A NEW RESONANCE IN $K^+\Lambda$ ELECTROPRODUCTION: THE $D_{13}(1895)$ AND ITS ELECTROMAGNETIC FORM FACTORS

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New SAPHIR $p(\gamma, K^+)\Lambda$ total cross section data show a resonance structure at a total c.m. energy around 1900 MeV. We investigate this feature with an isobar model and find that the structure can be well explained by including a new $D_{13}$ resonance at 1895 MeV. Such a state has been predicted by a relativistic quark model at 1960 MeV with significant $\gamma N$ and $K\Lambda$ branching ratios. We demonstrate how the measurement of single and double polarization observables can be used to obtain additional information on this resonance. Using recent $(e, e'K^+)\Lambda$ JLab data from Hall C we extract the electromagnetic form factors of this state.

1 Introduction

The physics of nucleon resonance excitation continues to provide a major challenge to hadronic physics due to the nonperturbative nature of QCD at these energies. While methods like Chiral Perturbation Theory are not amenable to $N^*$ physics, lattice QCD has only recently begun to contribute to this field. Most of the theoretical work on the nucleon excitation spectrum has been performed in the realm of quark models. Models that contain three constituent valence quarks predict a much richer resonance spectrum than has been observed in $\pi N \rightarrow \pi N$ scattering experiments. Quark model studies have suggested that those “missing” resonances may couple strongly to other channels, such as the $K\Lambda$ and $K\Sigma$ channels or final states involving vector mesons.

2 The Elementary Model

Using new SAPHIR data we reinvestigate the $p(\gamma, K^+)\Lambda$ process employing an isobar model described in Ref. We are especially interested in a structure around $W = 1900$ MeV, revealed in the $K^+\Lambda$ total cross section data for the
Table 1. Comparison between the extracted fractional decay widths and the result from
the quark model\cite{4},\cite{9} for the $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, and $D_{13}(1895)$ resonances.

| Resonance       | Status | $\sqrt{\Gamma_{N^*NB}N^*K\Lambda}/\Gamma_{N^*} \times 10^{-3}$ |
|-----------------|--------|----------------------------------------------------------------|
| $S_{11}(1650)$  | ****   | $-4.83 \pm 0.05$                                                |
| $P_{11}(1710)$  | ***    | $1.03 \pm 0.17$                                                 |
| $P_{13}(1720)$  | ****   | $1.17 \pm 0.04$                                                 |
| $D_{13}(1895)$  | †      | $2.29^{+0.72}_{-0.20}$                                          |

† Ref.\cite{4} obtains a mass of 1960 MeV for this state and relates it to the $D_{13}(2080)$,
given by PDG\cite{10} with a ** status.

first time. Guided by a recent coupled-channels analysis\cite{7}, the low-energy resonance part
of this model includes three states that have been found to have significant decay widths into the $K^+\Lambda$ channel, the $S_{11}(1650)$, $P_{11}(1710)$, and $P_{13}(1720)$ resonances. In order to approximately account for unitarity corrections at tree-level we include energy-dependent widths along with partial branching fractions in the resonance propagators\cite{6}. The background part includes the standard Born terms along with the $K^*(892)$ and $K_1(1270)$ vector meson poles in the $t$-channel. As in Ref.\cite{6}, we employ the gauge method
of Haberzettl\cite{8} to include hadronic form factors. The fit to the data was significantly improved by allowing for separate cut-offs for the background and resonant sector. For the former, the fits produce a soft value around 800 MeV, leading to a strong suppression of the background terms while the resonant cut-off is determined to be 1900 MeV.

3 Results from Kaon Photoproduction: a new $D_{13}$ State at
1895 MeV

Figure\cite{3} compares our model described above with the SAPHIR total cross section data. Our result shows only one peak near threshold and cannot reproduce the data at higher energies without the inclusion of a new resonance
with a mass of around 1900 MeV. While there are no 3- or 4-star isospin 1/2 resonances around 1900 MeV in the Particle Data Book, several 2-star states are listed, such as the $P_{13}(1900)$, $F_{17}(1990)$, $F_{15}(2000)$ and $D_{13}(2080)$. On the theoretical side, the constituent quark model by Capstick and Roberts\cite{9} pre-
predicts many new states around 1900 MeV, however, only few of them have been calculated to have a significant $K\Lambda$ decay width. These are the $[S_{11}]_3(1945)$, $[P_{11}]_5(1975)$, $[P_{13}]_4(1950)$, and $[D_{13}]_3(1960)$ states, where the subscript refers to the particular band that the state is predicted in. We have performed fits for each of these possible states, allowing the fit to determine the mass, width and coupling constants of the resonance. While we found that all four states can reproduce the structure at $W$ around 1900 MeV, it is only the $[D_{13}]_3(1960)$ state that is predicted to have a large photocoupling along with a sizeable decay width into the $K\Lambda$ channel. Table 1 presents the remarkable agreement, up to a sign, between the quark model predictions and our extracted results for the $[D_{13}]_3(1960)$ state. In our fit, the mass of the $D_{13}$ comes out to be 1895 MeV; we will use this energy to refer to this state below.

How reliable are the quark model predictions? Clearly, one test is to confront its predictions with the extracted couplings for the well-established resonances in the low-energy regime of the $p(\gamma, K^+)\Lambda$ reaction, the $S_{11}(1650)$, $P_{11}(1710)$ and $P_{13}(1720)$ excitations. Table 1 shows that the magnitudes of the extracted partial widths for the $S_{11}(1650)$, $P_{11}(1710)$, and $P_{13}(1720)$ are in good agreement with the quark model. Therefore, even though the amazing quantitative agreement for the decay widths of the $D_{13}$ (1895) is
Figure 2. Differential cross section for the fit without (top) and with (bottom) the $D_{13}(1895)$ resonance.
probably accidental we believe the structure in the SAPHIR data is in all likelihood produced by a state with these quantum numbers. Further evidence for this conclusion is found below in our discussion on the recent JLab kaon electroproduction data.

As shown in Ref. 12, the difference between the two calculations is much smaller for the differential cross sections. Including the $D_{13}(1960)$ does not affect the threshold and low-energy regime while it does improve the agreement at higher energies.

The difference between the two models can be seen more clearly in Fig. 2, where the differential cross section is plotted in a three-dimensional form. As shown by the lower part of Fig. 2, the signal for the missing resonance at $W$ around 1900 MeV is most pronounced in the forward and backward direction. Therefore, in order to see such an effect in the differential cross section, angular bins should be more precise for these two kaon directions.

Figure 3 shows that the influence of the new state on the recoil polarization is rather small for all angles, which demonstrates that the recoil polarization is not the appropriate observable to further study this resonance. On the other hand, the photon asymmetry of $K^+\Lambda$ photoproduction shows larger variations between the two calculations, especially for higher energies. Here the inclusion of the new state leads to a sign change in this observable, a signal that should be easily detectable by experiments with linearly polarized photons.

Figure 4 shows double polarization observables for an experiment with...
circularly polarized photon and polarized recoil. As expected, we find no influence of the $D_{13}(1895)$ at threshold. At resonance energies there are again clear differences between the two predictions.

4 Results from Kaon Electroproduction: Electromagnetic Form Factors of the $D_{13}(1895)$

All previous descriptions of the kaon electroproduction process have performed fits to both photo- and electroproduction data simultaneously, in an attempt to provide a better constraint on the coupling constants. This method clearly runs the danger of obscuring - rather than clarifying - the underlying production mechanism. For example, anomalous behavior of the response functions in a certain $k^2$ range would be parameterized into the effective coupling constants, rather than be expressed in a particular form factor. Here, we adopt the philosophy used in pion electroproduction over the last decade: we demand that the kaon electroproduction amplitude be fixed at the photon point by the fit to the photoproduction data. Thus, all hadronic couplings, photocouplings and hadronic form factors are fixed, the only remaining freedom comes from the electromagnetic form factors of the included mesons and baryons.

Extending our isobar model of Ref.\cite{6} to finite $k^2$ requires the introduction of additional contact terms in the Born sector in order to properly incorporate gauge invariance\cite{14}. We choose standard electromagnetic form factors for
Table 2. Parameters for the $P_{11}(1710)$, $P_{13}(1720)$, and $D_{13}(1895)$ form factors.

| Resonance      | $\Lambda_1$ (GeV) | $n_1$ | $\Lambda_2$ (GeV) | $n_2$ |
|----------------|-------------------|------|-------------------|------|
| $P_{11}(1710)$ | 1.37              | 4    | –                 | –    |
| $P_{13}(1720)$ | 2.00              | 1    | 2.00              | 3.31 |
| $D_{13}(1895)$ | 0.36              | 4    | 1.21              | 4    |

the nucleon [4], for the hyperons we use the hybrid vector meson dominance model [5]. We use the monopole form factors for the meson resonances, where their cut-offs are taken as free parameters, determined to be $\Lambda = 1.107$ GeV and 0.525 GeV for the $K^*(892)$ and $K_1(1270)$, respectively. That leaves the resonance form factors to be determined which in principle can be obtained from pion electroproduction. In practice, the quality of the data at higher $W$ has not permitted such an extraction. For the $S_{11}(1650)$ state, we use a parameterization given by Ref. [17]. For the $P_{11}(1710)$, $P_{13}(1720)$, and $D_{13}(1895)$ states we adopt the following functional form for their Dirac and Pauli form factors $F_1$ and $F_2$:

$$F(k^2) = \left(1 - \frac{k^2}{\Lambda^2}\right)^{-n},$$

with the parameters $\Lambda$ and $n$ to be determined by the kaon electroproduction data. The resulting parameters are listed in Table 2.

Figure 5 shows the result of our fit. Clearly, the amplitude that includes the $D_{13}(1895)$ resonance yields much better agreement with the new experimental data [18] from Hall C at JLab. The model without this resonance produces a transverse cross section which drops monotonically as a function of $-k^2$, while in the longitudinal case this model dramatically underpredicts the data for small momentum transfer. With a $W = 1.83$ GeV the data are close in energy to the new state, thus allowing us to study the $-k^2$ dependence of its form factors. The contribution of the Born terms is negligibly small for the transverse cross section but remains sizeable for the longitudinal one. We point out that without the $D_{13}(1895)$ we did not find a reasonable description of the JLab data, even if we provided for maximum flexibility in the functional form of the other resonance form factors. The same holds true if the new resonance is assumed to be an $S_{11}$ or a $P_{11}$ state. Even including an additional $P_{13}$ state around 1900 MeV does not improve the fit to the electroproduction data. It is only with the interference of two form factors given by the coupling structure of a different spin-parity state, viz. $D_{13}$, that a
Figure 5. Transverse and longitudinal cross section for \( p(e, e'K^+)\Lambda \). The dotted line shows the contributions from the background terms, otherwise the notation for the curves is the same as in Fig. 1. Solid squares show the new JLab data \(^{18}\), open squares are the old data \(^{19}\). In the transverse cross section a photoproduction datum (solid circle) is shown for comparison.

description becomes possible. We therefore find that these new kaon electro-production data provide additional evidence supporting our suggestion that the quantum numbers of the new state indeed correspond to a \( D_{13} \).

The form factors extracted for the \( D_{13}(1895) \) are shown in Fig. 6 in comparison to the Dirac and Pauli form factors of the proton and those of the \( \Delta(1232) \). While the \( F_2(k^2) \) form factors look similar for all three baryons, \( F_1(k^2) \) of the \( D_{13}(1895) \) resonance falls off dramatically at small \( k^2 \). It is the behavior of this form factor that leads to the structure of the transverse and longitudinal cross sections at \( -k^2 = 0.2 - 0.3 \text{ GeV}^2 \); at higher \( k^2 \) both response functions are dominated by \( F_2(k^2) \). The experimental exploration of the small \( k^2 \) regime could therefore provide stringent constraints on the extracted form factors.
5 Conclusion

We have investigated a structure around $W = 1900$ MeV in the new SAPHIR total cross section data in the framework of an isobar model and found that the data can be well reproduced by including a new $D_{13}$ resonance with a mass, width and coupling parameters in good agreement with the values predicted by the recent quark model calculation of Ref. 4. To further elucidate the role and nature of this state we suggest measurements of the polarized photon asymmetry around $W = 1900$ MeV for the $p(\gamma, K^+)\Lambda$ reaction. Furthermore, we extended our isobar description to kaon electroproduction by allowing only electromagnetic resonance transition form factors to vary. Employing the new JLab Hall C $p(e, e'K^+)\Lambda$ data at $W = 1.83$ GeV we find that a description of these data is only possible when the new $D_{13}$ state is included in the model. The dominance of this state at these energies allowed us to extract its transition form factors, one of which was found to be dramatically different from other resonance form factors.
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