Many measurements of pseudoscalar mesons with \( S = 0 \) photoproduced on the proton have been made recently. These new data are particularly useful in theoretical investigations of nucleon resonances. How the new data from various labs complement each other and help fill in the gaps in the world data set is discussed, with a glance at measurements to be made in the near future. Some theoretical techniques used to explain the data are briefly described.

1. Motivation

The \( S = 0 \) pseudoscalar mesons include the \( \pi^0 \), \( \pi^\pm \), \( \eta \), and \( \eta' \). The pions, as the lightest mesons, are copiously produced in the strong interaction. Pion photoproduction data have been vital to gain a first glimpse of the nucleon resonance spectrum. Whereas the pions have isospin 1, the \( \eta \) and \( \eta' \) mesons have isospin 0, so resonances decaying by emitting \( \eta \) or \( \eta' \) mesons can only have isospin \( \frac{3}{2} \). Thus, \( \eta \) and \( \eta' \) mesons act as “isospin filters” for the nucleon resonance spectrum. Further, as the only isosinglet, \( \eta' \) can be used to indirectly probe gluonic coupling to the proton through the flavor-singlet Goldberger-Treiman relation:

\[
g_A^0 = \frac{3}{4 m_N} \frac{F_0}{m_N} (g_{\eta' NN} - g_{GNN}), \tag{1}
\]

where \( m_N \) is the mass of the nucleon, \( g_{\eta' NN} \) is the \( \eta' \)-nucleon-nucleon coupling, \( g_{GNN} \) is the gluon-nucleon-nucleon coupling, and \( F_0 \) is a renormalization constant. The flavor singlet axial charge of the nucleon \( (g_A^0) \) has been measured with a value of \( g_A^0 = 0.20 \pm 0.35 \); however, the quark and gluon components have yet to be specifically determined.

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In addition to these theoretical motivations for studying photoproduction of $S = 0$ pseudoscalar mesons from the proton, there are practical motivations. Electromagnetic interactions are well understood and real photons are particularly simple (only two polarization states), so data from real photon beams are easier to analyze than data from other probes. Moreover, the $S = 0$ two-body final states for $\gamma p \rightarrow pX$ ($X$ is a meson), and $\gamma p \rightarrow n\pi^+$ have the benefit of having an outgoing proton or pion easy to identify and with relatively little contamination; $S \neq 0$ final states require identification of a kaon usually contaminated with both pions and protons. Thus, photoproduction of $S = 0$ mesons offers a relatively simple experimental means to explore nucleon resonances.

2. Recent results:

Four experimental facilities are providing new data on meson photoproduction from the proton: GRAAL, SAPHIR, CB-ELSA, and CLAS. Their contributions to $S = 0$ pseudoscalar meson photoproductions data will be summarized here.

a) $\gamma p \rightarrow p\pi^0$: Prior to 2005, the world data set (compiled in SAID) for $\gamma p \rightarrow p\pi^0$ differential cross sections had good coverage in incident energy ($E_\gamma$) and angle only up to $E_\gamma \approx 1.5$ GeV. In 2005, CB-ELSA published results which extended coverage in $E_\gamma$ up to 3.0 GeV. While the CB-ELSA data greatly enhance the coverage of $d\sigma/d\Omega$ for $\pi^0$ photoproduction from the proton, the systematic errors of the absolute normalization are estimated to be $\sim 15\%$ for $E_\gamma$ above 1.3 GeV. New preliminary data from CLAS cover $E_\gamma$ up to 2.125 GeV with an estimated systematic uncertainty in the absolute normalization to be $< 5\%$; a sample of this data is shown in Fig. 1. An additional data set has come
from GRAAL\cite{graal}, which measured differential cross sections and beam asymmetry $\Sigma$ for $E_\gamma$ up to 1.496 GeV.

Prior to the GRAAL measurements, angular coverage for $\Sigma$ was heavily biased in the forward direction. The new GRAAL data for $\Sigma$ populate the angular range much more uniformly for $E_\gamma$ up to 1.496 GeV. The rest of the polarization observables in the database are rather sparse. In the near future, a new generation of experiments specifically dedicated to polarization measurements should significantly expand our knowledge of polarization observables.

Thus, the world database for $\gamma p \to p\pi^0$ differential cross sections is becoming quite thorough for $E_\gamma$ up to $\sim 3$ GeV, and with coverage by more than one data set up to 2.125 GeV. The new GRAAL results for beam polarization extend the database for $\Sigma$ to $E_\gamma$ up to 1.496 GeV. All other polarization observables are very sparsely covered in energy and angle. Future experiments are expected to enhance our knowledge of the polarization observables. In particular, an approved experiment\cite{jefferson} at Jefferson Lab could start taking data for double polarization observables (beam and target) as soon as Fall 2006.

b) $\gamma p \to n\pi^+$: Of the four collaborations mentioned above, only the CLAS Collaboration has an analysis effort underway for the reaction $\gamma p \to n\pi^+$ which is in a very preliminary state. Preliminary differential cross section results for $\gamma p \to n\pi^+$ agree well with the SAID parameterization for $E_\gamma$ up to 1.925 GeV (see Fig. 2).

The CLAS cross sections were measured for $E_\gamma$ up to 2.225 GeV, and for $E_\gamma$ above 1.925 GeV the world database is nearly non-existent for the central angles between 50 and 150 degrees. It is here that the CLAS results will be of use in determining the differential cross sections for this reaction.

Figure 2. A sample of Differential cross sections for $\gamma p \to n\pi^+$. The data points are from CLAS and the lines are from SAID.
The coverages in the world database for polarization observables for the $\gamma p \rightarrow n\pi^+$ reaction are in a comparable state as that for the $\pi^0$ reaction, with the exception that the beam polarization observables are not as weighted in the forward direction. As with the $\pi^0$ reaction, there is an approved experiment at Jefferson Lab to obtain double polarization observables that could start taking data as soon as Fall 2006.

c) $\gamma p \rightarrow p\eta$: Before 2002 the world database for $\gamma p \rightarrow p\eta$ differential cross sections was only well covered for $E_\gamma$ from threshold (0.707 GeV) up to 0.8 GeV. In 2002 GRAAL published results on $d\sigma/d\Omega$ for $E_\gamma$ up to 1.1 GeV, and CLAS published $d\sigma/d\Omega$ for $E_\gamma$ up to 1.95 GeV. More recently (2005), CB-ELSA published $d\sigma/d\Omega$ results for $E_\gamma$ up to 3 GeV.

In 1998, GRAAL published $\gamma p \rightarrow p\eta$ beam polarization results for $E_\gamma$ up to 1.45 GeV. Polarization observables for $\gamma p \rightarrow p\pi^+$ remain very sparsely populated. This past summer, data were taken at CLAS for beam polarization that should allow extraction of that observable for $\eta$ photoproduction for $E_\gamma$ up to 2.1 GeV. As with the pions, an approved experiment at Jefferson Lab should help fill in the database for single and double polarization observables in $\eta$ photoproduction from the proton.

d) $\gamma p \rightarrow p\eta'$: Prior to 1998, only 18 $\eta'$ photoproduction events had been measured (11 events from the ABBHHM bubble chamber experiment, and 7 events from the AHHM streamer chamber experiment). In 1998, the SAPHIR collaboration published results extracted from an additional 250 $\eta'$ exclusive events. By contrast, the new (unpublished) CLAS results have over $2 \times 10^5$ $\eta'$ photoproduction events detected and used to extract differential cross sections shown in Fig. 3. These CLAS results span $E_\gamma$ from 1.527 to 2.227 GeV. No polarization observables have been measured for this reaction. Therefore, the differential cross sections provide the only experimental data for the reaction $\gamma p \rightarrow p\eta'$.
3. Theoretical Results

As noted above, there are many new differential cross section data for the reactions discussed here. However, these alone are not sufficient to constrain theoretical models to the extent that resonances can be uniquely determined. More data on the polarization observables are desperately needed, and a coupled channel approach is required, in order to constrain the contributions of various resonances.

One step in this direction comes from a model developed by A. V. Anisovich, E. Klempt, A.Sarantsev, and U. Thoma (AKST model) that couples the reactions $\gamma p \rightarrow p\pi^0$, $n\pi^+$, and $p\eta$. AKST included published differential cross sections, as well as the recent GRAAL beam polarization observables. The model uses a $K$ matrix approach for the $S_{11}(1535)$ and the $S_{11}(1650)$ resonances. The remaining resonances are described by Breit-Wigner amplitudes. The model also includes reggeized $u$- and $t$-channel contributions. Results from their analysis find evidence for a previously unseen $D_{15}(2070)$ resonance, and indications for a new $P_{13}(2200)$ resonance.

One model that considers the $\eta'$ exclusively comes from K. Nakayama and H. Haberzettl (NH). This model is based upon a relativistic meson-exchange model of hadronic interactions. Allowed processes include $s$-, $t$-, and $u$-channel contributions. The intermediate mesons in the $t$-channel exchanges are the $\omega$ and $\rho^0$. The NH model includes the $S_{11}(1535)$ and $P_{11}(1710)$ resonances ($j = 1/2$), which are known to decay strongly to the $\eta N$ channel, and also includes two additional $S_{11}$ and two additional $P_{11}$ resonances, albeit with relatively small couplings. The present adaptation of the NH model to the CLAS data now also requires $j = 3/2$ resonances [$P_{13}(1940)$, $D_{13}(1780)$, and $D_{13}(2090)$]. The observed $u$-channel contribution seen here allows the $g_{\eta'NN}$ coupling to be extracted (albeit in a model-dependent way). The value of $g_{\eta'NN}$ found from the particular NH fit is 1.33. Since differential cross sections alone do not provide sufficient constraints to this model, the $g_{\eta'NN}$ values should be taken with caution. Nonetheless, this value is consistent with the analysis of T. Feldmann, which gives $g_{\eta'NN} = 1.4 \pm 1.1$.

4. Summary

While there has been much progress in obtaining differential cross section data for pseudoscalar $S = 0$ meson photoproduction from the proton, and some new beam polarization ($\Sigma$) measurements for the pions and $\eta$, more polarization observables are needed in order to provide constraints to theo-
retical models. Experiments to obtain these needed constraints are planned for the near future. A comprehensive program for single, double and even triple polarization measurements in photoproduction is in preparation at Jefferson Lab. From the data already taken, there appears to be evidence for a new $D_{15}$ resonance at 2.09 GeV and indications of a new $P_{13}$ at 2.20 GeV. In addition to improving our knowledge about resonances and their parameters by fitting the $\gamma p \to p\pi^0, n\pi^+$, and $p\eta$ data, the new CLAS $\eta'$ data also has been analyzed to suggest a value of $g_{\eta'NN} \approx 1.3$, consistent with theoretical predictions. When this value can be determined with a high degree of confidence, it can be used to indirectly determine the gluonic coupling to the proton through the flavor-singlet Goldberger-Treiman relation.

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