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Report of the committee to review the ODU Analysis of Meson-baryon Interference

1 Preface

The committee was formed on February 27, 2009 and charged to review the ODU Analysis of Meson-baryon Interference, based on the analysis note dated October 29, 2008. The lead investigators of this analysis were M. Amarian (contact), G. Gavalian, L. Weinstein and M.V. Polyakov. The members of the Analysis Review Committee were Elton Smith (chair), Marco Battaglieri, David Ireland, Franz Klein, and Dennis Weygand. The charge to the committee can be found in Appendix A. This committee follows a review conducted in 2007, which concluded that "case has not been made for unambiguous observation of a peak, pentaquark or otherwise, which appears as a result of interference with the $\phi(1020)$." The 2007 Review was followed by an extensive collaboration-wide discussion, as well as substantial work by the authors to address issues that were raised during this period. The report of the first committee and collaboration discussion are documented on the Hadron Spectroscopy Working group wiki. Two of the current review members also served on the first review. A log of exchanges between the current committee and the authors can be found on the wiki on the Hadron Spectroscopy Working Group review pages under *ODU Analysis of Meson-baryon Interference Review#Communication Log Review 2009*.

2 Introduction

The ODU analysis uses the g11 data set to study the reaction $\gamma p \to p K_L K_S$ [1]. The dominant production mechanism proceeds via the production of the $\phi(1020)$ meson, with its subsequent decay to $\phi \to K_L K_S$. However, this reaction is of interest because it also allows for the production of the exotic S=+1 Θ^+ baryon, via either $\gamma p \to \Theta^+ K_S \to (K_L p) K_S$ or $\gamma p \to \Theta^+ K_L \to (K_S p) K_L$. [1] The K_S decays close to the interaction vertex and is reconstructed using its charged pion decay mode $K_S \to \pi^+\pi^-$. Therefore the invariant mass K_Sp can be determined from reconstructed $\pi^+\pi^- p$ particles. The K_L does not decay in the detector, but the K_Lp mass can be determined as the missing mass in the $\gamma p \to K_S M_X$ reaction.

[1] This reaction cannot tag the sign of the strangeness of the produced particles, so other experiments would be necessary to establish the exotic nature of any enhancement in the K_Sp or K_Lp mass spectra.

Negative searches using this data set have been reported by the CLAS collaboration, setting an upper limit (95% CL) of 1.3 nb to the decay mode $\Theta^+ \rightarrow pK^0$ and 1.0 nb for $\Theta^+ \rightarrow nK^+$ [2]. For the $\Theta^+ \rightarrow pK^0$ decay mode the CLAS acceptance has uniform sensitivity over the entire angular range. The upper limit (95% CL) of 0.8 nb was placed on the production and decay via $\Theta^+ \rightarrow nK^+$ from studies of $\gamma p \rightarrow \overline{K^0}\, nK^+$ [3]. The CLAS sensitivity to forward-angle production of this reaction is 10 times lower than for most of the angular range. These limits are to be compared with the cross section for ϕ meson production of about 400 nb. These analyses specifically excluded events for which $M_X(\gamma p \rightarrow pX) < 1.04$ GeV thereby eliminating ϕ mesons, which is a major channel for hadron production in this final state.

The present analysis relies on the quantum mechanical interference between the production amplitudes for ϕ and Θ production to enhance the baryon signal where they overlap. Previous searches for the Θ specifically excluded the ϕ mass region to eliminate this primary background. In contrast, this analysis chooses the ϕ mass region and turns this background into an advantage by using it to enhance the signal of interest. After careful analysis to improve experimental resolutions and remove backgrounds a peak is found in the $\gamma p \rightarrow K_S M_X$ missing mass spectrum at M_X=1.54 GeV, close to the reported mass of the exotic Θ^+.

3 Event reconstruction and event selection

Since the first review in 2007, the authors have invested significant effort in careful evaluation of the event reconstruction and optimizing vertex cuts to enhance the selection of the topology of interest relative to other backgrounds. They have shown that their analysis has been able to enhance the K^0_S signal over combinatorical background and also improve the CLAS experimental resolution of known resonances. *In reviewing the raw data, the committee did not identify any issues in the event reconstruction.* Also, in the comparison with an independent analysis (see Section 4), no significant issues were found in the reconstruction.

The number of selection cuts has been reduced to seven event identification cuts ($\mathrm{M}_{\pi\pi}$, $\mathrm{M}_x(pK_S)$, M_ϕ, $\mathrm{DOCA}_{\pi\pi}$, $\mathrm{DOCA}_{p\gamma}$, $\cos\Theta_{K_S}$, Z–vertex). Initially the analysis eliminated events with neutral hits in the calorimeter, but these events were later reinstated because that selection cut events when the K_L interacted in the calorimeter.[2] The cuts on photon energy have been relaxed to the point they are not of concern, as it has been shown that narrow cuts severely constrained the kinematics and created artificial peaks in the vicinity of the claimed signal. We applaud the authors for taking previous suggestions to heart and making every effort to address concerns by the collaboration and previous committee. Nevertheless, *the committee feels that the*

[2]This change approximately doubled the size of the event sample.

specific cuts that were chosen, which in most cases correspond to roughly $\pm 1\sigma$, *are too zealous because such tight cuts discard significant precious signal* [4]. We believe that relaxing these cuts would be beneficial to the final analysis. The physics analysis cut on t_K, however, has been of particular concern and discussed at length below.

4 Parallel analysis

A parallel analysis has been performed by Valery Kubarovsky using a completely independent analysis tool on the same BOS files. Tagger energy correction, momentum correction, particle identification and kinematic variables were independently calculated and applied. These analysis tools were used in searching for evidence of a pentaquark in different channels and the results of the main procedures were cross checked with the results of different groups (Genova, JLab and RPI). Valery performed two different analyses: in the first he applied exactly the same set of cuts reported by the ODU group ("Moskov analysis") while in the second he used the same cuts but with relaxed values ("vpk analysis"). The "vpk analysis" can be considered as a "blind" analysis since the author used his own judgment to choose the cut limits. The main difference in the second analysis was the relaxed cuts on momentum transfer $-t_K < 1 GeV^2$ (compared to $-t < 0.45 GeV^2$ in the Moskov analysis) and collinearity angle $cos(\theta) > 0.8$ (compared to $cos(\theta) > 0.95$ in Moskov analysis). The final results of the two analyses can be found in the Committee comments of Aug. 6 [5]. The number of events in the final $M_x(\pi^+\pi^-)$ spectrum was found to be 5k in the "Moskov analysis" and 60k in the "vpk analysis." In both cases there was no evidence for a peak at $M_x(\pi^+\pi^-)$=1540 MeV when no cuts were placed on t_K. Discrepancies in the specific histogram plots arose when Valery and Moskov compared their results with tight cuts, and they discussed in detail the possible origin of disagreement [5]. The ODU group claimed that Valery's calculation of the DOCA was incorrect while Valery defended his results. The Committee believes that, within statistical error, the two results are compatible and the disagreement arises from the slightly different analysis tools used by the two authors. A more sophisticated compatibility test was performed by D. Ireland (Kolmogorov-Smirnov test) finding that they were compatible at the 2% CL and rejecting the hypothesis that they were different samples at the 5% (2 σ) CL, but not at the 1% level (3σ) CL. The work done by Valery, and in particular the "vpk analysis" was highly appreciated by the Committee:

1. the high statistic $M_x(\pi^+\pi^-)$ spectrum obtained with relaxed cuts was used as a possible shape of the background in the specific analysis of the statistical significance of the peak (see Ref. [6]);

2. the effect on the S/B ratio of relaxing the cut on the momentum transfer was

studied in detail (see Ref. [7]) finding that the sensitivity cannot be improved very much by making tight cuts on t_K.

5 Main questions raised by the committee

After the first round of questions by the committee, many to bring the committee up-to-date on the large body of work by the authors, most of them were resolved in the response by the authors. Following that initial round of clarifications, the committee felt that there remained three fundamental issues that needed resolution:

5.1 Kinematic fitting and K^0p invariant mass

We felt that one of the unresolved issues from the previous committee (Item No. 3 of their report, p. 5) was the fact that the analysis lacked the commonly used technique of kinematic fitting to improve the experimental resolution and strengthen the significance of the result, for both K_S and K_L decays. We realize that this is a major effort, as well as sensitive to precise knowledge of the detector, and applaud the authors for taking up this challenge during the review and providing results from this new analysis [8]. A comparison of the missing mass spectrum with and without kinematic fitting yield similar results for the significance of the peak, although the probability of the kinematic fit is considerably reduced compared to the fit without constraints.

A real signal visible in the $\Theta^+ \to K_L p$ decay (as evidenced by a peak in the K_S missing mass spectrum), will also have an equal probability to decay into $\Theta^+ \to K_S p$. However, no signal was observed in the reconstructed $\pi^+\pi^- p$ invariant mass spectrum. Monte Carlo simulations by the authors (see Appendix 9.2 in Ref. [1]) indicate that, even though a generated signal is clearly present as a peak in the missing mass distribution, the resolution in the K_Sp invariant mass is too poor to resolve the corresponding peak. This result surprises the committee, based on previous experience, but it might occur in specific areas of phase space. Furthermore, the kinematic fit to the reaction, which one would expect to equalize the resolution of the missing and invariant masses, proved ineffective in helping to resolve a peak in the invariant mass [8].

5.2 Background shape

The dominant reaction resulting in the selected final state is ϕ production, particularly once the selection cut has been placed on 1.012< M_X <1.028 GeV in the missing mass of $\gamma p \to pX$. It is a great asset to be able to understand and model the background reaction and the simulation shows that ϕ production can account for the majority of the events in the MM_{K_S} missing mass spectra outside the region of the peak at 1.54 GeV. The committee does not comment on the quality of the chosen theoretical model for the reaction $\gamma p \to \phi p$. But the model under-predicts the level of background in the wings of the peak ($\sim$ 15.1 and $\sim$1.58 GeV). It is crucial to describe these regions reliably so that the signal is not overestimated. Several of the fits to the simulated background shape and a Gaussian peak results in fits with very low probability, that is, less than 1% [8]. Of the four fits shown in Fig. 2 of Ref [9], two of them have probabilities of less than 2%, and the highest has a probability of 22%. We agree with the authors that polynomial fits are poor choices for the description of the background and should be avoided. Instead, one should use empirical shapes which exhibit proper behavior over the fitting interval and reproduce the data in the critical region near the peak. For example, we have suggested empirical shapes that have been used together with a Gaussian to fit the data successfully with probabilities of greater than 50% [6].

5.3 Use of the cut on the momentum transferred t_K

Considerable discussion has centered on the justification for the physics cut which kept only events with $-t_{K_S} < 0.45$ GeV^2 in order to enhance the production of $\Theta \to pK_L$, which is expected to be produced preferentially at low $-t_{K_S}$ [3] . This cut would therefore enhance the signal-to-background (S/B) ratio in the data, where the background, B, is dominated by ϕ production. Based on the simulation, this cut would reduce the ϕ background by a factor of 2 [10]. We note that this cut reduces the yield obtained after the tight cuts to select the reaction $\gamma p \to \phi p$ by 75% (see Section 3).

It was shown through a series of examples in Ref. [11] that the naive significance estimator S/$\sqrt{B}$ tracks the Log likelihood measure of statistical significance. The signal S is assumed to be caused by the interference between the Θ and ϕ, and therefore proportional to $A_\theta\, A_\phi$, which are the production amplitudes for each process. The background is assumed to be dominated by ϕ production, and is therefore proportional to $A_\phi\, A_\phi$. In this situation where the signal and background rates are related, reducing the background rate can also affect the signal. This is especially true in this exclusive reaction, where the momentum transfer to the K_S and the ϕ are kinematically correlated. Therefore, making selection cuts on t_K has the effect of removing more signal events than expected because it is proportional to A_ϕ. This situation was studied in quantitative examples by both the committee [7] and the authors [9] with similar results. Our conclusion is that the gain in sensitivity by making selec-

[3]In the discussion that follows, we drop the S in the subscript for simplicity.

tion cuts on t_K will be less than at most 10%. This implies that a real signal should be visible in the data without any cuts on t_K. We also note that relaxing the t_K and the collinearity cuts increases the statistics by about an order of magnitude and completely wash out the observed structure.

6 Significance of peak

The peak significance tests are based on evaluating the likelihoods of two hypotheses:

1. S+B: mass spectrum is described by a background and a gaussian peak,
2. B: mass spectrum is described by a background only.

The ODU group supplied the committee with the maximum likelihood values for each hypothesis: $\ln L_{S+B} = 4600.02$, $\ln L_B = 4585.44$. The "significance," calculated as $\sqrt{2\ln(L_{S+B}/\ln_B)}$ comes out as 5.4σ. This translates to a rejection of the null hypothesis (B) at the 2×10^{-6} level. Other tests, such as an F-test, and a Bayesian Information Criterion show similar results. The conclusion from this is that, *given the assumption that the background is correctly modeled*, a model based on background-only does not fit the data.

On the other hand, *we do not believe that the background derived from the Titov-Lee model gives an accurate enough description of the data in the regions away from the peak, and so any statistical tests have to be robust to a more flexible choice of background shape.* A 3rd order polynomial was tried by the ODU group, but found to give poor results. The committee believes that, amongst many other more realistic choices of shape, an empirical distribution such as the form from Eq. 1 from Ref. [6] could be used as an alternative. Indeed in Ref. [6], it is shown that using such a shape results in a much better goodness-of-fit to the data reported by the ODU group. In that study, it is also shown that the significance of the peak is greatly reduced compared to the values quoted by the ODU group. Several different parameterizations are used, which lead to slightly different values of significance. However, none of those significances exceed the psychologically important 5σ threshold.

7 Simulation of the Θ-ϕ interference

In order to investigate the advantages of using the interference phenomena to enhance the experimental observation of the pentaquark signal, the interference between the proposed narrow Θ pentaquark and the $\phi(1020)$ vector meson was simulated using a Monte Carlo program based on the K_SK_Lp three-body phase space [12]. A description of the interference process can be found in Ref. [13]. Two versions exist, one with an exponential momentum distribution to the two-body sub- systems, and the other without. The ϕ resonance is generated in the K_SK_L mass with measured parameters for mass and width. The $\Theta(1540)$ is generated with a 1 MeV natural width in both pK_S and pK_L masses. The resonances are allowed to interfere. In addition there is a three-body phase-space background which does not interfere with the resonances. The simulation includes quantum interference between the two states, with an applied exponential t-distribution to both the ϕ production and the Θ. The exponential slope for the ϕ was $4.0\,\mathrm{GeV}^{-2}$, and $3.0\,\mathrm{GeV}^{-2}$ for the pentaquark. To compare directly with experimental data, the simulation was run with a cross section of the pentaquark relative to the ϕ meson consistent with the published upper limit from g11 (2.7 $\times 10^{-3}$). The phase angle between the interfering resonances was chosen to be zero, which maximizes the interference signal. The generated distributions were studied with and without the $-t_K < 0.45\ \mathrm{GeV}^2$ selection requirement. For studies at the center-of-mass energy of 2.1 GeV, corresponding to a beam energy of 1.89 GeV, the simulation showed no evidence that interference draws out the pentaquark signal.

This work represents a fairly sophisticated, but conceptionally simple simulation of the effects of interference between two narrow resonances. *No evidence of utilizing the interference in order to enhance the observation of a weakly produced object has been observed.* Of course, interference is a known technique that can enhance weak signals, the difficulty here is likely that both objects are narrow, and therefore any interference is limited. The addition of realistic cross section upper limits, together with statistics consistent with the CLAS g11 run, does not show this as a viable analysis technique.

8 Conclusions

The committee does not believe the excess of events in the MM_{K_S} missing mass represents a robust signal that can be used to claim a discovery. Neither the modeling of the interference process (Section 7), nor the modeling of significance through variation in cuts (Section 5.3) have shown evidence to support the ODU claims. We conclude by specifically addressing each of the main questions in the charge:

1. Are all the analysis cuts applied justified? No. There is no convincing evidence that the use of the t_K analysis cut should enhance an interference signal.

2. Could the claimed signal be an artifact of the analysis procedure used? Yes. The excess of events above background in the MM_{K_S} spectra depend on strong analysis cuts which enhance the peaking structure in a manner that is not expected from an interference signal.

3. What is a significance of the signal, if any. The excess of events in the MM_{K_S} missing mass spectra corresponds to a maximum significance of 4σ if interpreted as an interference signal.

References

[1] G. Gavalian et al. First observation of narrow strange baryon resonance structure via interference with ϕ-meson in photoproduction reaction $\gamma + p \to pK_SK_L$ on hydrogen target with clas. Original analysis note, October 29, 2008.

[2] R. De Vita et al. Search for the Θ^+ pentaquark in the reactions $\gamma p \to \overline{K^0}K^+n$ and $\gamma p \to \overline{K^0}K^0p$. *Phys. Rev.*, D74:032001, 2006.

[3] M. Battaglieri et al. Search for $\Theta(1540)^+$ pentaquark in high statistics measurement of $\gamma p \to \overline{K^0}K^+n$ at CLAS. *Phys. Rev. Lett.*, 96:042001, 2006.

[4] F. Klein. Event selection and reconstruction cuts. DRAFT plots, September 28, 2009.

[5] Review Committee. Comments on comparing histograms between “Moskov” and “vpk” analyses. Communication, August 6, 2009.

[6] E.S. Smith. Empirical backgrounds and estimated signal significance. DRAFT August 21, 2009.

[7] E.S. Smith. Study of signal-to-background ratios for various t_k selection cuts. DRAFT September 18, 2009.

[8] C. Nepali. Comment on kinematic fitting. Figures provided by Moskov, August 12, 2009.

[9] G. Gavalian. Significance estimation for observed signal from g11 data. Response to committee, Sep 13, 2009.

[10] M. Amaryan et al. Response to remaining questions and comments raised by the odu pentaquark analysis review committee. Second round of clarifications, July 21, 2009.

[11] E.S. Smith. Study of the dependence of the estimated signal significance on signal-to-background. DRAFT August 28, 2009.

[12] D.P. Weygand. Pentaquark-$\phi(1020)$ interference simulation. DRAFT, August 28, 2009.

[13] Moskov Amarian, Dmitri Diakonov, and Maxim V. Polyakov. Exotic Θ^+ baryon from interference. *Phys. Rev.*, D78:074003, 2008.

A Charge

Your committee will be the first to review this work in three step process. Subsequent to your review the full paper will be reviewed by a CLAS wide Ad Hoc committee, and then the entire Collaboration. Your charge is to concentrate on the analysis and experimental aspects rather than the physics interpretation (physics interpretation will be the primary focus of the CLAS Ad Hoc committee when you are done). When your work is completed, the data no longer need be considered "preliminary."

Below are some guidelines we hope will clarify your role and make the review process more efficient.

1. According to the CLAS Charter, the Physics Working Groups have the primary responsibility for determining that data are accurate and precise within the stated uncertainties and ready to be distributed. As representatives of the Hadron Spectroscopy Working Group, it is your task to determine that the data being presented meets these conditions. This means, for example, assuring that backgrounds have been determined correctly, that cuts are reasonable and justified, that systematic errors have been considered, etc. Among others, there a few important questions to be answered in the course of this review:

   - are all the analysis cuts applied justified?
   - could the claimed signal be an artifact of the analysis procedure used?
   - what is a significance of the signal, if any.

   This review was preceded by the group wide discussion. You will find a link to this site on the review page. You may find it useful in your review.

2. It will not be possible to do a good job on step 1 without some idea as to the physics to be presented in the paper to be published. Hopefully you will be supplied with a preliminary draft, or at least a detailed outline, of the paper to be prepared from the data analysis.

3. In the course of your work you may determine that certain aspects need to be more clearly explained, or that additional checks and calculations are needed in order to verify the data. In this endeavor you are urged to work closely with the authors, and hopefully in a constructive manner.

4. Multiple, disjoint communications with the authors are often confusing. You should, as much as possible, work as a committee, with agreement as to what if any clarifications or additions are needed. It will help if the communications with the lead investigators are funneled through the chair of your committee.

5. One of the more important aspects in the review process is communication, and particularly communication between the various committees. In the regard we ask you (or the authors) to keep a copy of all written communications between your committee and the authors in a file. This file will then be made available to the Ad Hoc committee when it starts its work.

6. While it is necessary to agree that the analysis supports the physics goals, and is therefore appropriate to comment and make suggestions on the draft of the paper, please remember that your primary responsibility is to determine that the data are correct.

When you are satisfied that your charge has been met, please inform the chair of the working group.

We know that the work on this committee will require a real commitment from you, but the process is an important step in assuring that the results reported by the CLAS Collaboration are trustworthy. The entire Collaboration appreciates the effort you are about to undertake.