$ spectator. Both are included in the asymmetries. The latter is dominated by $s\overline{s}$ coupled to 1^-. The calculations further confirm that the direct $s\overline{s}$ knockout with a *uud* spectator, is dominated by $s\overline{s}$ pairs coupled to 0^-. Finally, the calculations show that the optimal range of initial photon energy is 2-3 GeV. The contribution of the knockout mechanism at higher photon energy is suppressed due to a rapid decrease in the form factors.

These calculations were done using a relativistic harmonic oscillator model [72], an improvement over the original model used by Henley *et al.* [58] which used a nonrelativistic constituent quark model. The VMD amplitude was calculated using the model of Donnachie and Landshoff [62] and developed by others [70] where the Pomeron is described in terms of a non-perturbative multi-gluon exchange. The VMD contribution to the asymmetries includes the OPE corrections. These calculations also include contributions from both 0^- and 1^- $s\overline{s}$ pairs (in contrast to the naive arguments given earlier). The model is constrained such that it reproduces $|\frac{d\sigma}{dt}|_{\theta=0}$ at large s, as well as at low energies and is also constrained by the available data on the angular distributions of $d\sigma/dt$. The parameters needed to evaluate the exchange of the pseudoscalar mesons (π, η) as well as the scalar mesons (σ, a_0, f_0) and the ϕ radiation from the nucleon are determined from SU(3) symmetry and ϕ decay widths.

Clearly, the theoretical predictions depend strongly on the accuracy of the VMD model employed in describing the diffractive amplitude. This question has been addressed partially in Ref. [71]. It can be shown [75] that the VMD parameterization employed by Titov and Oh *et al.* is consistent with the quark-substructure of the ϕ meson in the low $-t$ region considered in this proposal.

The latest results of the photo production calculation by Oh *et al.* explicitly performed for the kinematics of this experiment [51] are displayed in Figs. 9-14. These calculations use all the latest refinements including the spin-dependence in Pomeron-exchange. We will discuss these results, but first we discuss possible contributions from effects which do not depend upon the existence of strange quarks in the sea, as shown in Figs. 5-7.

B. Non-strangeness effects in the ϕ meson photoproduction

The non-strange amplitude is due to the diffractive pomeron exchange, Fig. 1(a), meson exchange, Fig. 1(b), and direct ϕ radiation from nucleons (nucleon pole terms), Fig. 1(c), and 1(d). To demonstrate the negligible contributions to the polarization observables at low

$-t$ from these non-strangeness effects, many theorists such as Titov, Lee, Toke, Streltsova, and Oh and Bhang have done calculations, some of which we will briefly describe here.

Meson exchange contributions are two-fold: pseudo-scalar meson exchange (PSE), and scalar meson exchange (SE). In PSE π and η are expected to be most relevant to this process. Following the investigations of [63,64,73,66] for the effective lagrangian of the $\phi\gamma\psi$ where ψ = π^0, η interaction and using the pseudovector coupling for the NNψ interaction, the one meson exchange amplitude which is purely real, in the ϕ meson rest frame is written as follows:

$$T_{fi}^{PSE} = (2m_i\lambda_\gamma)\vec{\epsilon_\phi} \cdot \vec{\epsilon_\gamma} T_{0fi}^{PSE} \tag{1}$$

where

$$T_{0fi}^{PSE} = \frac{2m_i M_\phi E_\gamma}{t - M_\psi^2}\frac{e}{M_\phi} < g_{\psi NN} >< g_{\phi\gamma\psi} > W_{m_f,m_i}^F \tag{2}$$

where i and f correspond to the initial and final nucleon parameters, and $< g_{\psi NN} >, < g_{\phi\gamma\psi} >$ are the coupling constants related to the NNψ and $\phi\gamma\psi$ vertices. $< g_{\pi NN} >$ is taken to be 13.26 from Ref. [63] while $< g_{\eta NN} >$ is taken to be 3.53, determined using the SU(3) flavor symmetry relation [67], and from the value of $< g_{\pi NN} >$. Again using the SU(3) symmetry and the decay width, Γ, of the $\phi \rightarrow \gamma + \psi$ reaction, the phases and values of $< g_{\phi\gamma\pi} >$ and $< g_{\phi\gamma\eta} >$ were determined to be -0.141 and -0.707 respectively. Since the η and π exchange amplitudes are similar, and they have the same phase (in the case of $\gamma p \rightarrow \phi p$), they may interfere strongly and constructively.

The ϕ radiation amplitude is computed using the ϕNN and γNN interactions and has a more complicated spin dependence than the PSE and SE amplitudes. This amplitude, which is pure real, and its sign are determined by the constants $g_{\phi NN} = -0.24$ and $\kappa_\phi = 0.2$. Calculations by Oh and Bhang have shown that to describe CLAS data on ϕ photoproduction [48] at high $-t$, nucleon pole terms have a significant role, and a rather large $|g_{\phi NN}|$ value of 3.0 has been used to reproduce these data. The calculations specifically performed for this proposal by Oh *et al.* [68] at $E_\gamma = 2.5$ GeV (see Figs. 5-7) show the effects of above mentioned machanisms, *i.e.*, Pomeron exchange, pseudo-scaler meson exchange and nucleon pole contributions to the polarization observables of interest. Two curves are shown for two extreme values of $g_{\phi NN}$ (-3.0 and 3.0). The effects of using such extreme $g_{\phi NN}$ values still does not change the recoil polarizations at forward angles. As shown by Fig. 3a, in the low $-t$ region the ϕ meson photoproduction cross-section is well understood and could be explained by the theoretical model we have mentioned above. Figures 5-7 show the results of the same theoretical calculations applied to the induced polarization P_y, $C_{x'}$ and $C_{z'}$ respectively. At forward angles where this experiment is proposed, the effects of non-strangeness is minimal. This analysis shows that any significant transverse recoil polarization, $C_{x'}$ measured will likely be due to the manifestation of the direct $s\bar{s}$ knockout from the nucleon.

C. Nucleonic resonance effects in the ϕ meson photoproduction

Zhao *et al.* [49,50] have studied the nucleonic resonance effects in the ϕ meson photoproduction using a quark model approach based on the $SU(6) \times O(3)$ symmetry with an effective Lagrangian. The diffractive contribution is produced by the t-channel Pomeron exchange, and the $t-$channel non-diffractive π^0 exchange is also considered. Furthermore, the non-diffractive $s-$ and $u-$ channels are included and their contributions to the cross-section and polarization observables are found to be small at forward angles. Also, the $s-$channel resonance contributions are significantly smaller than the u-channel contributions in ϕ meson photoproduction. Such a feature, which is different from what has been seen in the ω meson photoproduction, suggests that ϕ meson photoproduction is not promising for the search of "missing resonances". Since a possible strangeness content has not been explicitly included in their calculation, the effective ϕqq coupling used in the model cannot distinguish between an OZI evading ϕNN coupling and a strangeness content of the nucleon. Nevertheless, the calculations by Zhao *et al.* [49,50] support the studies by Ref. [61,51,73] that the forward angle kinematics might be an ideal region for studying the strangeness content of the nucleon because the $s-$ and $u-$ channel processes only play a negligible role at forward angle.

D. Expected results from strangeness in the quark sea

Thus we see that at forward angles (small $-t$) non-strangeness induced processes other than the dominant VMD amplitude produce neither a significant contribution to the cross section nor a significant effect in the beam/recoil double polarization asymmetry. In this section we show that the calculations which do a good job of fitting the data over a wide range of $-t$ also predict a large effect due to strangeness in the nucleon in the beam/recoil double polarization asymmetry at small values of $-t$, in exactly the region where competing processes show little effect.

Specifically, Fig. 9 shows the photoproduction beam/recoil double polarization asymmetry $C^{BR}_{zx'} = C_{x'}$, with the photon circularly polarized along the beam axis z and the recoil proton polarization in the scattering plane but normal to its momentum direction z', as given by the latest calculations of Oh and Bhang [51] at kinematics matched to this proposal. As mentioned earlier, this asymmetry peaks at ϕ CM angles of $45° - 60°$. The high sensitivity to a small $s\bar{s}$ is clearly evident. This asymmetry was calculated for a photon energy of 2.0 GeV. Fig. 10 shows $C^{BR}_{zz'} = C_{z'}$ with the proton polarization along its momentum axis. There is still some sensitivity albeit reduced. Figs. 12 and 13 show $C_{x'}$ and $C_{z'}$ at a photon energy of 2.5 GeV; similar conclusions can be drawn by inspection. A comparison of the latest calculation in Fig. 9 with the earlier calculations, upper left panel of Fig. 4, [61] attests to the robustness; the additional refinements did not have a significant effect. Fig. 4 shows the calculated longitudinal beam-recoil asymmetries for four possible phase combinations in the mixing of the two spin configurations of $s\bar{s}$. For simplicity, the rest of the calculations (Figs. 9-14) are shown for the (+,+) phase combination only.

Thus it has been shown by calculations, refined over the past 6 years, that the double polarization asymmetries in ϕ photoproduction are very sensitive to a small $s\bar{s}$ contribution to the quark sea in the proton. While this measurement is only sensitive to $s\bar{s}$ pairs in the color neutral singlet state, and there must be a considerable content in the color octet configuration, nevertheless the observation of a large double polarization asymmetry would be the first truly unambiguous signature of $s\bar{s}$ in the proton sea. No other mechanism can seem to predict a large double polarization asymmetry, and all other inferences of $s\bar{s}$ pairs in the proton are less direct, ambiguous due to model dependencies, or controversial.

IV. EXISTING AND RELATED MEASUREMENTS

Recently there have been two studies of ϕ production on the proton at high energies which are closely related to the proposed experiment, with the aim of searching for evidence of strange sea quarks. HERMES [76] measured beam/target double spin asymmetries, complementary to what we propose here. However, the HERMES results were compromised by poor statistics resulting in a measured asymmetry of $0.20 \pm 0.45 \pm 0.03$ in the exclusive channel and of $0.052 \pm 0.084 \pm 0.003$ in the quasi-real photon channel. Thus they concluded that the strangeness content is consistent with zero but favors a negative phase between the $s\bar{s}$ knockout and diffractive amplitudes if a non-zero strangeness content is assumed. While both HERMES kinematics and our proposed measurements correspond to ϕ meson being produced at forward angle in the center-of-mass frame, the corresponding invariant mass of the photon-nucleon system is quite different: 4.2 GeV (2.15 and 2.36 GeV) for HERMES (this experiment). This is a major difference because the sensitivity to the strangeness content of the proton is greatly enhanced near the ϕ meson threshold [73] where we propose to run this experiment. Fig. 8 shows a calculation [73] of the absolute value of the beam-target asymmetry as a function of the photon energy at a fixed $-t$ value of 0.1 (GeV/c)^2. The non-strange background is shown as the black curve, the calculation which includes the strangeness knock-out contribution (1% strangeness probability) is shown as the blue curve, and the HERMES result is shown as the solid circle. Currently, beam-target asymmetry measurements near the ϕ meson photoproduction threshold are planned at Spring-8 in Japan.

The ZEUS collaboration [77] studied inclusive DIS e^+p scattering with 27.5 GeV positrons and 820 GeV protons and determined the cross sections for ϕ production at high Q^2, very low x, and high transverse ϕ momentum p_T^ϕ. They were compared to MC calculations based on the Lund fragmentation model [78] with a strangeness suppression factor $\lambda_s = P_s/P_{u,d}$ where $P_s(P_{u,d})$ is the probability of creating an $s(u,d)$ quark in the fragmentation process. A value of $\lambda_s = 0.22 \pm 0.02$ gave a good description of the total ϕ production cross section as long as events are restricted to the current region. The ϕ meson production in the current region of the Breit frame is expected to have a significant contribution from the hard scattering of a virtual photon on a strange sea quark. As a result ZEUS claims the first direct evidence for the existence of the strange sea in the proton at $x < 0.006$. However, the Lund MC did not agree with other differential cross sections. Polarization observables were not measured in this experiment.

Additionally, there are three approved experiments with the CLAS detector at JLab on ϕ meson production, which are complementary to the proposed experiment. Experiment E93-031 [48] as discussed previously, measured the differential cross-section of the photoproduction of ϕ meson at large $-t$. The CLAS data [48] at large $-t$ values rule out the diffractive Pomeron and strongly favor its two-gluon component, thus opening a window to the study of the quark correlation function inside the proton.

Experiment E93-022 [79], which is a partially completed CLAS experiment, measures the polarization of the ϕ meson in electroproduction from a proton target by measuring the angular distribution of the decay kaons. It is a single polarization measurement which aims at determining the fraction of ϕ production due to the pseudoscalar exchange mechanism relative to diffractive scattering with a sensitivity at the level of $\sim 5 - 10\%$. Although ϕ

production from a proton target through direct knockout of an $\bar{s}s$ is expected predominantly via the exchange of a pseudoscalar meson, π-exchange and η-exchange diagrams contribute as well to ϕ production because of the decay properties of ϕ mesons. The sensitivity to the $\bar{s}s$ content in the proton is therefore limited by measuring this single polarization observable.

Experiment E98-109 [80], is another partially completed CLAS experiment, proposed to measure photoproduction of ϕ meson with linearly polarized photons. The spin density matrix elements will be extracted by measuring the decay kaon angular distribution. The measurement is expected to be sensitive to new reaction mechanisms other than diffractive scattering or pseudoscalar meson exchange. Because of the dominance of VMD diffractive scattering at forward angles in ϕ photoproduction and electroproduction, the beam-vector meson double polarization observable is not sensitive to the direct knockout of $\bar{s}s$ component of the proton.

V. PROPOSED MEASUREMENTS

We propose to perform a measurement of p($\vec{\gamma}$,$\vec{\text{p}}$)ϕ in Hall C at JLab with longitudinally polarized electrons going through a 6% thick Cu radiator to give circularly polarized photons and the focal plane polarimeter (FPP) keeping $-t \leq 0.6$ (GeV/c)^2 with two ϕ_{cm} angles (35°, and 55°) at an incident electron beam energy of 2.5 GeV and one ϕ_{cm} angle (50°) at an incident electron beam energy of 2.0 GeV. The recoiling protons will be detected in the SOS spectrometer while the decayed K^- from the outgoing ϕ meson will be detected in coincidence with the proton in the new High resolution Kaon Spectrometer (HKS). Coincidence and the reconstructed missing mass technique will be used to identify the undetected ϕ mesons. The invariant mass of the real photon and proton system is fixed at a central value of 2.37 GeV and 2.15 GeV respectively, and the hadron arms SOS and HKS are set corresponding to the proton and the ϕ meson angle, respectively.

As we have discussed in the previous sections, the calculations by Titov *et al.* and Oh *et al.* show that reaction mechanisms for ϕ photo-production at low $-t$ are well understood. In particular Fig 3b shows the cross-section *vs.* $-t$ calculations by Oh $etal.$ for a photon energy of 2.5 GeV compared to the existing world data on ϕ photo-production confirming the insensitivity to processes other than VMD at the forward angles ($-t \leq 0.6$). Furthermore, Ref. [68] show that the double polarization asymmetries at forward angles will be essentially a pure manifestation of the direct $s\bar{s}$ knockout from the nucleon. Secondly, JLab experiment E93-031 measurements show [59] that the correlation from the direct K^+K^- production channel on the K^+K^- decay of ϕ^0 photo-production channel is negligible for $-t \leq 1$ (GeV/c)^2.

Therefore we plan to minimize the sensitivity from other reaction channels by staying at a $-t \leq 0.6$ (GeV/c)^2 to probe the strangeness content of the nucleon. Based on these theoretical predictions and due to the experimental complications and the low luminosity associated with the tagged photon flux and the solid polarized proton target in Hall B, we propose this measurement with a longitudinally polarized electron beam and radiator and a focal plane polarimeter to measure the recoil proton polarization from p($\vec{\gamma}$,$\vec{\text{p}}$)ϕ in coincidence with one of the decay particles from ϕ, the K^-. As we have shown, the maximum sensitivity to strangeness in the recoil polarization asymmetries are at forward angles $30° \leq \phi_{cm} \leq 60°$ at photon energies just above ϕ production threshold. We have chosen 2.0 and 2.5 GeV. Here we are mainly interested in measuring the transverse component of the polarization transfer, $C_{x'}$ which will enable us to distinguish between a strangeness content of 0% *vs.* 0.25% at the level of up to 4.5 σ.

A Monte-carlo simulation was written to estimate the count rates. The expression for the differential cross-section is taken from Ref. [60]:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\Big|_{t0} e^{(6t+1.4t^2)} (3)$$

where $\frac{d\sigma}{dt}|_{t0} = 1000$ nb/(GeV/c)^2

Figs. 18-20 (21-23) show the calculated recoil polarization observables, $C_{x'}$, $C_{z'}$,and P_y as a function ϕ angle in the center-of-mass frame of the real photon and proton system at a photon energy of 1.925 (2.425) GeV along with the projected error bars. The 3 lines are for VMD+OPE (no strangeness in the proton, an $\bar{s}s$ admixture of 0.25%, and 1% in the proton, respectively.

We emphasize that this experiment will utilize fully the unique features of Hall C: the high luminosity and the HKS spectrometer, which is optimized to detect kaons with low momenta at very forward angles and capable of handling rates as high as a few MHz. This experiment will provide in a timely way a very important measurement of the double polarization asymmetries in the photoproduction of the ϕ meson to probe the strangeness content of the proton. Future extensions of such an experiment to higher $-t$ are important for the determination of the direct coupling, the measurement of quark-quark correlations, and the search for a possible $\phi - N$ bound state. This initial measurement will motivate more theoretical work in this direction which certainly will help to interpret the data in a less model-dependent way. Furthermore, this measurement will be complementary to any possible future Hall B experiments in which a polarized tagged photon beam and a polarized solid proton target might be employed, thus providing a cross check of the theory. This experiment will also motivate future experiments in Hall A/ Hall C with polarized electron beam and the FPP on the ϕ meson production at higher energies (8-12 GeV).

VI. THE EXPERIMENT

A. Experimental Overview

This experiment requires a longitudinally polarized electron beam with polarization 80% at a maximum beam current of 50 μA. The experiment will employ the Hall C 4 cm long cryogenic liquid hydrogen target, a 6% Cu radiator, Short Orbit Spectrometer (SOS) with a FPP, and the High resolution Kaon Spectrometer (HKS). Two electron beam energies: 2.0 GeV and 2.5 GeV are required. We will use the missing mass technique to identify the undetected ϕ meson by measuring the recoiling protons in coincidence with the K^-'s from the decay of the photo-produced ϕ mesons: p($\vec{\gamma}$,$\vec{\text{p}}$)ϕ.

The following conditions were taken in to account to optimize the experiment.

- The $-t \leq 0.6$ region is forward peaked, requiring the kaon detection spectrometer at a forward angle (around 10°).

- Given the high singles rates at forward angles only the HKS, which could handle rates up to a few MHz, could be used to detect the kaons.
- The maximum kaon momentum required for this experiment is 1.01 GeV/c which is below the designed goal for the HKS of 1.2 GeV/c.
- The detection of K^- is subject to much less background than the detection of K^+ since, (1) the background from Λ production is eliminated, and (2) calculations show that the electron singles rates in the HKS are not a problem at these kinematics.
- Given the fact that the HKS will be used as the kaon spectrometer, the most convenient solution is to use the SOS as the proton detection spectrometer due to the following reasons:
  - The proton arm and the kaon arm have to be on either side of the beam line and the HMS is already on the HKS side.
  - The maximum proton momentum required for this experiment is about 0.83 GeV/c which is well below the maximum momentum of 1.5 GeV/c of SOS.
  - The only new requirement for this setup is to build a new Focal Plane Polarimeter (FPP) that fits in the SOS. This can be done reasonably easily, by the aid of using the two extra Horizontal Drift Chambers (HDC's) available for SOS. This will be discussed in more detail in the following sections.

B. Proposed experimental geometry

Given the fact that we are proposing to use the SOS, the target will be a 4 cm LH2 target, the maximum target length seen by the SOS at 90°. Since the LH2 target is at the SOS pivot, and the kaons have a mean life of 1.24 x 10^{-8} s, we tried to position the HKS such that the flight path for the K^- is as short as possible. This is achieved by moving the HKS upstream towards the SOS pivot from the position used in the Hypernuclear experiment, E01-011. Since the HKS spectrometer cannot see a forward angle of 10.4°, we also plan to use the splitter magnet to bend the K^- events outward to a larger angle. The minimum distance that the splitter magnet could be positioned due to the size of the scattering chamber is 1.25 m from the target. Keeping the splitter plus HKS system identical to the E01-011 experimental configuration, we thus need to move the splitter to a 1.25 m from the SOS pivot. By rotating the splitter plus HKS system 3.5° away from the beam line from the E01-011 configuration, we can achieve the necessary configuration. The HKS will be physically at an angle of 24.9° while the splitter would give a total bend angle of 11.5°. In this configuration the HKS detector stack plus walkway for people and 52$''$ concrete around the stack could be incorporated if one uses the HMS platform as well to stack concrete for the side where HMS (at its most backward angle) interferes. This experiment will need a smaller platform to hold the HKS detector stack rather than using the T_{20} platform that E01-011 is planning to use. The configuration for this experiment is shown in Figs. 14 and 15.

The three kinematic settings require kaon angles ranging from 10.3° to 16.3°. While the HKS does not have wheels to easily change the scattering angle, it can accept 7° in scattering angle, with the central angle of 13.3° matched to these requirements. The HKS specifications for the afore mentioned configuration for this experiment are shown in Table II.

We are planning to use SOS in the open collimator configuration. The aerogel Cerenkov of $n = 1.05$ (10cm thick) will be used to separate π^+'s from protons. A maximum π^+/p ratio of 100/1 can be separated using this aerogel. Time-of-flight will further improve the particle identification capability of the SOS, which is sufficient for this experiment.

C. The Polarized Electron Beam

Given the technical developments achieved over the years with strained GaAs cathodes, high electron polarization (80%) is already achieved at TJNAF. The polarization of the beam will be measured with the Hall C Möller polarimeter. We request a beam current of 35μA at an electron polarization of 80% in this proposal.

D. The Focal Plane Polarimeter

We are planning to remove the Gas Cerenkov counter in the SOS and install a FPP into this space. Since the proton momenta desired for this experiment range from 560 MeV/c to 830 MeV/c, a $3''$ graphite analyzer is optimum. The collaboration will make a support frame to hold the $3''$ analyzer and the two rear chambers for the FPP. The two HDC's at the focal plane of the SOS will also be used as the two front Chambers for the FPP while the two extra HDC's will be used as the two rear chambers for the FPP. The two HDC's that are at the SOS focal plane are 41 cm x 68 cm while the additional HDC's are 55 cm x 80 cm. This will be sufficient to cover a 20° scattering cone containing the majority of the events scattered from the secondary analyzer.

The analyzer covers the full spectrometer acceptance. Each HDC chamber consists of six planes of wires (2 U, 2V, and 2X). This gives sufficient redundancy that tracking efficiency is close to 100% over the entire active area. Since the SOS HDC's have a position resolution of better than 180 μm, by keeping the two rear chambers 20 cm apart, we could easily achieve an angular resolution of 1 mr for the scattered events. The efficiency and the analyzing power for events scattered between 5° and 20° for momenta of interest for this experiment are shown in Table III based on measurements performed at JLab Hall A.

E. Simulations

For the two-body process γp $\rightarrow$ ϕp one can reconstruct the energy of the incident real photon from the measured proton kinematics provided the undetected particle is a ϕ meson. In addition to the proton, we also detect the K^- decay from the ϕ meson which allows us to remove background events by reconstructing the square of the missing mass for the ϕ meson. Thus, it is very important to have good resolution in the reconstructed ϕ mass to reject backgrounds. A Monte Carlo simulation code was written for the purpose of the reconstruction of the square of the ϕ meson mass.

In our simulation, we used rms momentum resolutions of $\delta p/p = 2 \times 10^{-4}$ for the HKS and 1.5×10^{-3} for the SOS. 1.0 mr (7 mr) and 3.0 mr (0.5 mr) were used for the horizontal and vertical rms spectrometer angular resolutions of the HKS (SOS), respectively. Multiple scattering in the target, windows, and air gaps were included in the simulation, as well as straggling and energy loss for the outgoing particles. For the kinematics of our proposed measurements, the reconstructed ϕ mass resolution is dominated by multiple scattering in the target in the hadron arm. The missing mass squared resolution (FWHM) from kinematic reconstruction only is around 0.01 GeV^2. The total missing mass squared resolution is $\sim$ 0.013 GeV^2 which includes the natural decay width of the ϕ meson. Figure 17 shows the simulated missing mass squared resolution from the $\gamma + p \rightarrow p + \phi$ reaction along with the three-body final state K^+K^- production which is the primary source of background for this experiment. This is from one of the kinematics of this experiment, $< \theta^{\phi}_{cm} >= 35°$, and $E_\gamma = 2425$ MeV. With this kind of missing mass squared resolution, a missing mass squared cut of $m^2_\phi - 0.01 \leq M^2_{missing} \leq m^2_\phi + 0.01$ (GeV^2) can reject the backgrounds efficiently as will be discussed later in this proposal.

F. Backgrounds

γp $\rightarrow$ pϕ is a two-body process. Backgrounds will arise from other two-body as well as three-body final states. The dominant two-body final state background channels will be rejected by the missing mass cut on the ϕ mass peak.

Singles hadron rates in the HKS and SOS spectrometers were estimated using two methods: (a) using the Lightbody and O'Connell code [84] and (b) a parametrization of bremsstrahlung data at high energies [85], which essentially agree with each other. Quasifree kaon production was assumed to scale as $A^{0.8}$ and normalized to the data from Hall C experiment E89009, giving an upper limit of 840 Hz for the HKS for this experiment. The singles electron rates were estimated from the code QFS. Table IV shows the expected singles rates for the HKS and SOS spctrometers as well as the expected accidental coincidence rates from this experiment. Both the SOS and HKS total rates for this experiment are dominated by the singles $\pi^+(\pi^-)$ rates. While the HKS can handle a total rate up to a few MHz, the SOS can handle only up to 500 KHz. Therefore our beam currents vary for each kinematic point governed by the singles rates in the SOS. The maximum total singles rates estimated for SOS from this experiment is 471 kHz. With a coincidence timing cut of 2 ns, we have a maximum accidental coincidence rate of $R_{acc} = (0.13 \times 10^6 Hz)(2 \times 10^{-9})(840) \sim 0.22 Hz$. One can further reduce the coincidence rate by requiring a vertex cut.

The primary source of physics background for this measurement is the three-body final state s-wave K^+K^- production [86]. A Monte Carlo simulation code was writen to estimate this background, taking into account the momentum and angular resolutions of the two hadron spectrometers (SOS and HKS) and the full momentum and angular acceptances of SOS and HKS. As mentioned before, multiple scattering in the target, windows and air gaps were also included. An estimate of 1.5 μb for the total resonant and nonresonant s-wave K^+K^- photoproduction cross section, together with the knowledge of the differential cross section for the ϕ meson photoproduction at a photon energy of around 2.425 GeV allowed us to normalize the two mass squared spectra with respect to each other. The result of this simulation is shown in Fig 17. This shows that the s-wave K^+K^- direct production background is well under control for this experiment. With a missing mass resolution of 0.013 GeV^2 we will have an s-wave K^+K^- background of less than 20% for the K^+K^- background. Since the results of Hall B experiment, E93-031 show that the interference between the s-wave K^+K^- non-resonant background and the ϕ results in negligible polarization at low $-t$, The effect due to the s-wave K^+K^- production can be corrected by the combination of the following two measurements: (i) the recoil polarization measurement on either side of the ϕ mass peak to determine the polarization contribution of the non-resonant background (K^+K^-) under the ϕ peak, and (ii) the determination of the signal/background ratio at the ϕ mass peak.

G. Counting Rates

To estimate the coincidence rate for p(γ,p)ϕ measurement, we used the cross section formula shown previously and which was used by JLAB proposal E98-109. Table V lists the calculated differential cross section, and the coincidence rates at the proposed kinematics with the spectrometer acceptances taken into account. In estimating the rates, we assumed a maximum beam current of 50 μA. This corresponds to a luminosity of $5.0 \times 10^{37}/(cm^2 sec)$ for a 4-cm LH2 target cell. For the HKS and SOS spectrometers, we used solid angles of 6.7 and 9.0 msr with the extended target and 0.9 for the detection efficiency. In addition, we used a photon energy bin of 100 MeV near the end point, giving a centroid of the photon energy bin around 75 MeV below the end point.

H. Beam Time Estimate

By Fourier analysis of the azimuthal distribution of FPP events, two independent components can be extracted each with a statistical accuracy of

$$\delta P = \frac{\pi}{2\bar{A}_y}\sqrt{\frac{1}{fN}}, \tag{4}$$

where $\bar{A}_y$ is the mean analyzing power and f is the F efficiency, which is defined as the ratio of the events that are accepted by the FPP for polarization analysis to the total number, N, of the spectrometer events. For coplanar kinematics the recoil proton polarization vector, $\vec{P}$, can be expressed as

$$\vec{P} = P_y\hat{y}' + h(C_{x'}\hat{x}' + C_{z'}\hat{z}') \tag{5}$$

where $\hat{z}'$ is along the nucleon momentum direction, $\hat{x}'$ is in the reaction plane and transverse to the momentum, and $\hat{y}'$ is normal to the reaction plane in the laboratory frame. The polarization measured in the focal plane $\vec{P}^{fp}$, is then

$$C_{x'} = P_2^{fp} \tag{6}$$

$$P_y = P_1^{fp}\cos\chi - P_3^{fp}\sin\chi \tag{7}$$

$$C_{z'} = P_1^{fp}\sin\chi + P_3^{fp}\cos\chi \tag{8}$$

where P_1^{fp} is in the dispersion direction, P_2^{fp} is normal to the bend plane, P_3^{fp} is along the trajectory and χ is the spin precession angle.

In order to extract the polarization component of interest $C_{x'}$, which is expected to be sensitive to the strange quark content of the proton and which is calculated in the center-of-mass frame of the incident photon and the target proton, we need to measure both the $C_{x'}$ and the $C_{z'}$ components in the laboratory frame. Although P_3^{fp} cannot be measured with the FPP, the fact that $C_{z'}$ changes sign with the beam helicity whereas P_y does not allows separation of the focal-plane polarization within the spectrometer bend plane into two independent reaction components P_y and $C_{z'}$. Thus, all three components of the recoil proton polarization can be determined from the FPP for this experiment.

By flipping the beam helicities, all three polarization components can be measured with the following statistical uncertainties:

$$\delta C_{x'} = \frac{\delta P}{h} \tag{9}$$

$$\delta P_y = \frac{\delta P}{\cos(\chi)} \tag{10}$$

$$\delta C_{z'} = \frac{\delta P}{h \sin(\chi)} \tag{11}$$

The spin precession angles for the kinematics of this experiment are around 45°. Note that the beam-recoil asymmetry $C_{x'}$ is calculated in the center-of-mass frame of the incident photon and target proton. Thus transformations were performed to calculate the statistical uncertainty in $C_{x'}$ measurement for given beam time from the FPP measurements. In calculating the statistical uncertainty, an electron beam polarization of 80% was assumed. The statistical uncertainties of $C_{x'}, C_{z'}$, and P_y along with the running times are listed in Table V. The running time estimate include data taking for both radiator in and radiator out configurations. The projected statistical uncertainties include corrections due to the non-resonance s-wave K^+K^- contribution.

We request 526 hours of data taking time with 100 % efficiency and 3 additional days for checkout, radiator, and spectrometer changes. In total we request 25 days of beam time.

I. Systematic Uncertainties

The systematic uncertainty of the beam-recoil asymmetry $C_{x'}$ measurement is dominated by the systematic uncertainties in the measurements of the electron beam polarization and the recoil polarization in the FPP. eVThe electron beam polarization will be determined by the Hall C Möller polarimeter/Compton polarimeter and a 3% overall uncertainty can be achieved for the polarization measurement.

The major systematic uncertainties related to the FPP are the knowledge of the analyzing power and instrumental asymmetries. The analyzing power of graphite for protons in the energy range of interest in this experiment has been measured by Jefferson Lab Hall A experiments E93027, E89019, and E94102. The calibration results for the analyzing power were compared with the Los Alamos fit up to a proton momentum of 1.5 G/c and the Saclay fit above this energy, and are in good agreement. Overall uncertainty for the world average is estimated to be ±2% [88]. Instrumental asymmetries (ϵ_{inst}) of the focal plane polarimeter will not be an issue for this experiment since we are primarily interested in the polarization transfer observables which are insensitive to the false asymmetries of the polarimeter to first order. The uncertainty on the analyzing power and the instrumental asymmetries are thus both expected to contribute less to the absolute uncertainty than both the measurement of beam polarization and the statistical uncertainty.

VII. COLLABORATION BACKGROUND AND RESPONSIBILITIES

This experiment requires the longitudinally polarized electron beam, a bremstrahlung photon radiator, the standard Hall C liquid hydrogen target, the Hall C SOS spectrometer, and the new Kaon spectrometer (HKS). The recoil proton polarization will be measured in the SOS using a focal plane polarimeter, which will be installed by the collaboration. The experiment requires engineering and technical support from the Jefferson Lab in configuring a new platform for the HKS for the running configuration of this experiment. Many members in our collaboration have extensive experience in polarization experiments with bremsstrahlung photon beams and focal plane polarimeters. The expertise and manpower of this collaboration is adequate to carry out the proposed experiment. This collaboration also has strong theoretical support.

VIII. ACKNOWLEDGMENTS

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TABLES

E_e (GeV)	θ_{cm}^{ϕ} (degree)	θ_p (degree)	P_p (GeV/c)	θ_k (degree)	p_k (GeV/c)	W (GeV)	$-t$ $(GeV/2)^2$
2.0	50	-28.4	0.65	13.0	0.69	2.15	0.39
2.5	35	-40.1	0.56	10.3	1.01	2.37	0.29
2.5	55	-38.4	0.83	16.3	0.92	2.37	0.60

TABLE I. Kinematics for the proposed $\mathrm{p}(\vec{\gamma},\vec{\mathrm{p}})\phi$ reaction. The negative sign indicates that the proton arm (SOS) is on the opposite side of the beam line compared with the scattered K^- (HKS) direction. W is the invariant mass for the real photon and proton system and $-t$ is the Mandelstam variable.

Configuration	QQD and horizontal bend
Central momentum range	0.69 GeV/c - 1.01 GeV/c
Momentum acceptance	±10%
Momentum resolution ($\Delta p/p$)	2×10^{-4}
Solid angle	6.7 msr
Angular acceptance-scattering angle	119 mrad
Angular acceptance-out of plane	56 mrad
Angular resolution-scattering angle	1 mrad
Angular resolution-out of plane	3 mrad
kaon detection angle (central)	13.0°
Particle flight path	8.75 m

TABLE II. HKS spectrometer specifications specific to proposed experimental geometry.

P_p (GeV/c)	A_c	Efficiency (%)
0.654	0.50	4.0
0.562	0.35	2.5
0.834	0.45	7

TABLE III. Analyzer efficiencies and analyzing powers for the FPP for the kinematics of interest in this experiment.

			HKS			SOS			
E_γ (GeV)	θ^ϕ_{cm} (degree)	Beam current (μA)	π^- (kHz)	e^- (kHz)	K^- (Hz)	π^+ (kHz)	p (kHz)	accidental K^- (Hz)	signal/noise
1.925	50	30	124	38.6	504	371	100	0.10	40:1
2.425	35	30	136	70.0	504	320	84	0.08	20:1
2.425	55	50	174	30.0	840	220	130	0.22	4:1

TABLE IV. Singles rate estimate and signal to noise ratios for the proposed $\mathrm{p}(\vec{\gamma}, \vec{\mathrm{p}})\phi$ measurement.

E_γ (GeV)	θ^ϕ_{cm} (degree)	Beam current (μ A)	$p(\gamma,p)\phi$ (Hz)	Beam time (hours)	$\Delta C_{x'lab}$	$\Delta C_{z'lab}$	ΔP_y	$\Delta C_{x'cm}$	$\Delta C_{z'cm}$
1.925	50	30	4.0	145	0.030	0.045	0.03	0.05	0.03
2.425	35	30	1.6	200	0.040	0.065	0.04	0.06	0.04
2.425	55	50	0.9	181	0.035	0.050	0.04	0.05	0.04

TABLE V. Rate estimate and beam time request for the proposed $\mathrm{p}(\vec{\gamma}, \vec{\mathrm{p}})\phi$ measurement.

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FIGURES

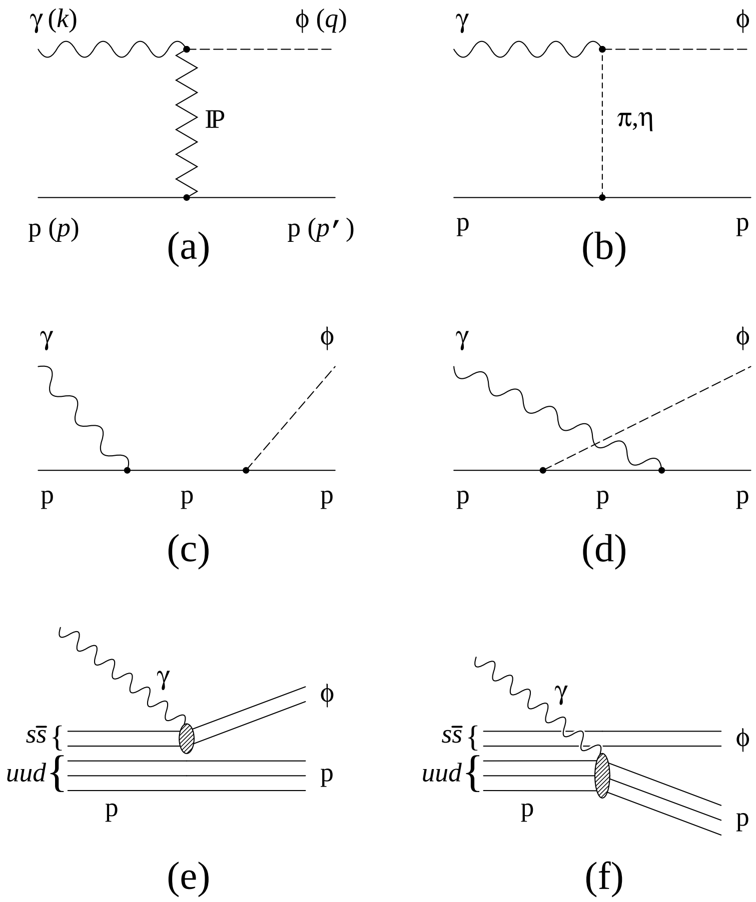

FIG. 1. Diagrammatic representation of ϕ photoproduction mechanisms. a) Pomeron exchange, b) (π, η) exchange, c), d) nucleon pole terms, and e), f) direct knockout processes.

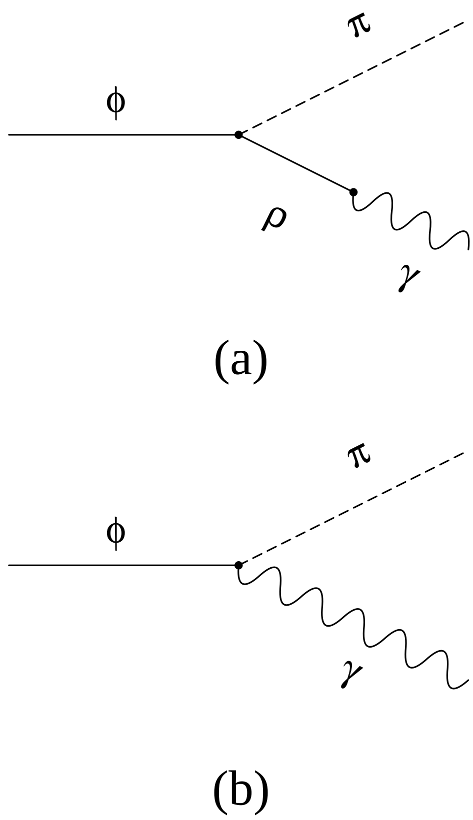

FIG. 2. Two possible mechanisms of $\phi \to \gamma\pi$ decay.

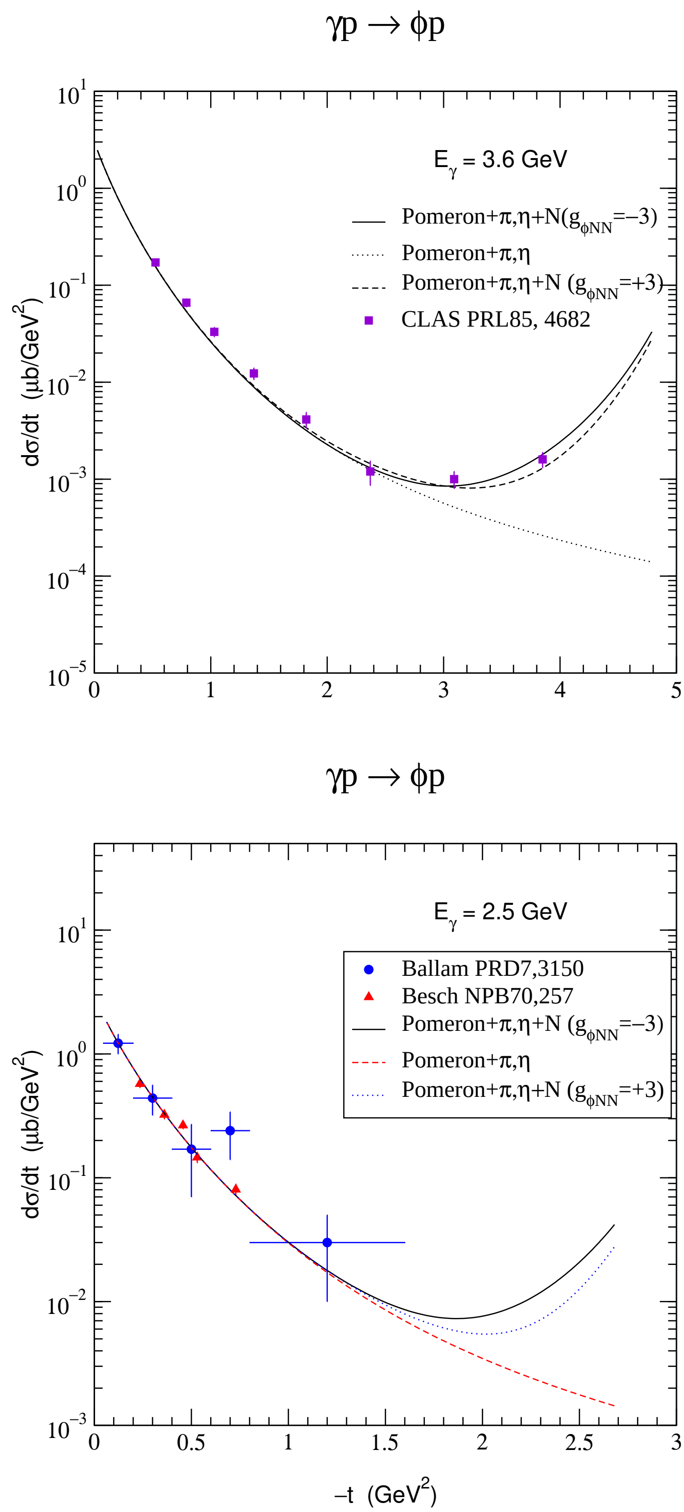

FIG. 3. The differential cross-section of ϕ meson photoproduction from proton as a function of -t for (a)top - photon energy of 3.6 GeV and (b) bottom - photon energy of 2.5 GeV. The dotted curve is a calculation from Oh and Bhang which includes Pomeron, and pseudoscalar meson exchange only. The solid and the dashed curves include additional nucleon pole term contribution, with $g_{\phi NN}$= -3, and 3, respectively.

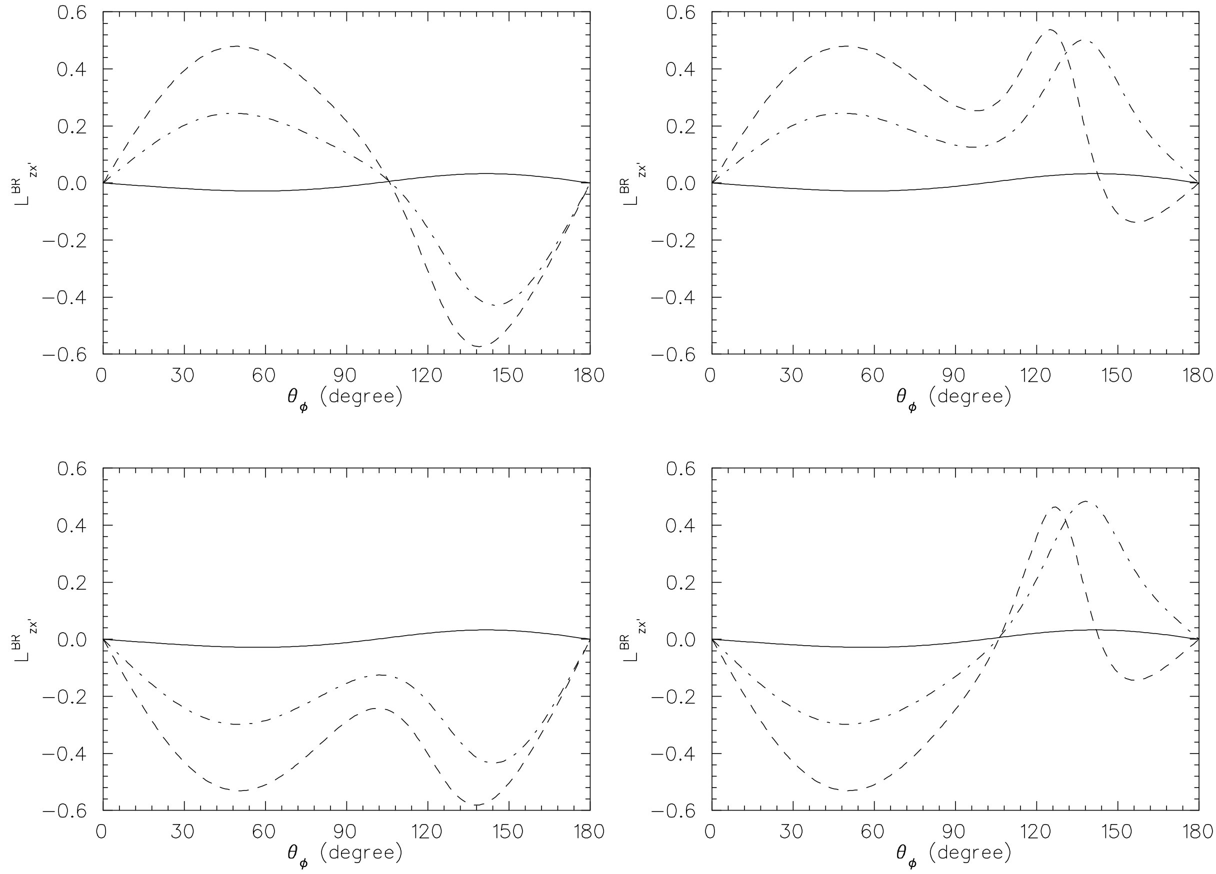

FIG. 4. Longitudinal beam-recoil asymmetry as a function of ϕ_{cm} at $E_\gamma = 1.925$ GeV, calculated by Titov, Oh and Yang [61,89] for photoproduction of ϕ mesons from protons . The solid, dash-dotted and dashed lines correspond to VMD+OPE, 0.25% $\bar{s}s$ probability, and 1% $\bar{s}s$, respectively. The four different panels correspond to four different phase combinations in the mixing of the two spin configurations of $\bar{s}s$.

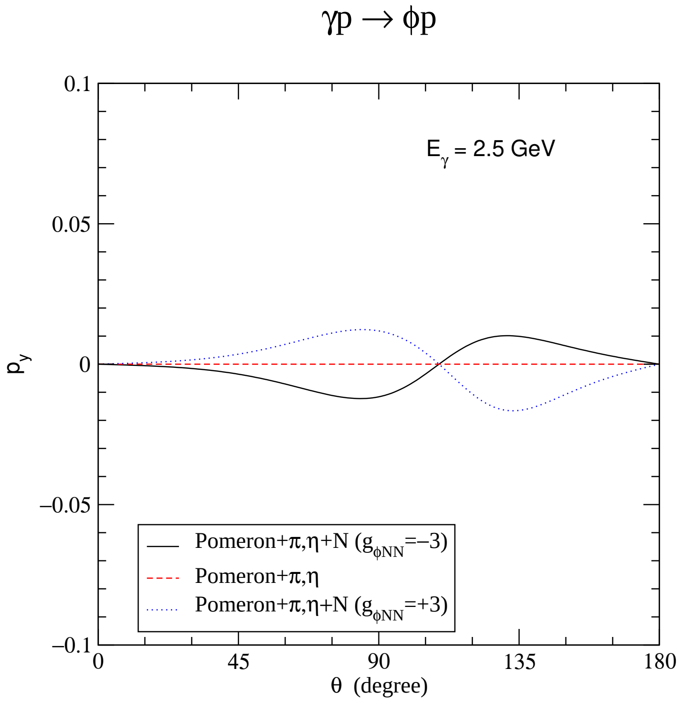

FIG. 5. The recoil proton polarization component P_y (normal to the reaction plane) in ϕ meson photoproduction from proton as a function of center-of-mass angle of ϕ meson. The red dashed curve is a calculation from Oh and Bhang which includes Pomeron, and pseudoscalar meson exchange only. The black and the blue curves include additional nucleon pole term contribution, with $g_{\phi NN}$= -3, and 3, respectively.

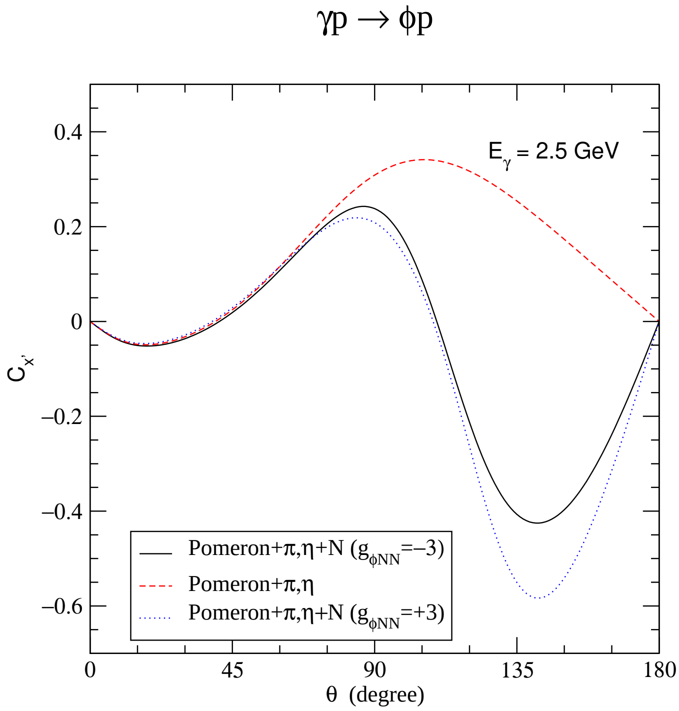

FIG. 6. The recoil proton polarization component $C_{x'}$ (in the reaction plane, transverse to the recoil proton momentum direction) in ϕ meson photoproduction from proton as a function of center-of-mass angle of ϕ meson. The red dashed curve is a calculation from Oh and Bhang which includes Pomeron, and pseudoscalar meson exchange only. The black and the blue curves include additional nucleon pole term contribution, with $g_{\phi NN}$= -3, and 3, respectively.

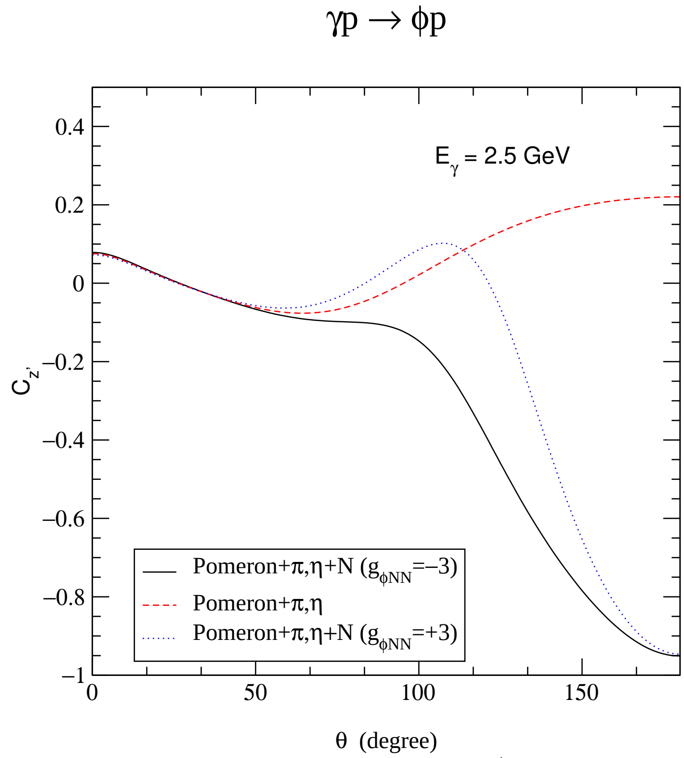

FIG. 7. The recoil proton polarization component $C_{z'}$ (in the reaction plane, along the recoil proton momentum direction) in ϕ meson photoproduction from proton as a function of center-of-mass angle of ϕ meson. The red dashed curve is a calculation from Oh and Bhang which includes Pomeron, and pseudoscalar meson exchange only. The black and the blue curves include additional nucleon pole term contribution, with $g_{\phi NN}$= -3, and 3, respectively.

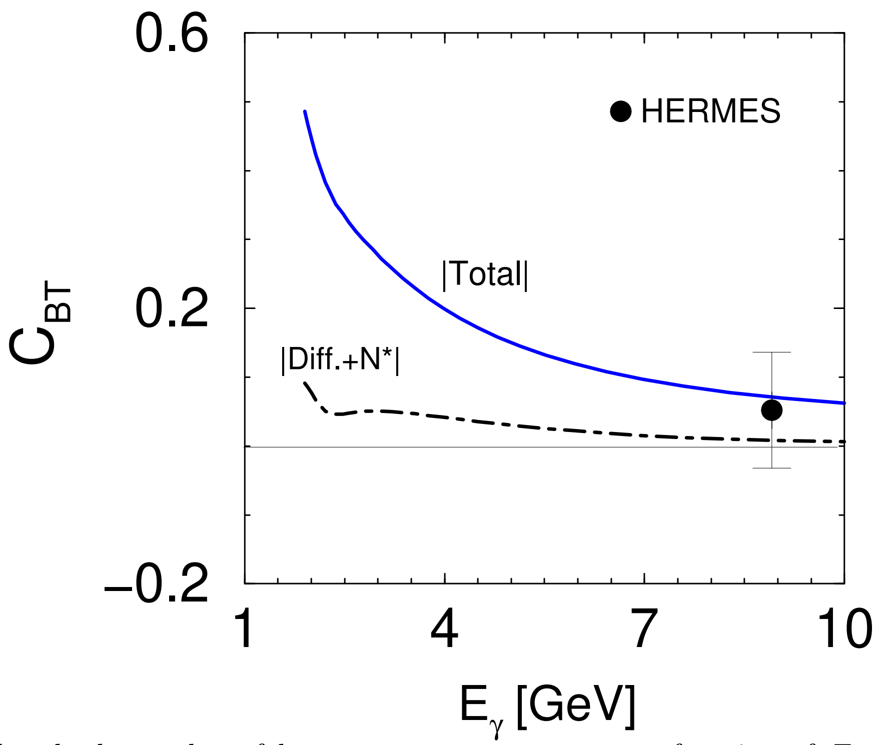

FIG. 8. The absolute value of beam-target asymmetry as a function of E_γ, calculated by Titov for photoproduction of ϕ mesons from protons at a fixed $-t$ value of 0.1 (GeV/c)^2. The non-strangeness contribution, calculation including strangeness knockout (1% strangeness probability), and the HEMRES result are shown as black curve, blue curve, and black solid circle, respectively.

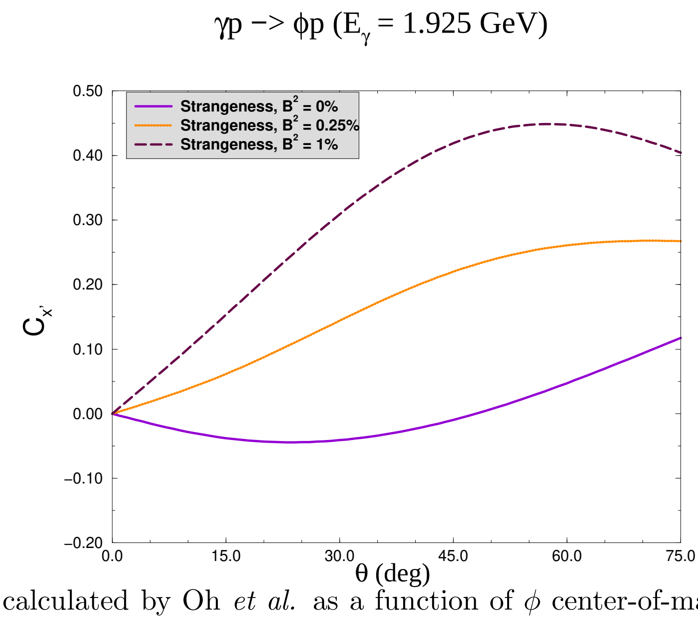

FIG. 9. The $C_{x'}$ calculated by Oh *et al.* as a function of ϕ center-of-mass angle for a photon energy of 1.925 GeV. The solid (purple), solid (orange), and dashed(blue) lines correspond to VMD+OPE (no strangeness), 0.25% $\bar{s}s$ probability, and 1% $\bar{s}s$, respectively.

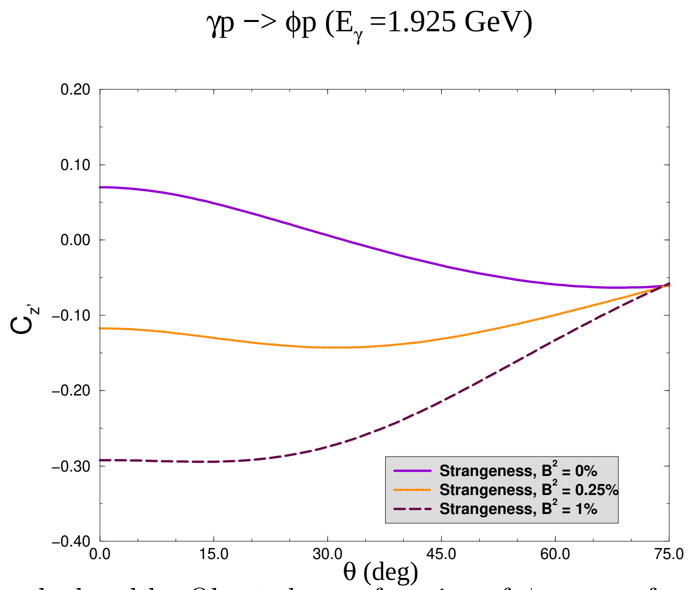

FIG. 10. The $C_{z'}$ calculated by Oh *et al.* as a function of ϕ center-of-mass angle for a photon energy of 1.925 GeV. The solid (purple), solid (orange), and dashed (blue) lines correspond to VMD+OPE (no strangeness), 0.25% $\bar{s}s$ probability, and 1% $\bar{s}s$, respectively.

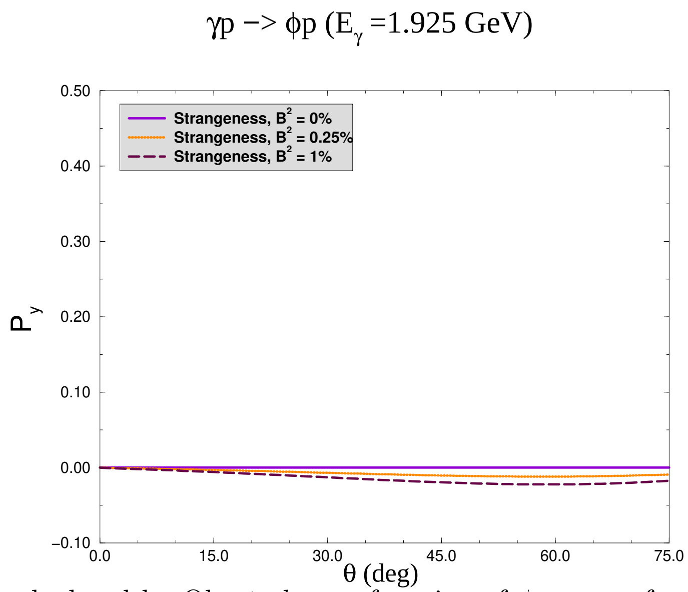

FIG. 11. The P_y calculated by Oh *et al.* as a function of ϕ center-of-mass angle for a photon energy of 1.925 GeV. The solid (purple), solid (orange), and dashed (blue) lines correspond to VMD+OPE (no strangeness), 0.25% $\bar{s}s$ probability, and 1% $\bar{s}s$, respectively.

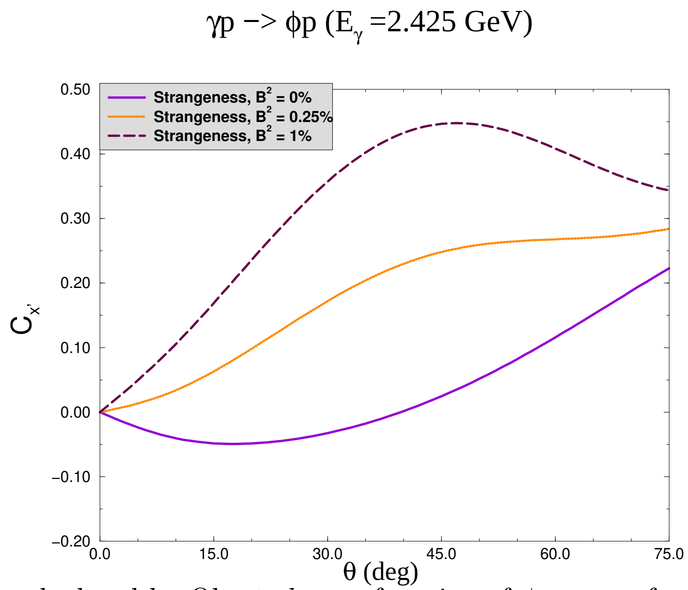

FIG. 12. The $C_{x'}$ calculated by Oh *et al.* as a function of ϕ center-of-mass angle for a photon energy of 2.425 GeV. The solid (purple), solid (orange), and dashed (blue) lines correspond to VMD+OPE (no strangeness), 0.25% $\bar{s}s$ probability, and 1% $\bar{s}s$, respectively.

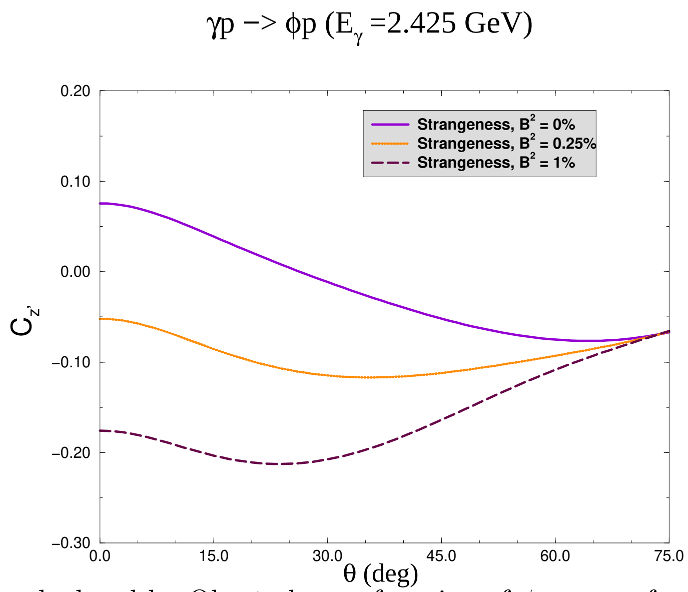

FIG. 13. The $C_{z'}$ calculated by Oh *et al.* as a function of ϕ center-of-mass angle for a photon energy of 2.425 GeV. The solid (purple), solid (orange), and dashed (blue) lines correspond to VMD+OPE (no strangeness), 0.25% $\bar{s}s$ probability, and 1% $\bar{s}s$, respectively.