ETA(547) AND ETA(958) MESON PHOTOPRODUCTION ON THE PROTON

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ABSTRACT

Photoproduction of η and η' mesons has been studied at the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) using a tagged photon beam incident on a hydrogen target with photon energies from the respective production thresholds up to 2.4 GeV. The photoproduced mesons were identified via missing mass reconstruction using recoil proton momentum and time of flight information. Data were obtained in a range of $\sqrt{s}$ from threshold to 2.2 GeV for each meson. In this study, differential cross-section measurements for the $\gamma p \rightarrow p\eta$ and $\gamma p \rightarrow p\eta'$ reactions are presented, and the results compared to recent data.

An isobar analysis of the differential cross-sections is performed. The predicted differential cross-sections from the isobar analysis are used to predict behavior in unmeasured regions of phase space, and to infer total cross sections. For the $\gamma p \rightarrow p\eta$ reaction, a value of the $S_{11}(1535)$ proton helicity amplitude also was extracted and compared to recent analyses.

The data presented greatly extends the energy and angle coverage for differential cross-sections of η photoproduction, and significantly improves the accuracy with which η' cross sections are known.

Chapter 1

Introduction

The η and η' mesons are members of the fundamental meson nonet, and as such share many of the motivations of the extensive pion photoproduction studies performed over the last few decades. One area that differentiates the study of η and η' photoproduction from that of π photoproduction, however, is that the η and η' , while having no net strangeness, do have strange quark content. This difference could help determine the role of strange quarks in the quark model properties of the nucleons. Furthermore, the isospin selectivity of the η mesons provides a tool to deconvolute the nucleon resonance spectrum in order to better isolate N^* nucleon resonances.

Despite all these reasons, photoproduction data for these mesons is very sparse. Facilities have not been adequate to provide this valuable source of information. The data to be presented here were obtained at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The unique capabilities of Jefferson Lab offered a great opportunity to provide η and η' differential cross sections to address the ideas noted above.

1.1 Motivation

Measurements of η and η' meson photoproduction on the proton are targeted at supplying an "isospin filter" to the nucleon resonance spectrum, due to the isoscalar nature of the eta mesons.

The $S_{11}(1535)$ resonance, lying at the η production threshold, has a large coupling to the ηN channel ($\sim 55\%$), and that resonance has continued to be a natural focus of both experimental and theoretical investigations of nucleon resonances. One particular issue regarding the $S_{11}(1535)$ is the value of the proton helicity amplitude. Recent η photoproduction analyses have obtained values of the $S_{11}(1535)$ proton helicity that are in disagreement with values obtained by analysis of pion photoproduction data, as seen in Table 1.1-1.

Table 1.1-1: Proton helicity amplitude table for the $S_{11}(1535)$ resonance taken from the PDG [1].

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.120(0.011)(0.015)	KRUSCHE [2]	97	DPWA	$\gamma N \rightarrow \eta N$
0.060(0.015)	ARNDT [3]	96	IPWA	$\gamma N \rightarrow \pi N$
0.097(0.006)	BENMERROU.. [4]	95	DPWA	$\gamma N \rightarrow \eta N$
0.095(0.011)	BENMERROU.. [5]	91		$\gamma p \rightarrow \eta p$
0.053(0.015)	CRAWFORD [6]	83	IPWA	$\gamma N \rightarrow \pi N$
0.077(0.021)	AWAJI [7]	81	DPWA	$\gamma N \rightarrow \pi N$
0.083(0.007)	ARAI [8]	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.080(0.007)	ARAI [8]	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.029(0.007)	BRATASHEV... [9]	80	DPWA	$\gamma N \rightarrow \pi N$
0.065(0.016)	CRAWFORD [10]	80	DPWA	$\gamma N \rightarrow \pi N$
0.0704(0.00091)	ISHII [11]	80	DPWA	Compton scattering

For η' meson photoproduction, the existing data are very sparse. With so little information available, even formulating questions is hard. Which resonances couple to this meson? Do any couple to a great extent?

1.2 Limitations of previous data on photoproduction

Data on η photoproduction have been very limited until recently. Figure 1.2-1 shows the energy and angle coverage for published data for the reaction $\gamma + p \rightarrow \eta + p$. (This figure does not include the GRAAL results [12] since these results, while submitted to Physical Review Letters, are not yet published.) Figure 1.2-2 includes the data coverage by GRAAL as well as the coverage obtained in this work (CLAS).

From Figure 1.2-1 and Figure 1.2-2, it is easy to see that the coverage added by this work greatly improves the world data set for η photoproduction on the proton.

For η' photoproduction, data are much more scarce. This can be underscored by simply considering the total number of η' events detected in previous experiments. Prior to 1998, 18 η' photoproduction events had been measured. There were 11 events from the ABBHHM bubble chamber experiment performed in 1968 [13], and 7 events were found in the AHHM streamer chamber experiment in 1976 [14]. In 1998, SAPHIR [15] published results that greatly improved the world's statistics, adding an additional 250 η' events.

In this work, many thousands of η' events were detected and used to expand the world database on differential cross sections for the photoproduction process. This reduces greatly the statistical uncertainties associated with η' photoproduction.

Figure 1.2-1: Existing data for η photoproduction (GRAAL results not shown).

Figure 1.2-2: η photoproduction data coverage for TAPS, GRAAL, and data presented herein (CLAS). The horizontal axis is incident photon energy in units of MeV, and the vertical axis is θ in the center-of-mass frame in units of degree.

1.3 Unique capabilities of Jefferson Lab

The Continuous Electron Beam Accelerator Facility (CEBAF) provides high quality continuous electron beams at energies much greater than the production threshold

needed to produce η or η' mesons. In addition to the high quality electron beam, Hall B at Jefferson Lab has a bremsstrahlung photon tagger that allows conversion of electron kinetic energy, through the bremsstrahlung process, to electromagnetic energy. The conversion of electron kinetic energy to electromagnetic energy is measured on an electron-by-electron basis, and thus allows photons to be "tagged" with a highly defined energy. In addition to the photon facilities provided at Jefferson Lab, a nearly 4π charged particle detector in Hall B allows measurement of the reactions $\gamma + p \rightarrow \eta + p$, and $\gamma + p \rightarrow \eta' + p$.

These unique capabilities provided by Jefferson Lab permitted measurements of the η differential cross sections in regions of phase space never measured before, and, in the case of η' photoproduction, measurements of much higher statistical quality than previously obtained.

Chapter 2

Background

In this chapter, a brief description of the bremsstrahlung process is presented. Some general properties of the photoproduction of isospin zero pseudoscalar mesons are discussed. In particular, π^+ photoproduction is contrasted to η photoproduction in order to illustrate how using η photoproduction as an "isospin filter" reduces complexity in measuring the N^* resonance spectrum. The relation between electromagnetic multipoles and differential cross sections is explored by way of CGLN amplitudes. A theoretic method (Hicks isobar analysis model) for relating the CGLN amplitudes to photoproduction data is also described

2.1 The bremsstrahlung process

Meson photoproduction requires photons with energies high enough to create the mesons. The process by which these high energy photons were created, and then used for the meson photoproduction described in this document, is bremsstrahlung. The incident photon energy threshold for η (η') photoproduction is 706 (1447) MeV. These photons created through bremsstrahlung then react with the proton target. The interactions studied here are the occasions when the photon-proton interaction has as final reaction products a proton and an η or η' meson.

Bremsstrahlung is a compound German word meaning "braking radiation." This is the radiation which arises when a charged particle is deflected by a Coulomb field.

Figure 2.1-1: Feynman diagrams for the bremsstrahlung process. In figure (a), the potential interacts with the electron before a photon is emitted. In figure (b), the potential interacts with the electron after the photon is emitted.

According to classical electromagnetic theory, when a charged particle is accelerated (deflected), electromagnetic radiation results. Quantum electrodynamics predicts there is a probability that a charged particle, when in a Coulomb field, will interact with that field and emit a photon. From reference [16]:

There are two (indistinguishable) orders in which the bremsstrahlung process can occur: (a) the electron interacts with the

Coulomb field and subsequently emits a photon, or (b) the electron first emits a photon and then interacts with the Coulomb field.

Figure 2.1-1 shows the Feynman diagrams discussed in the above quote.

The cross section for the bremsstrahlung process can be calculated using quantum electrodynamics. The exact form of the equation is lengthy. However, while the expression for the probability that a photon of a given energy will be emitted from bremsstrahlung is long, the overall energy dependence of the probability is inversely proportional to the energy of the emitted photon:

$$\frac{dN_\gamma}{dE_\gamma} \propto \frac{1}{E_\gamma}$$

Thus, the emission of lower energy photons is statistically favored over that of higher energy photons, weighted by $1/E_\gamma$.

2.2 Photoproduction of isospin zero pseudoscalar mesons

The electromagnetic interaction does not conserve isospin symmetry. However, it is still possible to use photoproduction of the isospin zero pseudoscalar mesons as an "isospin filter." Regardless of what particular interaction occurs during photoproduction, if the final reaction products are a proton and an isospin zero pseudoscalar meson, then, to first order, any nucleon resonance that might have been excited must have isospin 1/2. This is because the resonance decays through the strong interaction, and the strong force does conserve isospin symmetry. Since the only nucleon resonance states that can be excited to a proton and an isospin zero pseudoscalar meson must have isospin 1/2, then all isospin 3/2 (and higher) resonances can be ignored. This greatly reduces the number

of resonances states that must be considered in analyzing data from photoproduction on the proton.

To illustrate how measuring isospin zero pseudoscalar meson photoproduction aids in untangling the nucleon resonance spectrum, the πN channel may be contrasted with the ηN channel as in Figure 2.2-1 and Figure 2.2-2. The $\Delta(1232)$ (isospin 3/2) has a very large signal compared to other resonances in the $\gamma p \rightarrow \pi^+ n$ channel, as can be seen in Figure 2.2-1. For the $\gamma p \rightarrow \eta p$ reaction, no Δ (isospin 3/2) can be excited in this reaction in a one step process. This means that the low-lying N^* resonances can be more easily seen in the $\gamma p \rightarrow \eta p$ channel. Figure 2.2-2 shows the relative strengths of resonances thought to play a part in the ηp channel. In particular, the $S_{11}(1535)$ resonance is greatly enhanced relative to the other resonances for the ηp reaction, while, in the $\pi^+ p$ channel, the $S_{11}(1535)$ is very weak

A general form of the photoproduction amplitude can be written in terms of electric and magnetic multipoles. This is desirable since the multipoles can be directly related to resonances.

Chew, Goldberger, Low and Nambu gave a useful formalism for expressing the complete photoproduction amplitude [17]. We begin with the general expression

$$\frac{d\sigma}{d\Omega} = \frac{q}{k} |\langle 2 | \mathfrak{J} | 1 \rangle|^2. \quad (1)$$

Figure 2.2-1: Resonances and relative strengths for the $\gamma p \rightarrow \pi^+ n$ reaction

Figure 2.2-2: Resonances and relative strengths for the $\gamma p \rightarrow \eta p$ reaction

Here q is the center-of-mass momentum of the outgoing meson, and k is the center-of-mass momentum of the incident photon. The matrix elements are Pauli spinors, and the operator $\mathfrak{S}$ can be written as:

$$\mathfrak{S} = i\boldsymbol{\sigma} \cdot \boldsymbol{\varepsilon} \mathfrak{S}_1 + \frac{(\boldsymbol{\sigma} \cdot \bar{\mathbf{q}})(\boldsymbol{\sigma} \cdot (\bar{\mathbf{k}} \times \bar{\boldsymbol{\varepsilon}}))}{qk} \mathfrak{S}_2 + \frac{i(\boldsymbol{\sigma} \cdot \bar{\mathbf{k}})(\bar{\mathbf{q}} \cdot \bar{\boldsymbol{\varepsilon}})}{kq} \mathfrak{S}_3 + \frac{i(\boldsymbol{\sigma} \cdot \bar{\mathbf{q}})(\bar{\mathbf{q}} \cdot \bar{\boldsymbol{\varepsilon}})}{q^2} \mathfrak{S}_4, \quad (2)$$

where $\boldsymbol{\varepsilon}$ is the photon polarization unit vector and $\boldsymbol{\sigma}$ is the Pauli spin matrix. This form of $\mathfrak{S}$ is the most general form that can be obtained requiring:

- Lorentz invariance
- linearity and homogeneity in $\boldsymbol{\varepsilon}$
- gauge invariance
- parity conservation
- unitarity
- observance of crossing symmetry

The $\mathfrak{S}_i$ terms can be expanded in terms of electric and magnetic multipoles, and derivatives of Legendre polynomials: ($x = \cos \theta$), where θ is the center-of-mass angle.

$$\mathfrak{S}_1 = \sum_{l=0}^{\infty} [lM_{l+} + E_{l+}](P_{l+1}(x))' + [(l+1)M_{l-} + E_{l-}](P_{l-1}(x))' \quad (3)$$

$$\mathfrak{S}_2 = \sum_{l=1}^{\infty} [(l+1)M_{l+} + lM_{l-}](P_l(x))' \quad (4)$$

$$\mathfrak{S}_3 = \sum_{l=1}^{\infty} [E_{l+} - M_{l+}](P_{l+1}(x))'' + [E_{l-} + M_{l-}](P_{l-1}(x))'' \quad (5)$$

$$\mathfrak{S}_4 = \sum_{l=1}^{\infty} [M_{l+} - E_{l+} - M_{l-} - E_{l-}] (P_l(x))'' \quad (6)$$

The $\mathfrak{S}_i$ amplitudes are referred to as the Chew, Goldberger, Low and Nambu (CGLN) amplitudes. These CLGN amplitudes may be used to connect underlying electromagnetic multipoles to differential cross sections.

In order to obtain information about resonances from the electromagnetic multipoles, a connection between the two must be made. Fortunately, by looking at selection rules, the orbital and angular momentum of any excited resonance can easily be related to two, or fewer multipoles.

Decomposing electromagnetic radiation into multipoles requires that a coordinate system be defined. The most convenient coordinate system for scattering experiments is to have the origin set on the target particle.

Table 2.2-1 shows how the multipoles are related to the total angular momentum for the photon (J_γ), and the photon-proton system ($J_{\gamma p}$), and to parity.

Table 2.2-1: Possible values of total angular momentum for the photon (J_γ), and the photon proton system ($J_{\gamma p}$) and its relation to parity and the electromagnetic multipoles.

	E_{l+}	M_{l+}	M_{l-}	E_{l-}
$J_{\gamma p}$	$l + 1/2$	$l + 1/2$	$l - 1/2$	$l - 1/2$
J_γ	$l + 1$	l	l	$l - 1$
Parity	$(-1)^{J_\gamma} = (-1)^{l+1}$	$(-1)^{J_{\gamma p}} = (-1)^{l+1}$	$(-1)^{J_{\gamma p}} = (-1)^{l+1}$	$(-1)^{J_\gamma} = (-1)^{l+1}$

Since the N^* state has parity determined by angular momentum,

$$\text{parity} = (-1)^{l+1},$$

and the photon parity is determined identically (with respect to angular momentum and intrinsic parity), then parity is not an issue in the selection rules. In the multipole notation used here, the selection rules are simple:

- The orbital angular momentum (l) of the N^* state must match the l of the multipole.
- The total angular momentum (j) of the N^* state must match the $j_{\gamma p}$ of the multipole.

Given the above rules, a table relating the CGLN amplitudes to possible resonance states can be made. Some of these are given in Table 2.2-2.

Table 2.2-2: Relation of CGLN amplitudes to possible resonance states [18]. x is defined in the text.

	$\Im_1$	$\Im_2$	$\Im_3$	$\Im_4$
S_{11}	E_{0+}			
P_{11}		M_{1-}		
P_{13}	$3x(M_{1+} + E_{1+})$	$2M_{1+}$	$3(E_{1+} - M_{1+})$	
D_{13}	$3M_{2-} + E_{2-}$	$6xM_{2-}$		$-3(M_{2-} + E_{2-})$
D_{15}	$3/2(5x^2 - 1)(2M_{2+} + E_{2+})$	$9xM_{2+}$	$15x(E_{2+} - M_{2+})$	$3(M_{2+} - E_{2+})$
F_{15}	$3x(4M_{3-} + E_{3-})$	$9/2(5x^2 - 1)M_{3-}$	$3(M_{3-} + E_{3-})$	$-15x(M_{3-} + E_{3-})$

2.3 Hicks isobar analysis model

In order to obtain information about the resonances that take part in the $\gamma p \rightarrow \eta p$ reaction, the experimental data obtained must be interpreted by a theoretical model. The model used here is the Hicks isobar model [18]. The Hicks isobar model includes only s-

channel resonance and background terms. Any t-channel contributions are assumed to be adequately dealt with in the background terms.

The electric and magnetic multipoles are assumed to have the form:

$$E_{l\pm} = \frac{-ie^{i\phi}(\Gamma_{\eta p}^E \Gamma_{\eta p})^{1/2}}{2[qkj(j+1)]^{1/2}(W_r - W - \frac{1}{2}i\Gamma)} , \quad (9)$$

and

$$M_{l\pm} = \frac{-ie^{i\phi}(\Gamma_{\eta p}^M \Gamma_{\eta p})^{1/2}}{2[qkj(j+1)]^{1/2}(W_r - W - \frac{1}{2}i\Gamma)} . \quad (10)$$

The terms q and k have the same meaning as in the previous section, and the other symbols are defined as:

- W is the total center-of-mass energy,
- W_r is the nucleon resonance mass,
- ϕ is the relative phase,
- j is the total angular momentum quantum number for the resonance,
- Γ is the total energy-dependent width of the resonance,
- $\Gamma_{\eta p}$ is the partial width of forming the resonance through photoproduction, and
- $\Gamma_{\eta p}$ is the partial width of the resonance decaying to ηp .

The total energy-dependent width is approximated by

$$\Gamma = \frac{pv_l(Rp)}{p_r v_l(Rp_r)} \Gamma_r \quad (11)$$

The momentum p is the momentum that a pion would have if the resonance decayed to $\pi + p$. A subscript r means that the quantity is to be evaluated at resonance. R is an

interaction distance (here, $R = 1$ fm). The terms v_l are somewhat analogous to the penetration factors in nuclear physics [19].

The $S_{11}(1535)$ resonance is centered near photoproduction threshold for the η meson. Photoproduction threshold for the η is at a center-of-mass energy $W = 1.49$ GeV ($m_\eta + m_p$). The width of the $S_{11}(1535)$ as given by the PDG [1] is 150 to 200 MeV. This means that η photoproduction occurs well after the $S_{11}(1535)$ is able to be seen in the π channel. This would not cause much concern regarding the total energy-dependent width if the branching ratio to the η channel was very small. However, the η branching ratio given by the PDG is 35%-55%. Therefore, the total energy dependent width of the $S_{11}(1535)$ cannot simply be approximated by predictions based on the π -channel. To account for the special case of the $S_{11}(1535)$, prescription (11) is modified by using an energy-dependent width make up of two components

$$\Gamma_{S_{11}(1535)} = \Gamma_{\eta p} + \Gamma_{\pi p} \quad (12)$$

$$= b_\eta \frac{q_{\eta p}}{q_{\eta p}^r} \Gamma_r + b_\pi \frac{q_{\pi p}}{q_{\pi p}^r} \Gamma_r \quad (13)$$

The values used in this document for the branching ratios are that the pion branch is 45%, and the η branch is 55% (i.e. $b_\pi = 0.35$, and $b_\eta = 0.55$). As in (11) the lower case r means that the quantity is to be evaluated at the resonance energy. The momentum $q_{\eta p}$ is the momentum that an η would have if the resonance decayed to $\eta + p$. Likewise, the momentum $q_{\pi p}$ is the momentum that a π would have if the resonance decayed to $\pi + p$.

The product of partial widths in equations (7) and (8) is

$$(\Gamma_{\pi^0}^E \Gamma_{\eta\pi})^{1/2} = \begin{cases} [2kRv_l(kR)]^{1/2} [2kRv_l(kR)]^{1/2} \gamma^E, E_{l+} \\ [2kRv_{l-2}(kR)]^{1/2} [2kRv_l(kR)]^{1/2} \gamma^E, E_{l-} \end{cases} \quad (14)$$

and

$$(\Gamma_{\pi^0}^M \Gamma_{\eta\pi})^{1/2} = [2kRv_l(kR)]^{1/2} [2kRv_l(kR)]^{1/2} \gamma^M \quad (15)$$

The factor γ is the electromagnetic coupling and is a parameter of the model.

In addition to the resonance contributions, the Hicks isobar model includes two background terms. One term is an S -wave background and the other is a P -wave background, both of which have the desirable behavior at threshold. As stated in the paper [18], the precise form of the background terms is rather obscure. The background terms are

$$E_{0+}^b = \frac{(a+ib)R^2k}{[2(1+Rq)(1+R^3k^3)]^{1/2}}, \quad (16)$$

and

$$M_{1-}^b = \frac{(a+ib)R^2qk}{[2(1+R^3q^3)(1+R^3k^3)]^{1/2}}. \quad (17)$$

The unpolarized and polarized differential cross sections are given in terms of the CGLN amplitudes [18]. For the unpolarized differential cross section:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \frac{q}{k} & \left\{ [|\mathfrak{S}_1|^2 + |\mathfrak{S}_2|^2 - 2x \operatorname{Re}(\mathfrak{S}_1^* \mathfrak{S}_2)] \right. \\ & \left. + \frac{1}{2}(1-x^2) [|\mathfrak{S}_3|^2 + |\mathfrak{S}_4|^2 + 2 \operatorname{Re}(\mathfrak{S}_1^* \mathfrak{S}_4) + 2 \operatorname{Re}(\mathfrak{S}_2^* \mathfrak{S}_3) + 2x \operatorname{Re}(\mathfrak{S}_1^* \mathfrak{S}_2)] \right\} \end{aligned} \quad (18)$$

and the polarized differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{q}{k} (1-x^2)^{1/2} \text{Im} \left[-2\mathfrak{S}_1^* \mathfrak{S}_2 - \mathfrak{S}_1^* \mathfrak{S}_3 + \mathfrak{S}_2^* \mathfrak{S}_4 + (1-x^2) \mathfrak{S}_3^* \mathfrak{S}_4 + x(\mathfrak{S}_2^* \mathfrak{S}_3 - \mathfrak{S}_1^* \mathfrak{S}_4) \right] \quad (19)$$

where $x = \cos(\theta_{\text{c.m.}})$, and the polarization is in the direction $\hat{k} \times \hat{q}$.

The Hicks isobar model thus provides a theoretical framework that allows cross section data from η and η' photoproduction to be analyzed in terms of s-channel resonances. The model assumes Breit-Wigner forms of the electromagnetic multipoles. The electromagnetic multipoles are added together to form CGLN amplitudes. The CGLN amplitudes are then added together as described above, to yield polarized and unpolarized cross sections that can be used to extract resonance parameters by fitting the theoretical model to experimental data.

Chapter 3

Experimental Techniques

This chapter describes the experimental apparatus used in this work for the measurement of η and η' meson photoproduction on the proton. The identification of the η and η' mesons was performed by a missing mass reconstruction of the reaction $\gamma + p \rightarrow p + X$. This reconstruction of the missing mass M_x required knowledge of the incident photon energy and the momentum four-vector of the recoil proton. The bremsstrahlung photon tagger yielded the incident photon information needed. To construct the recoil proton's momentum four-vector, the three-vector momentum was measured by the CLAS drift chambers, and the energy part of the four-vector was inferred by including velocity information obtained by the time of flight, start counter, and drift chambers.

3.1 Accelerator

The heart of the Continuous Electron Beam Accelerator Facility (CEBAF), located at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), is an electron accelerator employing a “racetrack” geometry as seen in Figure 3.1-1. Initially, electrons are accelerated in an injector linac to an energy of 40 MeV, and then are inserted into the recirculating part of the accelerator. The bunch structure provided has a nominal frequency of 1.5 GHz and can have the bunch-to-bunch intensity modulated with

a periodicity of three, so as to serve the three separate hall with variable beam intensity [20].

Figure 3.1-1: The geometry of the Continuous Electron Beam Accelerator.

The injector accelerates electrons in two stages. The first stage operates at room temperature and contains an electron gun. The electron gun can provide a 1 MeV beam at a current of 2 mA DC, with an emittance of 1 mm. Two room temperature five-cell radio frequency (RF) cavities are then used in conjunction with a three-slit aperture to chop the beam (so that the three halls have access to the beam) and provide intensity modulation. The first cavity provides sweeping over three slits, which control the chopping and intensity that is received in the three halls. The second cavity is used to reduce the transverse momentum caused by the sweeping. After the two initial cavities,

two more room temperature five-cell cavities are used. Once the beam has gone through these cavities, the beam has an energy of 950 keV with an energy spread of 16 keV.

The second stage of the injector raises the beam energy to 40 MeV, using an injector linac. This linac contains $2\frac{1}{4}$ cryogenic modules of the same type used in the main linacs. Each cryogenic module contains eight five-cell superconducting RF cavity assemblies. These cavities also operate at 1.5 GHz. A picture of two such cavity assemblies can be seen in Figure 3.1-2.

Figure 3.1-2: Two five-cell superconducting RF cavity assemblies being inspected.

Once injected into the main accelerator, the beam enters the north linac and gains an additional 400 MeV of kinetic energy. Once through the north linac, the beam is bent horizontally through 180 degrees and is sent through the south linac, where once again the beam gains 400 MeV. At this point the beam can be either sent into an experimental hall or recirculated through the north linac. The choice to recirculate the beam can be

made up to four times. The beam picks up 800 MeV of kinetic energy each time the beam is allowed to recirculate. The three halls can request beams of varying intensity and energy. The different beams can exist in the same physical location in the linacs, but beams of differing energy must occupy different recirculating arcs.

The beam used in this experiment was recirculated three times to an energy of 2.44 GeV, and had an energy spread of $\Delta E/E \sim 10^{-4}$.

3.2 The CEBAF Large Acceptance Spectrometer (CLAS)

The main components of the CEBAF Large Acceptance Spectrometer, referred to as CLAS, are the start counter array, the drift chambers, and the time-of-flight system (There are, in addition, to these components, electromagnetic calorimeters; however, this equipment was not utilized in this study, and will not be discussed). The drift chambers allow measurement of a charged particle's momentum (to be discussed later), while the time-of-flight and start counters yield timing information. Taken together, the drift chambers, time-of-flight, and start counter data make possible determination of the sign of the electric charge (positive or negative), momentum, and velocity of a charged particle scattered into CLAS. Once the momentum and velocity of a particle have been determined, the mass of the particle can be calculated. The mass and charge of the particle determine its identity. Knowledge of the kinematic variables along with particle identification for each charged particle is crucial in this study of the η and η' mesons, since these mesons are not directly detected, but instead are inferred by way of missing mass reconstruction.

The CLAS, is a charged particle detector with nearly 4π sr acceptance.

Geometrically, the CLAS detector has an acceptance that ranges in polar angle from 8° to 142° , and covers 80% of the azimuthal direction, (The z -axis is defined as being coincident with the beam line with $+z$ in the direction of the incident beam.) In momentum space, the spectrometer accepts any charged particle with momentum greater than or equal to 200 MeV/c. A picture of the CLAS can be seen in Figure 3.2-1. From the photo, the overall geometry is seen to be that of a segmented sphere.

The segmentation of the CLAS is based on its six superconducting magnetic coils, as seen in Figure 3.2-2. Current passing through these coils provides the magnetic field necessary to bend a charged particle, and thus allow the momentum of the particle to be determined. When the magnets are turned on in the normal running condition, the magnetic field is such that positive particles are bent outward from the beam axis. The magnetic field geometry is such that the integral $\int \vec{B} \cdot d\vec{l}$, varies from a maximum of 2 T-m in the most forward polar directions to a maximum of 0.5 T-m for lower momentum particles beyond 90° [21]. This magnetic field is reversible. For this experiment, the magnetic field was 50% of maximum, with positive particles bending outward.

Figure 3.2-1: CEBAF large acceptance spectrometer. Drift chambers are in the center, and the time-of-flight scintillators are visible on either side, having been retracted from their normal position.

Figure 3.2-2: Installation of the six superconducting magnetic coils of CLAS.

3.2.1 Drift chambers

As a charged particle passes through a magnetic field, the path that is taken will be curved. The radius of curvature R is directly related to the magnitude of the magnetic field B and the momentum of the charged particle p given by the relation $R = cp/qB$, where the charge of the scattered particle is q . Once R of the particle has been measured, since B is known and most scattered particles are singly charged, the momentum p can be computed. The other information calculated from drift chamber information is the path length of the trajectory, and the polar and azimuthal angles at the reaction vertex

The drift chambers perform tracking of the charged particle. These drift chambers are segmented so that each one occupies only one of the gaps between the toroidal coils. These gaps are referred to as sectors. Within each sector there are three drift chambers, separated in the radial direction, and are designated as regions, as seen in Figure 3.2.1-1. The Region 1 drift chambers occupy the space between the beam axis and the superconducting coils. The Region 2 drift chambers are within the space between the coils. The last drift chambers, Region 3, lie outside the magnets. The relative placement of these regions in relation to the coils and beam line can be seen in Figure 3.2.1-1. Each drift chamber has two end plates located approximately 60° from each other in the azimuthal angle ϕ . The wires are, thus, approximately perpendicular to the plane defined by the particle trajectory, sense and field wires are strung. These wires are attached to the endplates of each chamber in two groupings. One grouping is axial to the magnetic field and is designated as the axial super layer. The other grouping is tilted at 6° stereo angle, and is called the stereo super layer. With this combination of layers, azimuthal information is obtained.

Within each super layer, there are six layers of sense wires, each layer located at a further radial distance from the target position than the previous. Around each sense wire are six field wires. This combination of sense and field wires defines a region of space that is called a cell. The trajectories are determined by electronics, which ascertain which cells have had a particle pass through them. These cells are packed together in a natural way, see Figure 3.2.1-2. In total there are 35,148 of these hexagonal drift cells, comprised from over 130,000 wires.

Figure 3.2.1-1: Cross-sectional illustration of the CLAS as seen from above. Also shown are two charged tracks hitting all detector elements. See Figure 3.2.1-2 for an expanded view of the dashed box.

Figure 3.2.1-2: Drawing of drift cells within a super layer. This is an expanded view taken from the dashed box in Figure 3.2.1-1.

3.2.2 Time-of-flight system

The time-of-flight system (TOF) is composed of six arrays of scintillation counters surrounding the CLAS. This group of counters together with the start counter and photon tagger determines the flight time of charged particles through the CLAS. This system covers the same polar angles as the CLAS (8° to 142°), and has a total area of 206 m^2 . Each of the six arrays of the TOF scintillation counters subtends one of the six sectors that make up the CLAS.

As can be seen in Figure 3.2.2-1, a time of flight sector has scintillation counters of two widths (with respect to momentum dispersion) arranged in four panels. Counters that are in the first panel (those in the forward polar angle) have a width of 15 cm and the

Figure 3.2.2-1: Drawing of a single time-of-flight sector.

remaining counters have width of 22 cm. The reason for the two widths is explained in [22]:

To ease the fabrication, assembly and testing of a large number of counters, we chose to build the system based on two widths.

Another reason for the differing width is due to the counting rate being higher in the forward direction. The lengths of the scintillation counters vary from 0.32 m to 4.45 m. Though there are 57 individual counters in each sector, there are only 48 “logical” counters per sector. Since the last 18 counters in each sector are paired to produce nine

“logical” counters (here the term “logical” refers to the counter as having electronics distinct from other counters).

The timing resolution (standard deviation) for the TOF system varies from 80 ps for the shorter scintillation counters to 160 ps for the longer counters.

3.2.3 Start counter

The start counter is a set of scintillators that surrounds the target with a geometric acceptance identical to the TOF system. The start counter indicates the time at which a charged particle has left the target region, and hence the start time of the event. The start counter information, taken together with the TOF information, determines the time that a charged particle is in the CLAS. Since the path length of the particle's trajectory through CLAS is determined from drift chamber information, the time-of-flight measurement yields the particles velocity.

Since the desired timing resolution requires that position along the scintillator must be determined, a photomultiplier tube must be placed on each end of the scintillator panels. But, since there is no room in the forward direction, two sectors of the start counter are, in fact, only one scintillator, bent in the forward polar angle such that both ends of the scintillator are in the upstream direction and allow for the placement of a photomultiplier tube to each of these ends. Figure 3.2.3-1 shows the dimension of a start counter scintillator.

Figure 3.2.3-1: Blueprint for a single start counter scintillator.

Figure 3.2.3-2, shows a sketch of one of the start counter scintillators with phototubes attached.

The start counter achieves a time resolution of 260 ps as noted in [23].

Figure 3.2.3-2: A start counter scintillator as installed.

3.3 Bremsstrahlung photon tagger

The bremsstrahlung photon tagger is located upstream of the CLAS and is used only in experiments requiring an incident real photon beam. Upstream to the tagger, and used only for photon experiments, is a thin ($\sim 10^{-4}$ radiation length) radiator foil. For photon running, electrons in the beam provided by the accelerator impinge upon the radiator and lose energy in the form of photons (the bremsstrahlung process). After the electrons have undergone the bremsstrahlung process, they enter the magnetic field of the tagger magnet. The interaction of the electron in the magnetic field causes the trajectory of the electron to curve. This curvature separates the trajectories of electrons with differing energies. By identifying which trajectory an electron takes, the final energy of the electron can be determined. Since the initial energy of the electron is known and the

final energy is measured, then the amount of energy given off as a photon can be calculated. A detail of the Bremsstrahlung photon tagger can be seen in Figure 3.3-1.

In creating the bremsstrahlung photon tagger, ASU had the role of designing and implementing the electronics used in the determination of the electron trajectory, and hence, the photon energy.

Figure 3.3-1: The Bremsstrahlung photon tagger in Hall-B at Jefferson Lab.

3.3.1 The magnet

The bremsstrahlung photon tagger consists of a dipole magnet and a hodoscope that contains two planes of scintillators. The choice of tagger magnet design is that of a “modified Elbek” spectrometer [24]. As stated in Ref [25],

the defining characteristic of an Elbek magnet is a uniform magnetic field configured so that the exit field boundary is a straight edge which projects back to the point at which the incident particle enters the field. Outgoing trajectories are parallel, and the bend-plane images lie along a plane outside the field.

One geometry that would generate the appropriate magnetic field is that of a segmented circle. The actual geometry chosen is this simple case with the sharp points trimmed. Due to this trimming, the magnet is not of a true Elbek type hence the term “modified Elbek”. Figure 3.3.1-1 shows a detail of the tagger magnet used, and Figure 3.3.1-2 shows electron trajectories relative to the tagger magnet and focal plane.

Figure 3.3.1-1: Tagger magnet side view, a cross-sectional area, and pole tip detail.

To determine the field generated by such a design a two-dimensional magnetic field program named POISSON [26] was used. The studies with this program were performed with resultant magnetic field having a magnitude of up to 1.75 T, which would be the field needed for a 6 GeV incident electron beam.

Figure 3.3.1-2: Electron trajectories relative to tagger magnet and focal plane scintillators (k/E_0 is the fraction of photon energy to incident electron energy).

3.3.2 Focal plane instrumentation: detectors

The photon tagger has two planes of scintillator detectors. The upper detector plane of the bremsstrahlung photon tagger focal plane is comprised of 384 overlapping scintillators that provide the energy resolution; this plane is thus called the “energy” or “E-plane,” and counters in this plane are called E-counters. This plane is coincident with the optical focal plane of the magnet. Each scintillator strip was cut and polished by the

manufacturer (Bicron). These strips are 20 cm long, 4 mm thick, and range in width (along the momentum dispersion direction) from 6 to 18 mm so as to have approximately the same width in momentum space. This constant width in momentum is approximately $0.003 E_o$. Considering the overlap regions of the scintillators approximately doubles the achievable resolution. The overlap is approximately a third of each of the width of a scintillator. Thus, by recording the coincidence, or a lack thereof, between neighboring scintillators, the momentum resolution is effectively increased. When utilizing the overlap regions, an energy resolution of about $0.001 E_o$ is achieved.

Each of the scintillators in the energy plane has an optical fiber light guide attached at one end. Flexible light guides are required due to the limited physical space within the hodoscope installation box. Attached at the opposite end of the fiber light guides is a Lucite cylinder of diameter and length 2.5 cm. The flexible fiber light guides bend 90° (from horizontal at the scintillator to vertical at the phototube). The Lucite cylinder is then inserted into a cylinder of μ -metal (i.e. a metal having a high magnetic permeability μ). Slid in from the opposite end, a low cost photomultiplier tube is also inside the μ -metal cylinder. The μ -metal is needed so as to shield the photomultiplier tube from the magnetic field generated by the tagger dipole magnet. High voltage is provided to the energy plane photomultiplier tubes in groups of four. Signals from these tubes are directed to the ADML electronics (discussed in the electronics section below).

The main goal of the second plane of scintillators, the timing counter scintillators, or "T-plane," is, as the name would suggest, the recording of timing information of the tagged photon. This is an especially important measurement due to the near continuous

nature of the accelerated electron beam, with a micropulse of electrons each 2 ns.

Because of this micropulse structure, a resolution of 300 ps or better must be achieved in order to know from which micropulse the tagged photon came.

This lower detector plane of the bremsstrahlung photon tagger focal plane instrumentation is comprised of 61 overlapping scintillators used for obtaining the timing information of the events. This timing counter plane is located 20 cm downstream of the energy plane, measured along the normal of both planes. However, when measuring the distance between planes along the electron trajectories, the inter-plane distances range from ~40 cm to ~120 cm. The timing counters are 2 cm thick and have solid light guides attached at both ends. These scintillator/light guide units were built by Bicron and shipped with the light guides already attached. High quality photomultiplier tubes are coupled to these counters

Since the photon flux falls as $1/E_\gamma$, the widths of the timing counter plane scintillators in the momentum dispersion direction are varied so as to have approximately identical rates within two groupings. The first group of counters consist of 19 scintillators that cover the range in tagged photon energy from $0.75 E_o$ to $0.95 E_o$. The second grouping consists of the remaining 42 counters, covering the range in tagged photon energy from $0.20 E_o$ to $0.75 E_o$. The scintillators in the first group -those of the higher tagged photon energy- have approximately one-third the rate of those in the lower incident photon energy. The reason for implementing such a rate scheme for the timing plane scintillators is to allow experiments to be run that would not be interested in the lower energy photons. For higher energy photon experiments, the incident electron beam

intensity could be set at a rate that would saturate the lower energy counters, and data would be collected only using the high energy timing counter grouping. Because of the much smaller width of the energy plane scintillators this rate problem would not be seen in these counters. The overlapping of the timing plane scintillators is only a few mm so as to make sure no electrons are missed due to lack of scintillator material.

In order to obtain the needed timing resolution, both ends of the T-counter scintillator have light guides and photomultiplier tubes attached to localize the position along the length of the scintillator where the scattered electron passed through the counter. In order to suppress background electrons, the lengths of the timing plane scintillators are varied from 20 cm at the high photon energy end to 9 cm at the low photon energy end. This choice of length was determined by requiring that 98% of electrons be in physical acceptance for $E_0=0.8$ GeV , and noting that the angular distribution of the scattered electrons is given by the relation $\vartheta_e = \vartheta_c E_\gamma/E_e$, where ϑ_c is defined as being the photons characteristic angle and has a value of $\vartheta_c = m_e c^2/E_0$

3.3.3 Focal plane instrumentation: electronics

A schematic of the general electronic layout can be seen in Figure 3.3.3-1. The electron first encounters an energy plane scintillator, and then passes through a timing plane scintillator. Once this occurs, the E-counter and T-counter signals are processed in separate signal paths. These paths come back together to form the tagger part of the event trigger. The signal coming from the energy plane photomultiplier is sent to an ADML module (to be discussed in more detail later), is amplified and discriminated, and the

discriminated output produces an ECL logic pulse. This pulse is then sent to an E-T mapping module and also to a common stop TDC module. The mapping module was built at Jefferson lab, and is used to reduce accidental triggers by forming appropriate coincidences between counters and the E and T-planes.

For a signal to continue past this point in the electronics scheme, an ECL signal from the timing plane counter must be in coincidence with the ECL signal from the energy plane counter such that both signals make sense physically (i.e., there could be a trajectory of an electron such that the particular timing plane counter and energy plane counter combination are struck). The output of the mapping module is set to be longer than the discriminated timing counter signal so that the logic pulse from the discriminator on the T-counter signal determines the timing. This signal (elongated by a Phillips 706 discriminator) is then sent to a coincidence module.

The signals (left and right) coming from a timing plane scintillator are sent to discriminators and then to common start TDC's (Time to Digital Converters), and a Phillips 754 logic module in coincidence mode.

For the tagger portion of the event trigger, a three-fold coincidence is required between the two sides of a timing counter scintillator and a geometrically matched energy counter scintillator. Since there are 61 timing counters, there are 61 possible trigger pulses. Each of these possible triggers are sent through a cascade of Phillips 754 logic modules set in OR mode. This cascade of OR modules is labeled as the Master OR in Figure 3.3.3-1.

Figure 3.3.3-1: Schematic of photon tagger electronics.

ADML (Analog/Digital/Multiplexer/Logic) modules were designed and built at Arizona State University. Each module has 16 photomultiplier signal inputs, and a discriminator threshold voltage input. An ADML module provides an amplified and discriminated pulse for each input. Moreover, the first eight E-counter inputs are put in OR logic. The second eight inputs are also put in a distinct OR logic. Both of these eight fold OR's are then used to determine coincidence between energy counters and timing

counters. In addition to these outputs, there is an amplified photomultiplier signal sent to the back plane of an ADML crate (also designed and built at Arizona State University).

Each ADML crate contains eight ADML modules (128 channels) as well as an ADML control module. The ADML control module allows the user to control which of the 128 amplified signals is available for inspection at a BNC-connector output on the control module. The multiplexing is accomplished in two parts. Inside the individual ADML modules there is a normally open reed relay for each amplified signal; the output of these relays are bussed together in each module. When a four-digit binary address is applied to the modules via the back plane, the appropriate relay closes in each module and applies the amplified signal for each of the eight modules to eight separate locations on the bus.

The second part of the multiplexing is accomplished in the control module. Again reed relays are utilized. This time the particular module whose signal is to be presented to the BNC connector is chosen as the set of possibilities to be multiplexed, as well as which particular crate is selected. The output from each control module in each crate is sent to the counting house. The input for the multiplexer is a 24-pin ribbon cable that is “daisy chained” to each of the three ADML control modules. The selection input comes from an ASU-built VME control system designed and built by the author.

The ASU VME control crate provides remote control over four particular functions of the tagger electronics. The first function is to supply the coded input used to select a particular E-counter signal to the counting house. The second function is to provide discriminator threshold voltages for each of the 24 ADML modules. The third

function that is performed is to turn the E-T mapping module on and off. The last function that is performed is providing prescale pulses (to be discussed in detail later).

The ASU VME control crate consists of a MVME-162e readout controller, two Pentland Systems MPV904 Analog Output boards, and a Pentland Systems MPV930 TTL I/O board. The readout controller is connected to an Ethernet line, runs the VMWORKS operating system, and is the unit that actually runs programs. The analog output boards yield the threshold voltages needed by the discriminators of the ADMLs. The TTL I/O board provides the signals needed in order to multiplex the E-counter signals, turn on or off the mapping module, and to prescale the tagger timing counters (as described next).

Because the bremsstrahlung spectrum falls off as $1/E$, lower energy events are prescaled by applying a veto to the appropriate T-counter, in order to more evenly distribute the events versus the photon energy spectrum. The scale decided upon -due to ease of implementation- was that highest energy timing counters were not prescaled. The next 16 timing counters in energy (counters 16-29) were vetoed half of the time. The next 16 timing counters (30-45) were vetoed three-fourths of the time, and the last 16 timing counters (46-61) were vetoed seven-eighths of the time.

In order that there would not be spikes in the dead time, the veto scheme was implemented as shown in the Figure 3.3.3-2. The fraction of time for which the counters are in the “on state” is shown bracketed to the left of the signals going into the fan-outs. The signals entering the fan-outs in Figure 3.3.3-2 show the relative timing of the vetoes

(vetoes being the high state). The numbers coming out of the fan-outs correspond to the coincidence unit (and timing counter) that the veto is plugged into. As

Figure 3.3.3-2: Prescale signal pulses relative to each other in time. On the left are prescale signal pulses relative to each other in time. The numbers on the right represent the E-T coincidence module the veto signal goes to.

shown, the signals are alternated such that for the prescale $\frac{1}{2}$ region adjacent counters are out of phase. This same type of arrangement is held for all of the prescaled timing counters so that adjacent counters are never on at the same time.

All of the functions of the ASU VME control crate are accessible through a special graphical user interface written by the author (see Figure 3.3.3-3). This Tagger GUI allows the user to (1) choose easily an amplified energy counter channel to be read out on an oscilloscope in the counting house, (2) turn the mapping module on or off, (3) turn the prescale on or off, and (4) change threshold voltages to the discriminators. To determine which E-counter channel is displayed on the oscilloscope, the bin number button is pressed, which drops down eight buttons that correspond to the individual modules within the bin. Then the energy counter within the module must be picked so as to display the desired signal.

If the “Show Threshold Controls” button at the top of the interface is selected, then an equalizer panel is dropped down, with the selected module shown in red. At this point modules can be selected by simply single clicking with the mouse on any of the red or blue lines that make up the equalizer. The selected red line is controlled by a scale on the far left side of the equalizer. Once the desired threshold voltage is set on the graphical interface, then all that is needed to actually set the voltage at the module is to press the “APPLY VOLTAGE” button at the top of the equalizer panel. The threshold panel can be hidden at any time by pressing the “HIDE THRESHOLD CONTROL” button at the top of the interface.

To the right of the multiplexer controls are the buttons that control the state of the tagger prescale, and to the right of this are the buttons that control the state of the E-T mapping module.

Figure 3.3.3-3: ASU VME control crate Graphical user interface for tagger electronics.

An additional function of the Tagger GUI, is to monitor the prescale unit operation. This is done by requesting to see the processes running on the VME readout

controller, and checking that the prescale process is running or not. If the prescale is not in the desired state, a flashing red message is written just above where the date is shown on the interface, and an alarm comprised of a distinct rhythm of beeps is heard. As far as monitoring chores are concerned, this is the only one that can be done given the range of activities performed by the ASU VME control crate.

3.4 Target

A cryogenic liquid hydrogen target was used. This target was designed and built at Saclay. In addition to the target, Saclay designed the control system for the refrigeration unit used to cool the target. This control system utilized fuzzy logic to control valves and heaters on the target system, and was controllable from the counting house. A picture of the target can be seen in Figure 3.4-1. The target is made of 0.170 mm thick Mylar, has a length (including semi-spherical end caps) of 180 mm, and has a cylindrical diameter of 59.68 mm.

Figure 3.4-1: Cryogenic target

3.5 Summary

This chapter has described the experimental apparatus used in measuring η and η' photoproduction cross-sections. The measurement was performed by analyzing the incident photon and recoil proton in the reactions $\gamma + p \rightarrow \eta + p$, and $\gamma + p \rightarrow \eta' + p$. The bremsstrahlung photon tagger was used to determine the incident photon energy, and has been described above. In order to determine the proton final state four-vector information from the start counter, time-of-flight, and drift chambers was utilized. These detector elements have also been described.

Chapter 4

Data Analysis

The analysis procedure for the extraction of differential and total cross sections for η and η' photoproduction from the g1a data set is described in this chapter. Examples of intermediate stage results will be shown to indicate the validity of the methods used. The initial photon running period for the CLAS Collaboration (g1a) provided the first set of data to be used for that group of experiments. During that run period, photon energies spanned the range from threshold up to 2.34 GeV. The methods used for extracting the differential and total cross sections for η and η' photoproduction will be presented here. The technique is outlined initially, and then each step is described in further detail. Data and tests, which support the validity of the approaches taken, will be shown for each step.

4.1 Overview of technique

The extracted cross sections were based on normalizing the observed yield of π^0 mesons (based on identification of the meson in a missing mass reconstruction for the recoil proton) to the established partial wave analysis predictions for neutral pion photoproduction. This provided a normalization by which the observed yields for η and η' mesons (also based on identification in a missing mass reconstruction for the recoil proton) were converted to cross sections.

The missing mass approach has been used previously by other collaborations for η and η' photoproduction (e.g. Ref. [27]) and is thus an established method of determining

the yields for the photoproduction reaction on the proton. The neutral pion photoproduction reaction has been studied extensively, and the associated partial wave analyses, constrained by a large database for many channels and numerous conservation laws, are very reliable up to 2 GeV. Above 2 GeV, the database is sparse and normalizations to previously published data are performed.

Briefly, the following steps are involved for this analysis:

1. Identify the subset of runs that have stable operation of CLAS and tagger.
2. Identify the recoil proton in CLAS, determining the scattering angle and momentum for the proton.
3. Calculate the missing mass for the recoil proton based on the assumption that the reaction observed is $\gamma + p \rightarrow p + X$.
4. Bin the resulting missing mass spectra into incident photon energy bins and $\cos(\theta_{c.m.})$ bins based on the assumption that the reaction observed is $\gamma + p \rightarrow p + X$.
5. Identify π^0 , η and η' meson missing mass peaks.
6. Determine yield for each meson by subtracting the background, most of which may be assumed to be due to multi-pion final states.
7. Correct the normalized yield for spectrometer acceptance using empirical measurements of the CLAS acceptance for a single proton, using the measured acceptance from the reaction $\gamma + p \rightarrow \pi^+ \pi^- p$.
8. Normalize the measured yield to partial wave predictions for pion photoproduction cross sections or existing data on that reaction.

The final step yields a normalization providing absolute differential cross sections for the $\gamma + p \rightarrow p + \eta$ and $\gamma + p \rightarrow p + \eta'$ reactions. These cross sections are fit by a Legendre polynomial series to extrapolate to regions of unmeasured phase space, yielding total cross sections.

4.2 Details of technique used

In the following sections, each of the steps mentioned in the introduction are described. Also presented are sample results, and in some cases tests, which establish the validity of the procedure used.

4.2.1 Valid run subset identification

Since the data analyzed here were the first data to be taken with the CLAS and photon tagger operating together, numerous problems were found during this “shakedown” run. To ensure that only runs with consistent and reliable CLAS and tagger operation were used in the analysis, a selection procedure was used to identify runs for analysis.

An initial selection criterion used was that the runs had to be within the subset of the “gold runs” identified by David Lawrence [28]. The selection criteria for these runs included a number of crude data cuts to ensure data quality, as well as exclusion of runs for which the gl1a logbooks indicated some problem was present. Within this gold set, however, there are still runs of questionable reliability or taken with abnormal running conditions. Some of the runs were taken at reduced magnetic field; only runs at the 50% full magnetic field setting were used for this analysis. Other runs excluded included empty target runs and runs where drift chamber or normalization problems were found.

Further pruning of this subset of runs was performed by looking for more subtle inconsistencies in the monitor histograms given in Ref. [28] not excluded by the initial crude cuts leading to the gl1a golden subset. A typical monitor histogram is shown in Figure 4.2.1-1. The ratio plotted in that figure is number of protons per event written to tape. As can be seen from that figure, within the subset of runs with 50% field in the “golden” set, runs prior to about 11600 are inconsistent with the general trend established by runs 11800 to 11910. These inconsistencies denote some source of instability with respect to the normal operation of the CLAS and tagger. To refine this subset, then, we looked for inconsistencies in all the following ratios for each run in the “golden set”:

1. Number of protons identified per event written.
2. Number of positive pions identified per event written.
3. Number of negative pions identified per event written.
4. Number of events with a $\pi^+ \pi^-$ pair detected per event written.
5. Number of protons detected with a $\pi^+ \pi^-$ pair per event written.

Only those runs with consistent behavior in these five tests were deemed acceptable for use.

These runs were further scrutinized to remove any runs for which the tagger T plane performance indicated any inconsistency in operation. Ratios of T-counter scalars were calculated, and only those runs that showed consistency in T-counter performance were used.

The subset of the “golden runs” identified by this approach is given in Table 4.2.1-1. These runs yielded 66.7 million triggers.

Figure 4.2.1-1: Typical monitor histogram used to identify “golden runs” in g1a. The horizontal axis denotes run number. The monitor shown here is the ratio of protons detected per event written to tape.

Table 4.2.1-1: The 18 data runs selected for use in this analysis from the g1a data set. The criteria used for selecting these runs are described in the text.

Run numbers					
11811	11822	11823	11864	11868	11870
11873	11882	11886	11888	11889	11891
11892	11898	11902	11903	11905	11910

4.2.2 Recoil proton and pion identification; kinematic variables

For electron data taking, the time-of-flight scintillator arrays provide information on the scattered electron and other particles that come from the target region. In real photon operation, the CLAS target region is surrounded by a scintillator array, known as the “start counter,” which is used to establish vertex time for the event. The drift chamber tracking information gives good momentum and scattering angle information on scattered charged particles. Time-of-flight information, coupled with the track information provided by the drift chambers, yields very good velocity and momentum determination. A sample β -versus-momentum plot is shown in Figure 4.2.2-1; the proton band is seen to be very well defined. Consequently, particle identification via the calculated mass of the scattered particle can be made, as shown in Figure 4.2.2-2.

Fiducial cuts of $\pm 13^\circ$ from the mid-plane of each coil were imposed on all protons. This region corresponds to a region of relatively uniform acceptance, as determined in the procedure described in section 4.2.6.

Runs were filtered such that events kept had to include either a proton or a $\pi^+ \pi^-$ pair. A cut, going from 0.8 to 1.2 MeV, was placed on this reconstructed mass to identify scattered protons. As can be seen in Figure 4.2.2-2, the background beneath this peak is significantly less than 1%, a level of contamination statistically insignificant for this analysis. Scattering angles and momenta were determined for each proton selected by this cut using drift chamber and time-of-flight information. A similar approach was used to identify scattered pions, with a reconstructed mass within the range 0.0 and 0.3 MeV. As seen in Figure 4.2.2-2, the background beneath this peak is also less than 1%.

Figure 4.2.2-1: β versus momentum for charged particles detected in CLAS in selected gl data set.

Figure 4.2.2-2: Mass of scattered particle determined from kinematic information in CLAS. The shaded areas represent the particle identification limits for identifying pions [left] and protons [right].

4.2.3 Missing mass reconstruction

The kinematic quantities determined from the time-of-flight and drift chamber systems yield good momentum definition for the proton. The momentum determined by the CLAS was corrected for energy loss in the target cell and start counter scintillator to

reconstruct the momentum at the vertex. The scattering angle and momentum can be used to construct a missing mass based on the assumption that the reaction observed is $\gamma + p \rightarrow p + X$, where X is the other body in the two-body final state using the relation:

$$mass_x = \sqrt{2m_p^2 + 2E_\gamma m_p - 2\sqrt{m_p^2 + p_p^2}(m_p + E_\gamma) + 2E_\gamma p_{p,z}}$$

Based on this assumption, the missing mass spectrum for the full spectrometer acceptance for all photon energies is shown in Figure 4.2.5-1. The η and η' peaks are clearly seen atop a background dominated by multi-pion events. The π^0 peak, though broad, is clearly discernible.

4.2.4 Binning of missing mass spectrum in photon energy and $\cos(\theta_{c.m.}^p)$.

The full missing mass spectrum described in the previous section was broken into bins in photon energy and $\cos(\theta_{c.m.}^p)$. The bin sizes chosen ($\Delta E_\gamma = 50$ MeV in photon energy for π^0 and η , 100 MeV for η' ; $\Delta \cos(\theta_{c.m.}^p) = 0.2$) were such that, in general, there were at least 100 meson events in each E_γ - $\cos(\theta_{c.m.}^p)$ bin. In all cases for which cross sections are reported here, the meson peak is unambiguously seen above the background.

4.2.5 Determination of meson yields within each photon energy and $\cos(\theta_{c.m.}^p)$ bin.

For each missing mass spectrum within the photon energy and $\cos(\theta_{c.m.}^p)$ bin, the meson yield is extracted by removing the background under the meson peak. The background beneath the meson peaks is assumed to be dominated by multi-pion photoproduction processes. We have proceeded with the assumption that the background in the missing mass spectra arises from two particular reactions:

1. Two pion photoproduction via the reaction $\gamma + p \rightarrow p + X$, where $X = \pi\pi$. In this case, we measure with the CLAS $X = \pi^+ \pi^-$. We assume other pion charge combinations yield a background with the same shape in missing mass.
2. Three pion photoproduction via the reaction $\gamma + p \rightarrow p + X$, where $X = \pi\pi\pi$. In this case, we measure with the CLAS $X = \pi^+ \pi^- \pi^0$. We assume other pion charge combinations yield a background with the same shape in missing mass.

Data for the reaction $\gamma + p \rightarrow \pi^+ + \pi^- + p$ was selected by requiring that, for the events in the data runs identified in Table 4.2.1-1, each particle in the final state had to be identified through normal particle ID procedures, and that the missing mass was consistent with zero. The zero mass consistency was defined as being met if mass X , in the reaction $\gamma + p \rightarrow \pi^+ + \pi^- + p + X$ is less than 0.04 GeV. For the three π channel, the reaction $\gamma + p \rightarrow \pi^+ + \pi^- + \pi^0 + p$ was determined by requiring that all the charged final state particles were identified through normal particle ID procedures, and that the missing mass X in the reaction $\gamma + p \rightarrow \pi^+ + \pi^- + p + X$ was consistent with a π^0 ; this consistency was demonstrated by X having a mass greater than 0.07 GeV, and less than 0.16 GeV.

Figure 4.2.5-2 shows $\gamma + p \rightarrow p + X$ missing mass spectra for the two-pion event data (where $X = \pi^+ + \pi^-$) for all incident photon energies and $\cos(\theta_{c.m.}^p)$. One can clearly see the ρ^0 peak (since ρ^0 decays to $\pi^+ + \pi^-$ approximately 100% of the time). One also sees some contribution from the η' due to the decay chain $\eta' \rightarrow \rho^0 \gamma \rightarrow \pi^+ \pi^- \gamma$.

Similarly, Figure 4.2.5-3 shows the $\gamma + p \rightarrow p + X$ missing mass spectra for the three-pion event data (where $X = \pi^+ + \pi^- + \pi^0$). For this three-pion final state, the η

(which decays to $\pi^+ + \pi^- + \pi^0$ 23.1% of the time) and omega (ω decays to $\pi^+ + \pi^- + \pi^0$, 88.8% of the time) mesons are easily identified. These figures indicate the general shape of the multi-pion background.

Figure 4.2.5-1: Missing mass spectrum from gl a data runs assuming $\gamma + p \rightarrow p + X$.

Figure 4.2.5-2: Missing mass of 2π system in $\gamma + p \rightarrow p + X$ reaction.

The $\gamma + p \rightarrow p + X$ missing mass spectra determined from the two- and three-pion event data are binned in the same manner described in Section 4.2.4; the shape of the multi-pion background beneath the meson peaks is determined from these spectra. To

Figure 4.2.5-3: Missing mass of 3π system in $\gamma + p \rightarrow p + X$ reaction.

parameterize the missing mass dependence of this background, an iterative fitting algorithm is used, illustrated here for the η peak in Figure 4.2.5-4:

1. A gaussian function was fit to a GSIM-simulated η peak that was binned in the manner described above. A simple gaussian fit this peak well. The width of this fitted peak was denoted by σ . This is illustrated in Figure 4.2.5-4a.

2. Points along the missing mass axis within $\pm 2.58 \sigma$ (i.e.: the region of the gaussian containing 99% of the peak area) of the plotted eta mass were labeled *trial η -peak-points*. These determined a region to be excluded in the background fits described next.
3. For the two-pion event data, the binned $\gamma + p \rightarrow p + X$ missing mass spectra (where $X = \pi^+ + \pi^-$) were fit with a third-degree polynomial, where the fits excluded all *trial η -peak-points* defined in step 2. The polynomial resulting from this fit for each bin was called the *2- π -poly* for that bin. This is illustrated in Figure 4.2.5-4b.
4. Often there were very few counts in the 3-or-more pion background. Thus, for the three-pion data, the entire (i.e.: summed over all angle bins) $\gamma + p \rightarrow p + X$ missing mass spectrum (where $X = \pi^+ + \pi^- + \pi^0$) was fit with a third-degree polynomial, where the fits excluded all *trial η -peak-points* defined in step 2. The polynomial resulting from this fit for each bin is called the *3- π -poly* for that bin. This is illustrated in Figure 4.2.5-4c.
5. Each binned recoil proton missing mass spectrum was fit with a function F given by

$$F(\text{missing mass}) = A \times (2\text{-}\pi\text{-poly}) + B \times (3\text{-}\pi\text{-poly}),$$

where A and B were the free parameters of the fit, and where all *trial η -peak-points* were excluded. The polynomial for each bin resulting from this fit was called the *background-poly* for that bin. This is illustrated in Figure 4.2.5-4d. The parameters A and B varied smoothly with energy.

6. The *background-poly* for each bin was subtracted from the recoil missing mass spectrum for that bin. The resulting spectrum was the *η -spectrum* for that bin.
7. A gaussian function was fit to each *η -spectrum*. This fit determined a *provisional set of η -peak-points* as defined in step 2. If the *trial η -peak-points* were not identical with the *provisional η -peak-points*, then the algorithm went back to step 3, using the *provisional η -peak-points* as the new *trial η -peak-points*.
8. The yield for each of the *η -peak-points* in the *η -spectrum* were added together and called the *η -yield* for that bin.

For the η' reactions, the approach used was identical.

For the π^0 reaction, there were several modifications to this procedure. In step 2, only points from the centroid to $+2.58 \sigma$ (i.e.: the higher energy 49% of the peak) were used in that step since little background existed under the left side of the peak. Further, since the number of events was small for the background under the peak, and a fourth degree polynomial was used to parameterize the shape of the back-ground. The results of this procedure for the π^0 , η and η' mesons are illustrated by examples in Figure 4.2.5-5, Figure 4.2.5-6, and Figure 4.2.5-7, respectively. The complete set of fit results is in Appendix A.

For small scattering angle bins (i.e.: $\cos\theta = \pm 0.9$), inspection of the fits revealed significant broadening of the meson peaks, and more complex background structure. The

broadening most likely represents the presence of large multiple Coulomb scattering effects and usually occurred in bins where significant bin migration also occurred. These

Figure 4.2.5-4: Histograms illustrating procedure used to determine background and peak in the analysis described here.

Figure 4.2.5-5: Representative yield results for η photoproduction cross sections.

Figure 4.2.5-6: Representative yield determination results for η' photoproduction cross sections.

Figure 4.2.5-7: Representative yield determination results for π^0 photoproduction cross sections.

bins were deemed suspect and no cross sections were derived for them. The uncertainties in the yield from this approach is generated by

$$\frac{\delta Y}{Y} = \sqrt{\left(\frac{\delta N_{peak}}{N_{peak}}\right)^2 + \left(\frac{\delta N_{bkgd}}{N_{bkgd}}\right)^2}$$

where N_{peak} and N_{bkgd} indicate the counts in the peak and background, respectively.

4.2.6 Acceptance determination

The acceptance for recoil protons detected in CLAS was measured empirically.

The reaction used to determine the acceptance of protons in the CLAS was

$\gamma + p \rightarrow \pi^+ + \pi^- + p$, due to the high number of events for this final state, and that all of the final products leave charged tracks in the CLAS, making them easily observable.

Both pions were required to be detected in the event. Assuming the proton acceptance is not correlated to the presence of either of these pions, the pion acceptance does not bias the proton acceptance.

The same fiducial cuts applied to the protons noted above were applied to both reconstructed and CLAS-identified protons. These cuts accepted protons within $\pm 13^\circ$ of the mid-plane of CLAS sectors.

The data used for acceptance calculations were events where two and only two pions were detected in the CLAS. (Note: This two-pion requirement does not exclude events where unobserved pions were present in the final state.) To determine the proton acceptance, the signature for the acceptance data sets for the reaction $\gamma + p \rightarrow \pi^+ + \pi^- + p$ was set to require detection of both pions. A missing mass reconstruction from the kinematical information from the two pions was performed to determine if a proton

should have been seen in the CLAS. As shown in Figure 4.2.6-1, the proton generally was very cleanly defined, so that the determination that a proton should have been seen could be made without ambiguity. The background beneath this peak was removed by subtracting a polynomial fit to the background region from the spectrum.

Figure 4.2.6-1: Proton mass reconstructed from pion information from $\gamma + p \rightarrow \pi^+ + \pi^- + p$ reaction.

The proton acceptance α empirically determined in this fashion is the ratio of the number of protons “seen” N_{seen} (i.e.: identified in CLAS through the normal particle ID procedure in the empirical acceptance data set with events containing unobserved pions removed) divided by the total number of events where a proton should have been seen, based on reconstructed four vectors from the pions, detected in the same subset of events

(with the unobserved pion events removed) N_{recon} :

$$\alpha = \frac{N_{seen}}{N_{recon}}$$

Thus, the uncertainty for the acceptance in each bin was given by

$$\frac{\delta\alpha}{\alpha} = \sqrt{\left(\frac{1}{N_{seen}}\right)^2 + \left(\frac{1}{N_{recon}}\right)^2}$$

In principle, the acceptance determined in this fashion should be independent of the azimuthal angle ϕ . To test this, reconstructed proton ϕ angles were binned (modulo 60 degrees) and inspected for any significant variation. As seen in Figure 4.2.6-2, no such variation was observed.

The four vector of the proton was defined as the reconstructed four-vector (denoted as four-vector X). The four-vector X was then used to parameterize and bin the measured acceptance. The proton acceptance determined in this way is a function of the values of the four-vector of the proton for each of these two pion events. However, the cross sections of interest here are for bins in angle and photon energy for $\gamma + p \rightarrow \pi^0 + p$, $\gamma + p \rightarrow \eta + p$, and $\gamma + p \rightarrow \eta' + p$. Thus, these four-vectors must be sorted into appropriate angle and photon energy bins for the reaction of interest.

For this sorting procedure, the reaction from which the proton arose (i.e., $\gamma + p \rightarrow \pi^+ + \pi^- + p$) is forgotten, but the value of the four-vector for that proton is kept. A new equivalent incident photon energy $\tilde{E}_\gamma$ for that event is calculated; this equivalent incident photon energy $\tilde{E}_\gamma$ is the photon energy which results in that particular proton

four-vector value, but for the reaction $\gamma + p \rightarrow \pi^0 + p$, $\gamma + p \rightarrow \eta + p$, or $\gamma + p \rightarrow \eta' + p$, as required.

Figure 4.2.6-2: Azimuthal angle ϕ distribution of reconstructed proton kinematical information (modulo 60 degrees). Center of sector has been shifted to 30 degrees.

Once this $\tilde{E}_\gamma$ is calculated, then the center of mass angle θ (or, more precisely, $\cos(\tilde{\theta}_{c.m.}^p)$) can be found by again calculating as though the proton came from, for example, η photoproduction. $\tilde{E}_\gamma$ is thus found by the relation:

$$\tilde{E}_\gamma = \frac{m_\eta^2 - 2m_p^2 + 2m_p^2 + 2m_p E_p}{2(m_p - E_p) + 2p_{p,z}}$$

and $\cos(\tilde{\theta}_{c.m.}^p)$ is found by the relation:

$$\cos(\tilde{\theta}_{c.m.}^p) = \frac{\tilde{\gamma}(p_{p,z} - \tilde{\beta}(p_p^2 + m_p^2))}{\sqrt{p_x^2 + p_y^2 + (\tilde{\gamma}(p_{p,z} - \tilde{\beta}(p_p^2 + m_p^2)))^2}},$$

where $\tilde{\gamma} \equiv \frac{\tilde{E}_\gamma + m_p}{\sqrt{(\tilde{E}_\gamma + m_p)^2 - \tilde{E}_\gamma^2}},$ and $\tilde{\beta} \equiv \frac{\tilde{E}_\gamma}{\tilde{E}_\gamma + m_p}.$

This approach does not provide a direct means to correct for the effects of bin migration. To make that correction ϵ_{bin} , bin migration was studied using GSIM.

Simulated events were obtained by generating $\gamma + p \rightarrow \pi^+ + \pi^- + p$ isotropic in phase space, and included target smearing of -9.0 cm to +9.0 cm, and then processed through a GEANT simulation created by the Jefferson laboratory GSIM working group (version used: release-2-2). 2 million such events were used in this study. Once the simulated events were obtained, they were processed in the same manner as that of actual data. These simulated acceptance data included the effects of bin migration that were not possible to determine from the actual acceptance data set. In all cases, effects of bin migration were found to be negligible.

4.2.7 Absolute normalization based on data for pion photoproduction

Since, the neutral pion yield at each photon energy has been determined, comparison of these measured yields to accepted cross sections for π^0 photoproduction provides an absolute normalization of the photon flux at each energy. With this normalization, the cross sections for η and η' photoproduction for those energies are established.

The SAID partial wave analysis presently extends up to 2 GeV, and that work was chosen for the normalization process up to that energy in this work. Using this partial wave analysis has the advantages that (1) the analysis provides a best estimate of the cross sections for π^0 photoproduction in those cases in which experiments disagree, and (2) through isospin relations and constraints, the partial wave analysis incorporates the results of measurements in the $\pi^+ n$ channel as well. In all, more than 4000 differential cross section points are involved in this analysis in the energy range from 0.7 to 2.4 GeV, as presented in Figure 4.2.7-1, and Figure 4.2.7-2. (With various conservation laws involved, data present in other channels provides a database of several times this size for the global solution.) This thorough angle and energy coverage provides a stringent test of estimates of the spectrometer acceptance and, for most energies, a very precise source of absolute normalizations (typically with uncertainties on the order of a few percent).

Figure 4.2.7-3 illustrates the agreement with the normalized π^0 cross sections and the SAID partial wave analysis at several energies for photon bins 50 MeV wide. As seen in that figure, the shapes of the angular distributions agree very well with the partial wave predictions. This indicates the empirically measured acceptance and the yield extraction

procedure used is reliable. This also illustrates that the estimated systematic uncertainty in the absolute normalization process, which ranges from ~5% at 750 MeV to ~15% at 2 GeV. For the η' photoproduction cross sections, photon energy bins were 100 MeV wide.

Figure 4.2.7-1: Existing π^0 photoproduction data (2333 points).

The agreement with the normalized π^0 cross sections and the SAID partial waves for photon bins 100 MeV wide is similar to that observed for the 50 MeV wide bins. As seen in Figure 4.2.7-2, above 2 GeV the data set is considerably sparser. However, several measurements have been made in that energy region for π^0 photoproduction, with a total of 30 points above 2 GeV. Since the acceptance for this analysis is well understood, a

normalization using the existing sparse data can be obtained. We have chosen to normalize to the $\theta_{cm}=120^\circ$ of Feller *et al.* [29] at 2100 MeV ($d\sigma/d\Omega = 89 \pm 8$ nb/sr) and 2200 MeV ($d\sigma/d\Omega = 61 \pm 7$ nb/sr). These published data points have uncertainties of approximately 9 and 12%, which is used as the absolute normalization uncertainty at those energies.

Figure 4.2.7-2: Existing π^0 photoproduction data (1858 points).

Figure 4.2.7-3: Example of comparisons of SAID predictions (stars, with no error bars) to normalized π^0 photoproduction cross sections (with error bars). Photon energy bins are 50 MeV wide

4.3 Summary

This chapter has described the manner in which cross sections for η and η' meson photoproduction via the reactions $\gamma + p \rightarrow p + \eta$ and $\gamma + p \rightarrow p + \eta'$ from gl data have been determined. All derived cross sections were based on recoil proton missing mass reconstruction. The relative cross sections were determined from a peak extraction method (with the peak isolated above a well-determined background) using an empirical measurement of the recoil proton acceptance. Partial waves and or existing data were used to derive an absolute normalization. The normalization uncertainty in this approach is in all cases less than 10% and generally less than 5%.

Chapter 5

Results and Interpretation

Differential cross-sections and inferred total cross sections for η and η' photoproduction are presented in this chapter. The η and η' cross-sections obtained here are compared to recent investigations where applicable. An isobar analysis of the differential cross sections is performed, including polarization observables and differential cross sections from other recent experiments. The results from the isobar analysis are then used to infer total cross sections. The helicity amplitude for the $S_{11}(1535)$ resonance is then extracted from the η photoproduction channel.

5.1 Comparison with previous data

The η differential cross sections determined here span an energy range, in incident photon energy E_γ , from 775 MeV to 1.925 GeV, with bin widths of 50 MeV. This energy range overlaps two recent (1990 and newer) experiments: TAPS [2], and GRAAL [12]. For the η' reaction channel, previous data are very sparse, and there is only one recent experiment with which to compare (SAPHIR [15]).

5.1.1 η photoproduction results

Figure 5.1.1-1 and Figure 5.1.1-2 show differential cross sections at energies for η photoproduction where comparisons can be made to previous work. The lowest energy presented (775 MeV) shows a comparison to data taken with the TAPS detector and data

taken with the GRAAL detector. (It should be noted that the energies shown from TAPS and GRAAL are different for each experiment, but are the closest to those used in this work.) With one exception ($\cos(\theta_{c.m.}) = -0.7$) the agreement between the CLAS data points and the data points of TAPS and GRAAL is very good. The agreement between CLAS and GRAAL for the next two energies ($E_\gamma = 825$ MeV and $E_\gamma = 875$ MeV) may not seem very good at first glance. However, it should be noted that the cross section (dominated by the $S_{11}(1535)$) is declining rapidly until an incident photon energy of about 1.025 GeV; thus, much of the "apparent" disagreement is attributable to the difference in incident photon energy. Due to this rapid decrease of the total cross section, comparisons made at different energies (yet within 10 MeV) will show differences of at least a common factor.

In Figure 5.1.1-2 there is one energy where a disagreement between CLAS and GRAAL is easily discernible. At an incident photon energy of 1.075 GeV, CLAS and GRAAL data can be compared at identical energies. At this energy, the shapes of the differential cross sections seem nearly identical. However, there is a systematic difference between GRAAL and CLAS in overall normalization. The differential cross sections of GRAAL appear to be systematically higher than those of CLAS. New measurements are needed to determine which measurement is more correct. However, since the pion photoproduction cross sections are well known in this energy region the normalization in this work does not appear to be at fault.

Figure 5.1.1-1: η photoproduction differential cross sections determined in this work, and those from TAPS [2] and GRAAL [12], for incident photon energies from 775 to 925 MeV.

Figure 5.1.1-2: η photoproduction differential cross sections determined in this work, and those from TAPS [2] and GRAAL [12], for incident photon energies from 975 to 1125 MeV.

5.1.2 η' photoproduction results.

The data set of η' differential cross sections determined using CLAS has six (out of eight) energies where a comparison can be made with SAPHIR (see Figure 5.1.2-1 and Figure 5.1.2-2)

Figure 5.1.2-1: η' photoproduction differential cross sections determined in this work, and those from SAPHIR [15], for incident photon energies from 1500 to 1800 MeV.

Figure 5.1.2-2: η' photoproduction differential cross sections determined in this work, and those from SAPHIR [15], for incident photon energies from 1900 to 2200 MeV.

Due to the large uncertainties in the SAPHIR data and coarser binning, it is difficult to make many comments regarding how well the two data sets agree. However, the SAPHIR data do appear systematically higher than the CLAS data. This may be due to an error in the rather indirect relative normalization of the SAPHIR data, which was

based on measuring the event rate for three charged outgoing particles [15], and comparing this event rate to the energy-dependent cross sections determined by the AHHM Collaboration [14]. In general, the two data sets agree in shape.

5.2 Hicks model isobar analysis.

In order to obtain total cross sections for η and η' photoproduction from the proton for the differential cross sections measured here, these differential cross sections must be modelled so that the behavior of the cross section in unmeasured regions of phase space can be extrapolated. The total cross sections presented in this below were determined by fits using a Hicks model approach (described in chapter 2). The data used in this analysis is summarized in Table 5.2-1.

Table 5.2-1: Data used in isobar analysis.

Experiment	Energy range (MeV)	Number of Points	Type of measurement
CLAS	775-1925	192	differential cross sections
TAPS [2]	716-790	100	differential cross sections
GRAAL [12]	732-1100	233	differential cross sections
BATES [30]	729-753	12	differential cross sections
GRAAL [31]	807-1050	44	beam asymmetry
BONN [32]	765-1105	38	target asymmetry

Since there are 16 isospin $\frac{1}{2}$ resonances listed in the summary table from the PDG in the W range 1440-2190 MeV, the author first decided to split the data into two energy regions and fit each region individually to find the most prominent resonances in those regions. For each fit performed, the $\chi^2_{reduced}$ was determined, and was used to distinguish which resonance combinations were most important. When the choice of resonances for

each region were made, then a fit was performed utilizing all of the data in Table 5.2-1, over the entire incident photon energy range.

Table 5.2-2 shows all the resonances considered in the isobar analyses of η and η' photoproduction. The choice of where to distinguish between low energy fits and high

Table 5.2-2: Table of resonances used in isobar analysis. Ranges shown are limits that the parameter are restricted to.

	Status	Values allowed in isobar analysis					
Resonance	Overall	$N \eta$	Mass (MeV)	Width(MeV)	E coupling	M coupling	Phase
P_{11} (1440)	****	*			NA	-0.9 to 0.9	0 to 180
D_{13} (1520)	****	*	1520	120	-0.9 to 0.9	-0.9 to 0.9	0 to 180
S_{11} (1535)	****	****	1510 to 1565	100 to 250	-0.9 to 0.9	NA	0
S_{11} (1650)	****	*	1650	150	-0.9 to 0.9	NA	0 to 180
D_{15} (1675)	****	*	1675	150	-0.9 to 0.9	-0.9 to 0.9	0 to 180
F_{15} (1680)	****		1680	130	-0.9 to 0.9	-0.9 to 0.9	0 to 180
D_{13} (1700)	***	*	1700	100	-0.9 to 0.9	-0.9 to 0.9	0 to 180
P_{11} (1710)	***	**	1710	100	NA	-0.9 to 0.9	0 to 180
P_{13} (1720)	****	*	1720	150	-0.9 to 0.9	-0.9 to 0.9	0 to 180
P_{13} (1900)	**		1800 to 2000	100 to 600	-0.9 to 0.9	-0.9 to 0.9	0 to 180
F_{17} (1990)	**	*	1890 to 2100	200 to 600	-0.9 to 0.9	-0.9 to 0.9	0 to 180
F_{15} (2000)	**	*	1900 to 2200	100 to 600	-0.9 to 0.9	-0.9 to 0.9	0 to 180
D_{13} (2080)	**	*	1800 to 2100	100 to 600	-0.9 to 0.9	-0.9 to 0.9	0 to 180
S_{11} (2090)	*		1860 to 2190	80 to 600	-0.9 to 0.9	NA	0 to 180
P_{11} (2100)	*	*	1850 to 2200	80 to 300	NA	-0.9 to 0.9	0 to 180
G_{17} (2190)	****	*	2100 to 2200	350 to 550	-0.9 to 0.9	-0.9 to 0.9	0 to 180

energy fits was determined by the large gap in energy between the P_{13} (1720), and the P_{13} (1900).

5.2.1 Isobar analysis for η photoproduction

A plot of $\chi^2_{reduced}$ versus number of variable resonances included in the fit for $E_\gamma \leq 1.35$ GeV can be seen in Figure 5.2.1-1. In the key shown in Figure 5.2.1-1, each resonance is given a number. This number is then used in the designation of the resonance combination. Since the $S_{11}(1535)$ is the only four star resonance for the reaction channel $\gamma + p \rightarrow \eta + p$, this resonance was included in each fit performed, and was given the identity 0. For example, the combination 820 located on Figure 5.2.1-1 at $N = 2$, and $\chi^2_{reduced} \approx 4$, means that the fit performed includes the resonances $D_{13}(1520)$, $P_{11}(1440)$, and $S_{11}(1535)$.

Since the combinations that include the $D_{13}(1520)$ are more likely to be found at lower $\chi^2_{reduced}$, that resonance was always included in the fits to the full data set. Likewise, since the combinations that include the Roper ($P_{11}(1440)$) resonance tend to be at relatively high $\chi^2_{reduced}$, that resonance was removed initially from consideration in fits of the full data set. This omission of the Roper resonance and inclusion of the $D_{13}(1520)$ is consistent with the analyses of TAPS[2] and GRAAL[12].

For incident photon energies greater than 1.35 GeV, a plot similar to that of Figure 5.2.1-1 is shown. This plot (Figure 5.2.1-2) includes higher energy resonances, but, unlike the lower energy region, no resonance is automatically included. So, a value of $N = 1$ has only one resonance included in the fit. In particular, the $S_{11}(1535)$ is not automatically included in these fits of higher energy.

Figure 5.2.1-1: χ^2_{reduced} versus number of variable resonances for $E_\gamma \leq 1.35$ GeV resulting from the Hicks model fits described in the text.

Figure 5.2.1-2: χ^2_{reduced} versus number of variable resonance's for $E_\gamma > 1.35$ GeV resulting from the Hicks model fits described in the text.

Figure 5.2.1-3: χ^2_{reduced} versus number of variable resonances for the full data set resulting from the Hicks model fits described in the text.

Since the χ^2_{reduced} for the higher energy fits converges rapidly with increasing N , only two resonances were required to achieve a reasonable χ^2_{reduced} . The resonances chosen were the $F_{15}(2000)$, and the $P_{13}(1900)$.

Fits then were performed with the full data set (see Figure 5.2.1-3), but this process did not yield a small subset of resonances that was clearly superior to any other. The Roper ($P_{11}(1440)$) was added so as to be more complete. The fit that includes all of the resonances shown in the key on Figure 5.2.1-3 along with the Roper is designated as the S fit. The S fit is shown as a straight line on the plot, and has a $\chi^2_{reduced}$ of 1.81. The resonance parameters of the final fit (S fit) can be seen in Table 5.2.1-1.

Table 5.2.1-1: Table of resonance parameters obtained from isobar analysis of η photoproduction. Values with uncertainties listed indicate parameters that were varied in the fits. All other values were set to recommend PDG values.

Resonance	Values obtained from isobar analysis	
	Mass (MeV)	Width (MeV)
$P_{11}(1440)$	1440	350
$D_{13}(1520)$	1520	120
$S_{11}(1535)$	1552.8(3)	168.7(3)
$S_{11}(1650)$	1650	150
$D_{15}(1675)$	1675	150
$F_{15}(1680)$	1680	130
$D_{13}(1700)$	1700	100
$P_{11}(1710)$	1710	100
$P_{13}(1720)$	1720	150
$P_{13}(1900)$	1848(2)	182(3)
$F_{15}(2000)$	2061(4)	145(6)

5.2.2 Isobar analysis for η' photoproduction

For η' photoproduction, the same method was used as that for the η high energy fits. The resulting $\chi^2_{reduced}$ versus N plot can be seen in Figure 5.2.2-1. The resonance combination designated as 542 was the only fit in Figure 5.2.2-1 that was able to converge without any of the parameters hitting a limit on variation of that parameter.) The $\chi^2_{reduced}$ for the fit 542 ($P_{11}(2100)$, $S_{11}(2090)$, and $F_{15}(2000)$), is 1.79. Table 5.2.2-1 shows the resonance parameters obtained from that fit.

Table 5.2.2-1 resonance parameters obtained from isobar analysis of η' photoproduction.

	Values obtained from isobar analysis	
Resonance	Mass (MeV)	Width (MeV)
$S_{11}(2090)$	1931(8)	81(5)
$P_{11}(2100)$	2160(10)	100(200)
$F_{15}(2000)$	1950(40)	200(100)

It is interesting to note that the isobar analysis fit for η' photoproduction used here includes both the resonances ($S_{11}(2090)$, $P_{11}(2100)$), used in the SAPHIR analysis.

Table 5.2.2-2 shows the resonance parameters obtained by SAPHIR.

Table 5.2.2-2: Resonance parameter obtained by the SAPHIR analysis.

	SAPHIR analysis	
Resonance	Mass (MeV)	Width (MeV)
$S_{11}(2090)$	1897(50)	396(155)
$P_{11}(2100)$	1986(26)	296(100)

Figure 5.2.2-1: χ^2_{reduced} versus number of variable resonances for η' photoproduction resulting from the Hicks model fits described in the text.

5.3 Cross-sections for η , and η' photoproduction

Since the isobar analysis fit is a global fit to data, including data other than that obtained here, some care must be used in determining the total cross sections best representing CLAS data. The method used to obtain the total CLAS photoproduction cross sections was to assume the isobar analysis fit obtained the correct shape, but that this fit could be off by a common factor when considering only CLAS data. To estimate the common factor x which the isobar analysis would need to best represent CLAS data, the experimental values obtained here were divided by the results of the isobar analysis fit for each energy. The result of this division is then fit with a straight line to obtain the weighted average for x .

The differential cross sections for η photoproduction are shown in Figure 5.3-1 to Figure 5.3-6. These figures include the results of the isobar analysis fit, and show the x factor described above at each energy. It is important to note that, while x has been determined, the fit shown in the graph does not include the factor x .

The differential cross sections for η' photoproduction are shown in Figure 5.3-7 and Figure 5.3-8

Figure 5.3-1: Differential cross sections for η photoproduction. Energies shown are $E_\gamma = 775, 825, 875,$ and 925 MeV . Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-2: Differential cross sections for η photoproduction. Energies shown are $E_\gamma = 975, 1025, 1075$, and 1125 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-3: Differential cross sections for η photoproduction. Energies shown are $E_\gamma = 1175, 1225, 1275,$ and 1325 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-4: Differential cross sections for η photoproduction. Energies shown are $E_\gamma = 1375, 1425, 1475$, and 1525 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-5: Differential cross sections for η photoproduction. Energies shown are $E_\gamma = 1575, 1625, 1675$, and 1725 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-6: Differential cross sections for η photoproduction. Energies shown are $E_\gamma = 1775, 1825, 1875$, and 1925 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-7: Differential cross sections for η' photoproduction. Energies shown are $E_\gamma = 1500, 1600, 1700$, and 1800 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

Figure 5.3-8: Differential cross sections for η' photoproduction. Energies shown are $E_\gamma = 1900, 2000, 2100$, and 2200 MeV. Included on the plots is the result of the Hicks model isobar analysis (solid curve). x is explained in the text.

The total cross sections for η photoproduction are shown in Figure 5.3-9, and the η' results are in Figure 5.3-10. The CLAS total cross sections were determined by integrating the prediction of the isobar analysis for the differential cross section (multiplied by x) at each energy. The uncertainties shown are from the percent error in x . A plot of the x factors for both η and η' can be seen in Figure 5.3-11.

The η total cross sections (Figure 5.3-9) for GRAAL were obtained from the SAID solutions. The GRAAL cross sections agree very well with the CLAS cross sections until $W \sim 1700$ MeV. At $W \sim 1700$ MeV the GRAAL total cross sections are systematically higher than CLAS, as discussed above. Additional measurements will have to be made to resolve this disagreement. TAPS cross section data agrees well with CLAS at the one energy that they can be compared ($E_\gamma = 775$ MeV).

Figure 5.3-10 shows the world data set for η' total cross sections. It is interesting to note that the SAPHIR total cross sections agree more with those of AHHM than to either CLAS or ABBHBM. What makes this so interesting is that SAPHIR normalized their data to the event rate of any three charged outgoing particles determined by AHHM. Thus, SAPHIR essentially normalized their data to that of AHHM.

Figure 5.3-9: Total cross sections for η photoproduction.

Figure 5.3-10: Total cross sections for η' photoproduction.

Figure 5.3-11: x factors (described in the text) for η and η' .

Another way to display the result of the isobar analysis is to plot the contributions from each resonance. The individual strength of a participating resonance is determined by finding the total cross section that would be attained using only the parameters of the resonance that is of interest. The strength of each resonance is plotted in Figure 5.3-12 for η photoproduction, and Figure 5.3-13 for η' reaction channel, with the width of the resonance shown as the horizontal error bar.

Because the x factors are derived by dividing the CLAS obtained differential cross sections by the predicted differential cross section using all recent (year 1990+) data, then any systematic trend in the x factors would point to normalization errors in the CLAS differential cross sections. However, while a systematic trend in x would signify problems with the normalization used here, the lack of a trend does not mean that the normalization used in this document is without error. Keeping in mind the significance of systematic trends in x , no such trends exist in these x factors (Figure 5.3-11).

Figure 5.3-12: Total cross sections for η photoproduction. Included on the plot are the strengths of the resonances used in the Hicks model isobar analysis.

Figure 5.3-13: Total cross sections for η' photoproduction. Included on the plot are the strengths of the resonances used in the Hicks model isobar analysis.

5.4 Proton helicity amplitude for the $S_{11}(1535)$ resonance

The $S_{11}(1535)$ proton helicity amplitude ($A_{1/2}^p$) can be extracted using the relation [2]

$$|E_{0+}(W_R)| = \sqrt{\frac{k_\gamma^* m_p \Gamma_\eta}{q_\eta^* W_R 2\pi}} \frac{|A_{1/2}^p|}{\Gamma_R} \quad (1)$$

where $A_{1/2}^p$ is the proton helicity amplitude, E_{0+} is the electric multipole (monopole with positive parity), Γ_R is the width of the resonance, Γ_η is the partial width of the resonance decaying to the η meson branch, k_γ^* is the center of mass photon momentum, q_η^* is the center of mass η momentum, and W_R is the energy of the resonance evaluated at its peak value.

Since the Hicks model isobar analysis allows the phase of each multipole to be a parameter of the fit, it is not possible to obtain the sign of $A_{1/2}^p$. Therefore, only $|A_{1/2}^p|$ is reported here.

Table 5.4-1 shows the values used to obtain the $S_{11}(1535)$ proton helicity amplitude ($A_{1/2}^p$). Using this table the value of $A_{1/2}^p$ is $0.0859 \text{ GeV}^{-1/2}$.

Table 5.4-1: Values used to obtain the $S_{11}(1535)$ proton helicity amplitude

k^* (GeV)	q^* (GeV)	W_R (GeV)	Γ_R (GeV)	$ E_{0+}(W_R) \text{ (GeV)}^{-1}$	b_η	$ A_{1/2}^p \text{ (GeV)}^{-1/2}$
0.485	0.198	1.541	0.166	7.62E-02	55%	8.59E-02

The value of $|A_{1/2}^p|$ obtained above is consistent with the estimate $0.090 \pm 0.030 \text{ GeV}^{-1/2}$ given by the PDG [1]. Table 5.4-2 shows the values that the PDG uses to obtain

this estimate of $A_{1/2}^p$. It is interesting to note that the helicity amplitudes derived from the η meson decay channel are all systematically higher than those values obtained with pion data. The value obtained here for $A_{1/2}^p$ is lower than the TAPS value [2], but measurement over the high energy portion of the resonances combined with the TAPS data, make this value more consistent with pion photoproduction.

Table 5.4-2: Proton helicity amplitude table for the $S11(1535)$ resonance taken from the PDG [1].

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.120(11)(15)	KRUSCHE	97	DPWA	$\gamma N \rightarrow \eta N$
0.060(15)	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
0.097(6)	BENMERROU..	95	DPWA	$\gamma N \rightarrow \eta N$
0.095(11)	BENMERROU..	91		$\gamma p \rightarrow \eta p$
0.053(15)	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.077(21)	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.083(7)	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.080(7)	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.029(7)	BRATASHEV...	80	DPWA	$\gamma N \rightarrow \pi N$
0.065(16)	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
0.0704(9)	ISHII	80	DPWA	Compton scattering

5.5 Summary of results

The differential cross sections for η and η' photoproduction off of the proton have been presented and compared to recently published data. Overall, the agreement between differential cross sections obtained here and those of other analysis efforts is quite good, with the exception of possible normalization discrepancies. An isobar analysis has been performed for both reaction channels ($\gamma p \rightarrow \eta p$, and $\gamma p \rightarrow \eta' p$). The

isobar analysis of η photoproduction did not converge to a small subset of included resonances. However, the η' isobar analysis did favor the limited set of resonances: $F_{15}(2000)$, $S_{11}(2090)$, and the $P_{11}(2100)$. The set of resonances used for the η' isobar analysis is consistent with the choice made by SAPHIR [15].

Total cross sections have been determined based on fits with the isobar analysis. From the $\gamma p \rightarrow \eta p$ channel, the $S_{11}(1535)$ proton helicity amplitude has been extracted and is in good agreement with the estimate given by the PDG [1].

Chapter 6

Conclusions

This chapter describes the accomplishments of this work and the future directions that η and η' photoproduction on the proton at CLAS will need to take.

6.1 Accomplishments

The data presented here was taken with the CEBAF Large Acceptance Spectrometer and the Bremsstrahlung photon tagger located in Hall-B at Jefferson Lab. Cross sections for η and η' photoproduction on the proton were presented.

6.1.1 CLAS and the photon tagger work

At the time that the data was taken for this work, CLAS and the photon tagger had never before been used for experiments, and CLAS was the most complex detector ever used for nuclear physics research. The work presented here is from the first data utilizing the CLAS and full range of the photon tagger. The CLAS detector functioned as was expected, and thus allowed the measurements presented in the work.

The photon tagger provided more than sufficient energy resolution and photon flux to undertake these initial studies. The missing mass resolution was more than adequate to determine the η and η' meson yields.

The software tools needed to analyze the data were successfully developed and employed (The development of the software needed to run an experiment of this size represents much effort.)

6.1.2 η photoproduction cross sections were measured

The extensive angular coverage greatly expands the world database. This is especially true for incident photon energies above 1.1 GeV. At energies above 1.1 GeV the world database on η photoproduction was very sparse until this work.

The wide coverage in incident photon energy and center-of-mass angle presented here allows a much better comparison of theoretical models to actual experimental data. The model used here shows that the resonance spectrum for η photoproduction could not be limited to a small number of resonances such as that observed in the TAPS and GRAAL analyses.

This data will be useful in testing theoretical models that are much more sophisticated than the rather dated model used in this work. Since the entire low energy resonance region is now measured, and thus better background subtractions can be performed, a better picture of the $S_{11}(1535)$ proton helicity amplitude can be obtained.

6.1.3 η' photoproduction cross sections were measured

Previous to this work, the total number of η' events measured was less than 300. With the inclusion of this work, the world database now has many thousands η' events. This much expanded database for η' photoproduction allows a better knowledge of the differential cross sections. The improved differential cross section information gives

some insight as to possible resonance couplings to the $\eta' p$ channel. In particular, this work and that of SAPHIR points to the possibility that the $S_{11}(2090)$, and $P_{11}(2100)$ play a prominent role in η' photoproduction.

6.2 Future work

While the work presented here provides a much improved database for η and η' photoproduction on the proton, there needs to be much more work done so as to obtain a complete picture of the reactions.

6.2.1 Need for more extensive data

To further elucidate the nucleon resonance spectrum with the η and η' photoproduction channel, higher resolution measurements with smaller uncertainties will need to be obtained. Work currently being done at Jefferson Lab using the CLAS and bremsstrahlung tagger has a statistical base perhaps 20 or more times as large as that of the work shown here. The availability of such a large quantity of data will allow much finer binning of events in incident photon energy and center-of-mass angles. Moreover, improved statistics should also allow branching ratios to be measured to higher accuracy than has been done previously.

In addition to a larger statistical base, the absolute normalization issues which required the normalization to pion photoproduction cross sections have been addressed. This better understanding of the absolute normalization will reduce the reliance on π photoproduction cross sections, and, indeed, permit high accuracy measurements of those cross sections.

6.2.2 Need for polarization observables

Differential cross sections alone are not sufficient in determining the details of the nucleon resonance spectrum. Where recent data was available, it was utilized in the Hicks model analysis presented here. Unfortunately, the number of polarization observables measured thus far is quite small. Experiments should be undertaken which permit measurement of spin observables to better resolve questions about nucleon resonances.

APPENDIX A

Differential π^0 Cross Sections Normalized to SAID Predictions

Figure A-1: Comparison of SAID predictions (stars, with no error bars) to normalized π^0 photoproduction cross sections (with error bars), for energies 775, 825, 875, 925, 975, 1025, 1075, and 1125 MeV.

Figure A-2: Comparison of SAID predictions (stars, with no error bars) to normalized π^0 photoproduction cross sections (with error bars), for energies 1175, 1225, 1275, 1325, 1375, 1425, 1475, and 1525 MeV.

Figure A-3: Comparison of SAID predictions (stars, with no error bars) to normalized π^0 photoproduction cross sections (with error bars), for energies 1575, 1625, 1675, 1725, 1775, 1825, 1875, and 1925 MeV.

APPENDIX B

Differential η Cross Sections

Table B-1: $d\sigma/d\Omega$ for η photoproduction. $E_\gamma=775, 825, 875$ and 925 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
775	134.4952	1.46E+00	5.47E-02
775	120.0609	1.30E+00	4.49E-02
775	107.5121	1.33E+00	4.65E-02
775	95.7877	1.31E+00	4.88E-02
775	84.3036	1.28E+00	4.53E-02
775	72.5792	1.31E+00	4.78E-02
775	60.0304	1.27E+00	5.45E-02
775	45.5961	1.10E+00	5.42E-02
825	134.4952	1.17E+00	4.01E-02
825	120.0609	1.17E+00	3.67E-02
825	107.5121	1.22E+00	3.95E-02
825	95.7877	1.18E+00	4.07E-02
825	84.3036	1.13E+00	4.03E-02
825	72.5792	1.11E+00	4.09E-02
825	60.0304	9.92E-01	4.37E-02
825	45.5961	7.62E-01	4.92E-02
875	134.4952	8.90E-01	3.12E-02
875	120.0609	8.38E-01	2.82E-02
875	107.5121	9.24E-01	3.05E-02
875	95.7877	8.41E-01	2.91E-02
875	84.3036	7.79E-01	2.88E-02
875	72.5792	8.02E-01	3.08E-02
875	60.0304	8.29E-01	3.70E-02
875	45.5961	7.31E-01	4.11E-02
925	134.4952	7.00E-01	2.71E-02
925	120.0609	6.64E-01	2.47E-02
925	107.5121	6.02E-01	2.40E-02
925	95.7877	6.20E-01	2.74E-02
925	84.3036	6.09E-01	2.92E-02
925	72.5792	5.65E-01	2.93E-02
925	60.0304	4.88E-01	3.25E-02
925	45.5961	5.23E-01	4.16E-02

Table B-2: $d\sigma/d\Omega$ for η photoproduction. $E_\gamma=975, 925, 1075$ and 1125 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
975	134.4952	4.18E-01	2.38E-02
975	120.0609	4.33E-01	2.32E-02
975	107.5121	4.30E-01	2.49E-02
975	95.7877	4.25E-01	2.44E-02
975	84.3036	3.61E-01	2.63E-02
975	72.5792	3.11E-01	2.48E-02
975	60.0304	2.45E-01	2.93E-02
975	45.5961	3.15E-01	4.51E-02
1025	134.4952	2.81E-01	2.45E-02
1025	120.0609	2.60E-01	2.19E-02
1025	107.5121	2.83E-01	2.36E-02
1025	95.7877	2.77E-01	2.47E-02
1025	84.3036	3.01E-01	2.86E-02
1025	72.5792	2.08E-01	2.08E-02
1025	60.0304	1.91E-01	3.15E-02
1025	45.5961	1.52E-01	3.64E-02
1075	134.4952	1.72E-01	1.88E-02
1075	120.0609	2.20E-01	1.90E-02
1075	107.5121	2.48E-01	1.97E-02
1075	95.7877	2.43E-01	1.96E-02
1075	84.3036	2.66E-01	2.11E-02
1075	72.5792	2.95E-01	2.36E-02
1075	60.0304	3.54E-01	2.70E-02
1075	45.5961	2.95E-01	3.71E-02
1125	134.4952	1.60E-01	2.03E-02
1125	120.0609	2.21E-01	1.96E-02
1125	107.5121	2.68E-01	2.28E-02
1125	95.7877	3.10E-01	2.38E-02
1125	84.3036	3.41E-01	2.52E-02
1125	72.5792	3.12E-01	2.58E-02
1125	60.0304	3.66E-01	2.90E-02
1125	45.5961	2.93E-01	3.77E-02

Table B-3: $d\sigma/d\Omega$ for η photoproduction. $E_\gamma=1175, 1125, 1275$ and 1325 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
1175	134.4952	1.65E-01	1.84E-02
1175	120.0609	2.00E-01	1.89E-02
1175	107.5121	2.21E-01	2.21E-02
1175	95.7877	2.85E-01	2.42E-02
1175	84.3036	2.75E-01	2.57E-02
1175	72.5792	2.86E-01	2.44E-02
1175	60.0304	2.82E-01	2.60E-02
1175	45.5961	2.72E-01	4.21E-02
1225	134.4952	1.54E-01	2.57E-02
1225	120.0609	1.94E-01	2.46E-02
1225	107.5121	2.82E-01	2.82E-02
1225	95.7877	2.80E-01	2.95E-02
1225	84.3036	2.89E-01	3.13E-02
1225	72.5792	3.18E-01	3.49E-02
1225	60.0304	3.08E-01	3.72E-02
1225	45.5961	3.13E-01	4.64E-02
1275	134.4952	1.06E-01	1.68E-02
1275	120.0609	1.88E-01	2.15E-02
1275	107.5121	2.61E-01	2.23E-02
1275	95.7877	2.44E-01	2.59E-02
1275	84.3036	2.60E-01	2.46E-02
1275	72.5792	2.68E-01	2.58E-02
1275	60.0304	2.81E-01	2.74E-02
1275	45.5961	3.12E-01	4.04E-02
1325	134.4952	1.06E-01	1.68E-02
1325	120.0609	1.96E-01	2.33E-02
1325	107.5121	2.14E-01	2.26E-02
1325	95.7877	2.25E-01	2.32E-02
1325	84.3036	2.69E-01	2.62E-02
1325	72.5792	2.86E-01	2.97E-02
1325	60.0304	3.43E-01	3.36E-02
1325	45.5961	3.32E-01	4.16E-02

Table B-4: $d\sigma/d\Omega$ for η photoproduction. $E_\gamma=1375, 1425, 1475$ and 1525 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
1375	134.4952	1.02E-01	1.40E-02
1375	120.0609	1.78E-01	1.72E-02
1375	107.5121	1.65E-01	1.68E-02
1375	95.7877	2.17E-01	1.86E-02
1375	84.3036	2.55E-01	2.25E-02
1375	72.5792	2.74E-01	2.29E-02
1375	60.0304	3.36E-01	2.59E-02
1375	45.5961	2.95E-01	3.00E-02
1425	134.4952	9.20E-02	1.09E-02
1425	120.0609	1.11E-01	1.16E-02
1425	107.5121	1.31E-01	1.26E-02
1425	95.7877	1.69E-01	1.50E-02
1425	84.3036	1.83E-01	1.52E-02
1425	72.5792	2.30E-01	1.67E-02
1425	60.0304	2.54E-01	1.87E-02
1425	45.5961	3.08E-01	2.31E-02
1475	134.4952	7.49E-02	1.25E-02
1475	120.0609	9.99E-02	1.43E-02
1475	107.5121	1.02E-01	1.39E-02
1475	95.7877	1.08E-01	1.56E-02
1475	84.3036	1.57E-01	1.78E-02
1475	72.5792	1.64E-01	1.78E-02
1475	60.0304	2.55E-01	2.27E-02
1475	45.5961	3.17E-01	2.97E-02
1525	134.4952	6.96E-02	1.14E-02
1525	120.0609	8.20E-02	1.16E-02
1525	107.5121	1.27E-01	1.26E-02
1525	95.7877	1.32E-01	1.33E-02
1525	84.3036	1.80E-01	1.55E-02
1525	72.5792	1.47E-01	1.52E-02
1525	60.0304	2.19E-01	1.73E-02
1525	45.5961	2.85E-01	2.44E-02

Table B-5: $d\sigma/d\Omega$ for η photoproduction. $E_\gamma=1575, 1625, 1675$ and 1725 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
1575	134.4952	8.30E-02	1.18E-02
1575	120.0609	6.87E-02	1.20E-02
1575	107.5121	1.12E-01	1.38E-02
1575	95.7877	1.13E-01	1.48E-02
1575	84.3036	1.74E-01	1.69E-02
1575	72.5792	1.59E-01	1.76E-02
1575	60.0304	1.61E-01	1.91E-02
1575	45.5961	2.59E-01	2.70E-02
1625	134.4952	6.37E-02	1.24E-02
1625	120.0609	4.86E-02	2.32E-02
1625	107.5121	1.07E-01	1.63E-02
1625	95.7877	9.06E-02	1.53E-02
1625	84.3036	1.30E-01	1.76E-02
1625	72.5792	1.25E-01	1.70E-02
1625	60.0304	1.67E-01	2.29E-02
1625	45.5961	3.17E-01	3.12E-02
1675	134.4952	6.92E-02	1.02E-02
1675	120.0609	1.11E-01	1.17E-02
1675	107.5121	1.28E-01	1.29E-02
1675	95.7877	1.12E-01	1.39E-02
1675	84.3036	1.16E-01	1.27E-02
1675	72.5792	1.08E-01	1.41E-02
1675	60.0304	1.62E-01	1.79E-02
1675	45.5961	2.31E-01	2.20E-02
1725	134.4952	9.88E-02	1.43E-02
1725	120.0609	9.50E-02	1.42E-02
1725	107.5121	1.12E-01	1.56E-02
1725	95.7877	9.46E-02	1.50E-02
1725	84.3036	1.11E-01	1.75E-02
1725	72.5792	1.32E-01	1.90E-02
1725	60.0304	1.05E-01	1.99E-02
1725	45.5961	2.47E-01	3.25E-02

Table B-6: $d\sigma/d\Omega$ for η photoproduction. $E_\gamma=1775, 1825, 1875$ and 1925 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
1775	134.4952	9.26E-02	1.14E-02
1775	120.0609	9.09E-02	1.03E-02
1775	107.5121	8.69E-02	1.10E-02
1775	95.7877	1.09E-01	1.18E-02
1775	84.3036	1.35E-01	1.43E-02
1775	72.5792	8.33E-02	1.31E-02
1775	60.0304	1.23E-01	1.57E-02
1775	45.5961	2.02E-01	2.19E-02
1825	134.4952	6.78E-02	1.10E-02
1825	120.0609	5.08E-02	9.61E-03
1825	107.5121	4.71E-02	1.15E-02
1825	95.7877	8.10E-02	1.38E-02
1825	84.3036	1.26E-01	1.67E-02
1825	72.5792	9.64E-02	1.49E-02
1825	60.0304	1.47E-01	1.83E-02
1825	45.5961	2.54E-01	2.74E-02
1875	134.4952	1.25E-01	1.70E-02
1875	120.0609	8.62E-02	1.28E-02
1875	107.5121	6.02E-02	1.71E-02
1875	95.7877	3.33E-02	1.38E-02
1875	84.3036	7.31E-02	1.61E-02
1875	72.5792	6.66E-02	1.77E-02
1875	60.0304	1.10E-01	1.94E-02
1875	45.5961	3.60E-01	3.85E-02
1925	134.4952	1.05E-01	1.49E-02
1925	120.0609	4.51E-02	1.03E-02
1925	107.5121	4.95E-02	1.36E-02
1925	95.7877	7.17E-02	1.30E-02
1925	84.3036	8.28E-02	1.58E-02
1925	72.5792	7.69E-02	1.65E-02
1925	60.0304	1.71E-01	2.01E-02
1925	45.5961	2.36E-01	2.98E-02

APPENDIX C

Differential η' Cross Sections

Table C-1: $d\sigma/d\Omega$ for η' photoproduction. $E_\gamma=1500, 1600, 1700$ and 1800 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
1500	120.0609	8.74E-02	1.71E-02
1500	107.5121	1.16E-01	1.76E-02
1500	95.7877	1.01E-01	1.68E-02
1500	84.3036	1.04E-01	1.57E-02
1500	72.5792	1.10E-01	1.52E-02
1500	60.0304	1.05E-01	1.69E-02
1600	134.4952	1.17E-01	1.79E-02
1600	120.0609	1.40E-01	1.50E-02
1600	107.5121	8.74E-02	1.10E-02
1600	95.7877	9.52E-02	1.51E-02
1600	84.3036	1.07E-01	1.57E-02
1600	72.5792	1.14E-01	1.61E-02
1600	60.0304	1.67E-01	1.75E-02
1600	45.5961	1.59E-01	2.01E-02
1700	134.4952	5.90E-02	1.28E-02
1700	120.0609	5.14E-02	7.75E-03
1700	107.5121	6.50E-02	9.10E-03
1700	95.7877	8.10E-02	1.38E-02
1700	84.3036	8.57E-02	1.38E-02
1700	72.5792	1.03E-01	1.53E-02
1700	60.0304	9.66E-02	1.60E-02
1700	45.5961	1.08E-01	1.91E-02
1800	134.4952	5.11E-02	1.12E-02
1800	120.0609	5.82E-02	1.09E-02
1800	107.5121	8.06E-02	1.24E-02
1800	95.7877	7.21E-02	1.23E-02
1800	84.3036	8.53E-02	1.29E-02
1800	72.5792	1.01E-01	1.38E-02
1800	60.0304	1.26E-01	1.57E-02
1800	45.5961	1.26E-01	1.88E-02

Table C-2: $d\sigma/d\Omega$ for η' photoproduction. $E_\gamma=1900, 2000, 2100$ and 2200 MeV

Incident photon Energy	Center-of-mass angle (θ)	$d\sigma/d\Omega$	$\Delta(d\sigma/d\Omega)$
1900	134.4952	3.98E-02	1.45E-02
1900	120.0609	4.84E-02	1.40E-02
1900	107.5121	7.68E-02	1.60E-02
1900	95.7877	6.21E-02	1.51E-02
1900	84.3036	7.23E-02	1.57E-02
1900	72.5792	1.01E-01	1.74E-02
1900	60.0304	1.53E-01	2.03E-02
1900	45.5961	1.57E-01	2.57E-02
2000	134.4952	2.82E-02	1.45E-02
2000	120.0609	4.45E-02	1.43E-02
2000	107.5121	6.45E-02	1.89E-02
2000	95.7877	9.59E-02	1.67E-02
2000	84.3036	8.57E-02	1.70E-02
2000	72.5792	1.48E-01	2.48E-02
2000	60.0304	1.34E-01	2.18E-02
2000	45.5961	2.00E-01	2.59E-02
2100	134.4952	5.11E-02	1.65E-02
2100	120.0609	1.62E-02	7.15E-03
2100	107.5121	2.10E-02	1.24E-02
2100	95.7877	2.16E-02	7.49E-03
2100	84.3036	8.97E-02	1.84E-02
2100	72.5792	6.09E-02	1.59E-02
2100	60.0304	1.06E-01	1.93E-02
2100	45.5961	1.27E-01	2.39E-02
2200	134.4952	5.11E-02	1.69E-02
2200	120.0609	4.08E-02	1.32E-02
2200	107.5121	1.47E-02	1.25E-02
2200	95.7877	1.12E-02	1.05E-02
2200	84.3036	2.15E-02	1.20E-02
2200	72.5792	9.16E-02	2.04E-02
2200	60.0304	1.23E-01	2.16E-02
2200	45.5961	1.47E-01	2.46E-02