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# Baryon Spectroscopy: Recent Results from the CBELSA/TAPS Experiment

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The study of the light quark baryon spectrum requires the measurement of not only high resolution differential cross sections but also of polarization observables to isolate the contributing broad and overlapping resonances. Without including both polarized and unpolarized data into a simultaneous analysis an unambigious partial wave analysis to extract the resonances from the data is not possible.
The CBELSA/TAPS experiment at the electron accelerator ELSA is dedicated to measure the photoproduction observables needed to study the light quark baryon spectrum. New data measured in the photoproduction of the p$\pi^0$, p$\eta$, p$\omega$, and p$\pi^0\pi^0$ final states show how the current understanding can be improved with the inclusion of new observables. Recent results obtained will refine the interpretations of previous data and ultimately result in the better understanding of the well-known baryon resonances. In addition, this data allows to search for new and "missing" baryon resonances.

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## 1. Introduction

The pattern of baryon resonances is a result of the nature of the strong interaction which holds the quarks together. By analyzing the pattern of baryon resonances, the low energy regime of the strong interaction and its bound states can be studied. This fact is the reason why the light quark baryon resonances have been studied for many years using $\pi$ beams. However using a $\pi$ beam depends exclusively on the resonances coupling to the $\pi$ meson. Predictions from quark model calculations in [1, 2] show many resonances may not show up in $\pi N$ scattering experiments. Therefore to maximize the probability of detecting these states, experiments around the globe such as those at ELSA, JLab and in Mainz have used photon beams and the electromagnetic interaction to excite the nucleon and to study the baryon resonances.

The current theoretical models and calculations show significant differences from the known baryon spectrum. At masses below 1.8 GeV/$c^2$, the current $N^*$ and $\Delta$ spectra show much similarity with the general pattern of states predicted by the Constituent Quark Models (CQMs), such as [3, 4]. In addition, the most recent Lattice QCD calculations [5] confirm the general pattern of states from the non-relativistic CQMs in this same mass range. However at higher masses, the number of predicted states in both types of theory vastly outnumbers the known states; these supernumary predicted states are sometimes called the “missing” baryon resonances. Also the mass ordering of some of the lowest mass states such as the $N(1440)\frac{1}{2}^+$ and $N(1535)\frac{1}{2}^-$ is not well reproduced in the CQMs or in the Lattice QCD calculations. Measuring the properties of known resonances more precisely and searching for the existence of these higher mass predicted states will help us to understand the discrepancies between theory and experiment.

The known and predicted $N^*$ and $\Delta$ baryon resonances have widths which are in most cases larger than the distance in mass to the nearest resonance, i.e. overlapping. Therefore, resonances must be deduced by analyzing the experimentally measured data by simultaneously accounting for the resonances and contributing background, for example in a Partial Wave Analysis (PWA). However, one of the largest difficulties in isolating overlapping baryon resonances is the ambiguous interpretations of the data. Experimental efforts therefore attempt to achieve the "complete" experiment [6, 7]. The "complete" experiment requires the measurement of observables with polarized beams and polarized targets as well as, in many cases, detecting the spin polarization of final state particles and is required for unambiguous, model-independent data interpretations. Therefore, the high resolution cross sections along with the corresponding polarized observables are critical to the detection of baryon resonances in photoproduction experiments.

The recent results from the CBELSA/TAPS experiment consist of differential cross sections along with single and double polarization observables with the resolution required for the isolation of baryon resonances. These measurements are making significant progress toward the "complete" experiment and the understanding of the baryon resonance spectrum.

## 2. Experiment

The CBELSA/TAPS experiment is located at the Electron Stretcher Accelerator ELSA (Bonn) [8]. In order to measure polarization observables, the beam and target can be chosen to have either no polarization, circular polarization or linear polarization [9]. In the same measure-

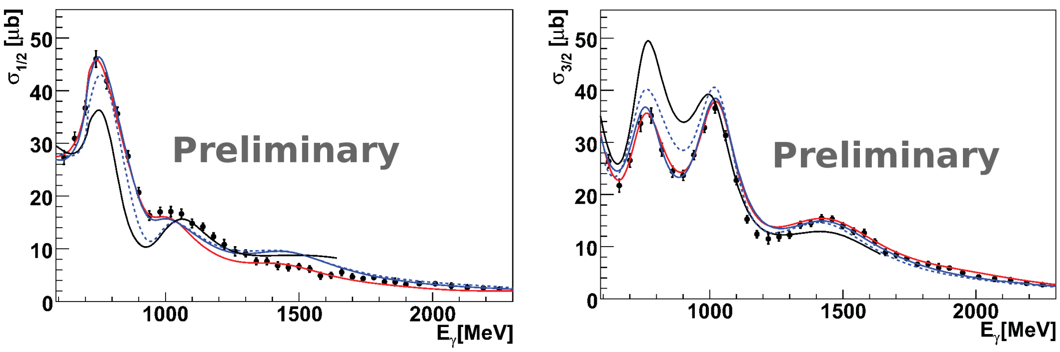


**Figure 1:** (Color Online) The polarized total cross sections for $\gamma p \to p\pi^0$ [17] are plotted as a function of the energy of the initial photon in the lab frame. The red solid line is the prediction from the Bonn-Gatchina PWA solution (2011-02) [18]. Two SAID PWA solutions are shown: SN11 is the blue dashed line and CM12 is the blue solid line [19]. The solid black line is the prediction from the MAID analysis [20].



ment, the target can be chosen to be unpolarized liquid hydrogen or polarized butanol, $C_4H_9OH$ [10]. The polarizable protons in the butanol are the protons in the hydrogen atoms and can be polarized either transverse or longitudinal to the photon beam.

The most essential parts of the detector system are the electromagnetic calorimeters which are optimized to reconstruct mesons decaying to photons. The calorimeter detectors, Crystal Barrel Detector [11] and TAPS Detector [12], cover the whole azimuthal range and from $1^\circ$ to $156^\circ$ in polar angle coverage, when the outgoing beam line is considered for reference. This coverage allows the reconstruction of mesons over almost the whole angular range. With the CBELSA/TAPS experiment, baryon resonances with masses up to 2.5 GeV/c$^2$ can be studied.

## 3. Recent Results

To study the lowest mass baryon resonances, $\pi$ production was investigated and is believed to be well understood through the $\pi$ beam experiments. The differential cross sections for this final state have been measured by many experiments in the past, including recently in photoproduction [13, 14, 15]. However in the recently published paper [16] on the polarization observable G from the CBELSA/TAPS collaboration, the differences which appear between the data and the latest partial wave analyses show how much still needs to be learned about $\pi^0$ photoproduction. In particular, these data are sensitive to a discrepancy in the predictions involving well-known, low-mass resonances which contribute to the $3/2^-$ and $1/2^-$ partial waves. This data shows how new observables can refine the understanding of the properties of even the low mass resonances, e.g. masses, widths and decay couplings.

When a circularly polarized photon beam is scattered off of a target which is polarized along the same axis as the photon beam, the observable measured (Helicity Asymmetry E) can give information on baryon resonances produced with different spin projections. Figure 1 shows the recent results for the spin-projected polarized total cross section. The predictions from several analyses, which result from analyses of previous data, show differences from the data and each other. The differences in the second resonance region ($E_\gamma \approx 400$ MeV) in Figure 1 cannot be traced

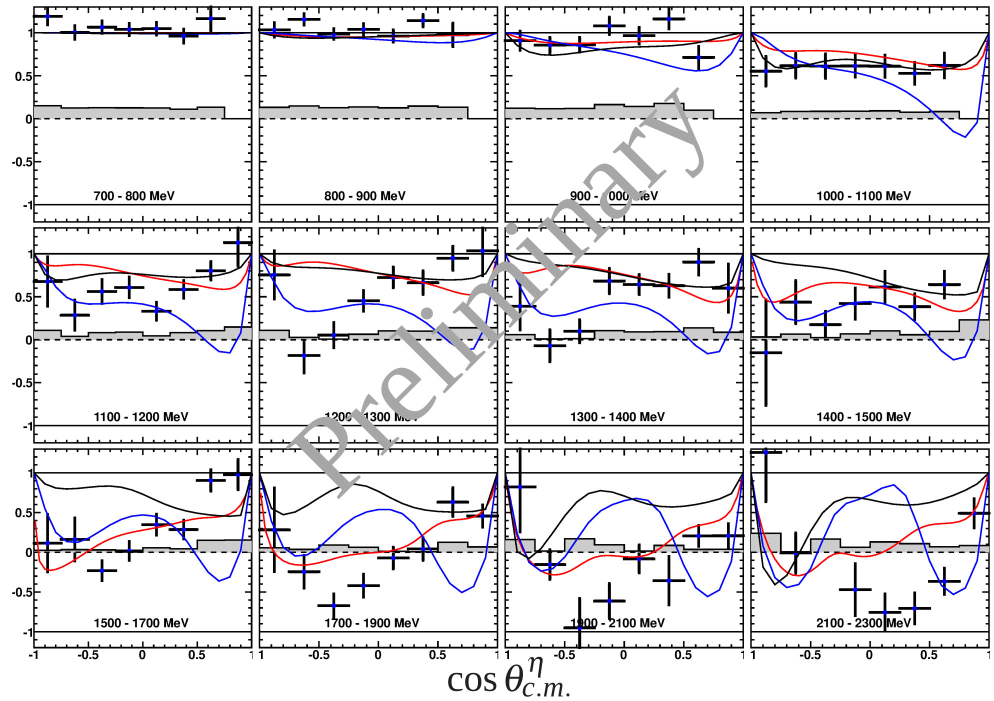


**Figure 2:** (Color Online) The Helicity Asymmetry for $\gamma p \to p\eta$ [24] is labeled with its range in initial photon energy measured in the lab frame. The grey shaded area in each plot is the systematic uncertainty for each data point. The red line is the prediction from the Bonn-Gatchina PWA solution (2011-02) [18]. The blue line is from the prediction of the SAID PWA solution (GE09) [23]. The black line is the prediction from the MAID analysis [25].

to the same partial waves as in [16], but have a unique resolving power. The discrepancies in the fourth resonance region ($E_\gamma \approx 1500$ MeV) are in the lowest mass range where the "missing" baryon resonances are predicted to be. The Helicity Asymmetry measurement is further broken up into angular distributions and is published in [17].

The photoproduction of $\eta$ mesons off the free proton is an excellent final state to find new resonances which would not have been found in the previously studied $\pi$ beam experiments. Also since the $\eta$ is an isospin zero meson, the $p\eta$ final state can only couple to $N^*$ (isospin one-half) resonances; a final state like this is sometimes called an isospin filter. Many observables for this final state have been measured and studied, including most recently in photoproduction [21, 22, 23]. However when the polarization observable Helicity Asymmetry E is considered in Figure 2, the ambiguities in the interpretations of this final state can be seen. At low energies, the Helicity Asymmetry is approximately one due to the dominance of the $N(1535)\frac{1}{2}^-$ resonance. At higher energies, the predictions and the data disagree with each other and show the effect this data will have in resolving the differences between PWA solutions and presumably in finding new resonances.

The final state with one $\omega$ meson and one proton has been predicted to be a good state to find baryon resonances [2]. Like the $p\eta$ final state, the $p\omega$ final state can only couple to $N^*$ resonances. However due to the quantum numbers of the $\omega$ meson, there is known to be a significant amount of background in photoproduction due to the $t$-channel exchange of mesons. In order to

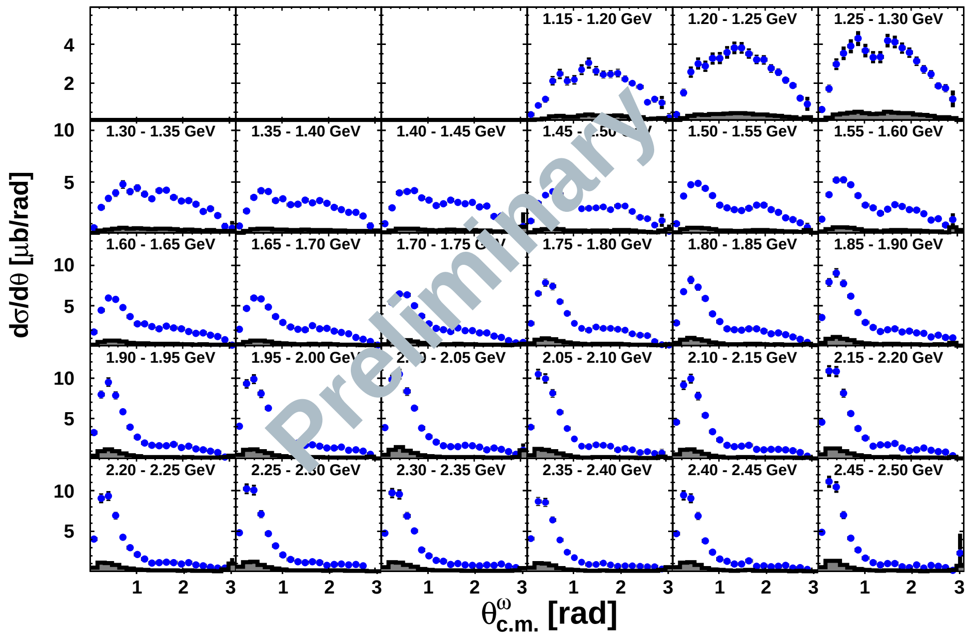


**Figure 3:** (Color Online) The differential cross sections for $\gamma p \to p\omega$ [26] are labeled with its range in initial photon energy measured in the lab frame. The shaded area in each plot is the systematic uncertainty for each data point.

get a good handle on this background, a high resolution measurement of the differential cross sections is needed over the whole angular range along with polarization observables. In Figure 3, the differential cross sections show a precise measurement of the whole angular range up to 2.5 GeV in incoming photon energy. The increase on the left side of each of the higher energy plots is an indication of $t$-channel meson exchange and is in agreement with earlier studies of this final state. At low energies, the distributions are nearly symmetric and is an indication of significant baryon resonance production.

The data in Figure 3 has been included in a preliminary partial wave analysis by the Bonn-Gatchina PWA group along with preliminary $\gamma p \to p\omega$ Helicity Asymmetry data [27] and the published data in [28]. In their preliminary analysis, the $N(1875)\frac{3}{2}^-$ and $N(1720)\frac{3}{2}^+$ resonances cause the low energy resonance behavior along with a significant amount of $t$-channel meson exchange of both pomerons and $\pi^0$ mesons.

When two mesons are produced in photoproduction reactions, baryon resonances can be observed in direct formation from the photon-nucleon scattering or in cascade decays such as $\gamma p \to N_1^* \to N_2^* \pi^0 \to \mathrm{p}\pi^0\pi^0$. The evidence for these cascade decays can be seen in the Dalitz plots in Figure 4 (Left). This final state was explored recently by fitting unpolarized data in [29]. However, as before, the difficulties in interpreting data with an incomplete set of observables is shown by considering the polarization observable T shown in Figure 4. The polarization observable T is measured by taking data on a proton target with polarization transverse to the photon beam. This observable is shown at energies where the known baryon resonances contribute and as a function of the quasi-two body angle $\cos\theta^{c.m.}_{\pi^0\pi^0}$, the cosine of the polar angle of the $\pi^0\pi^0$ system in

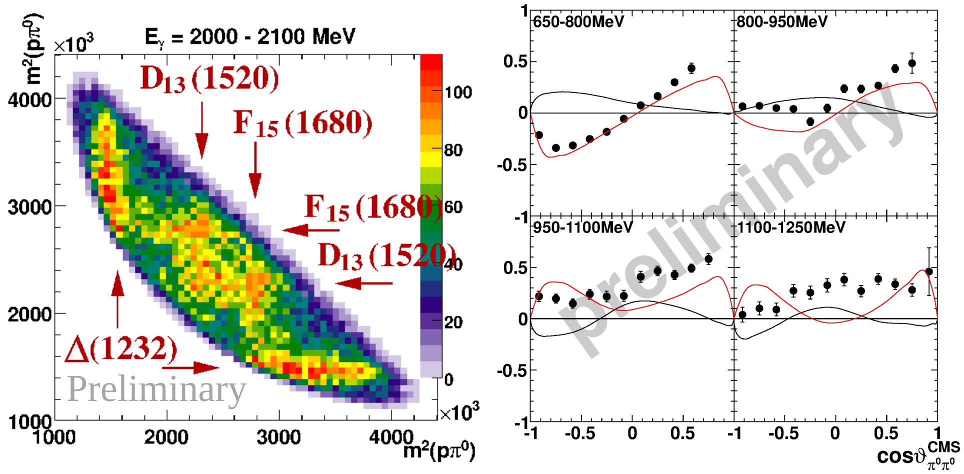


**Figure 4:** (Color Online)Preliminary data on $\gamma p \to p\pi^0\pi^0$ [30]. (Left) Dalitz plot for events from 2000-2100 MeV in initial photon energy. The labeled resonances are the likely contributions based on preliminary Bonn-Gatchina PWA fits. (Right) The Target Asymmetry is labeled with its range in initial photon energy measured in the lab frame. The red solid line is the prediction from the Bonn-Gatchina PWA solution (2011-02) [18]. The solid black line is the prediction from the MAID analysis [25].

the center-of-mass frame. The predictions show clear deviations from the data and highlight both the ambiguities in the interpretation and the resolving power of polarization observables. Further measurements of other polarization observables for the $p\pi^0\pi^0$ final state at higher energies by the CBELSA/TAPS collaboration are under analysis, which will continue to refine our understanding of baryon resonances and their decays .

## 4. Summary and Outlook

Recent data taken from photoproduction experiments around the world, including the CBELSA/TAPS experiment, have contributed to the recent increase in the number of baryon resonances included in the RPP published by the Particle Data Group [32]. In a recent Bonn-Gatchina PWA paper [18], new resonances and star assignments were suggested upon analyses of recent photoproduction data and were adopted by the PDG into the 2012 RPP. The observables presented here represent the next wave of experimental data which will increase our understanding of the spectrum of baryon resonances and will hopefully lead to the observation of new baryon resonances in the future. These newly measured observables are refining our knowledge of the known baryon resonances and facilitating the discovery of previously unknown baryon resonances.

For the CBELSA/TAPS experiment, the data shown in this paper is but the "tip of the iceberg". Work is being done on measuring the polarization observables for many photoproduction final states, including $p\pi^0, p\eta, p\eta', p\omega$, and $p\pi^0\pi^0$. These data will drive forward the understanding of baryon resonances for years to come.

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## References


[1] S. Capstick, Phys. Rev. D **46**, 2864 (1992).

[2] S. Capstick and W. Roberts, Phys. Rev. D **49**, 4570 (1994).

[3] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).

[4] U. Loring, B. C. Metsch and H. R. Petry, Eur. Phys. J. A **10**, 395 (2001).

[5] R. G. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011).

[6] G. Keaton and R. Workman, Phys. Rev. C **54**, 1437 (1996).

[7] W. -T. Chiang and F. Tabakin, Phys. Rev. C **55**, 2054 (1997).

[8] W. Hillert, Eur. Phys. J. A **28S1**, 139 (2006).

[9] D. Elsner *et al.* [CBELSA/TAPS Collaborations], Eur. Phys. J. A **39**, 373 (2009).

[10] H. Dutz *et al.*, Nucl. Instrum. Meth. A **340**, 272 (1994).

[11] E. Aker *et al.* [Crystal Barrel Collaboration], Nucl. Instrum. Meth. A **321**, 69 (1992).

[12] A. R. Gabler *et al.*, Nucl. Instrum. Meth. A **346**, 168 (1994).

[13] H. van Pee *et al.* [CB-ELSA Collaboration], Eur. Phys. J. A **31**, 61 (2007).

[14] M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **76**, 025211 (2007).

[15] V. Crede *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. C **84**, 055203 (2011).

[16] A. Thiel *et al.* [CBELSA/TAPS Collaboration] Phys. Rev. Lett. **109**, 102001 (2012).

[17] M. Gottschall *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **112**, 012003 (2014).

[18] A. V. Anisovich *et al.*, Eur. Phys. J. A **48**, 15 (2012).

[19] R. L. Workman *et al.*, Phys. Rev. C **85**, 025201 (2012).

[20] D. Drechsel, S. S. Kamalov and L. Tiator, Eur. Phys. J. A **34**, 69 (2007).

[21] V. Crede *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. C **80**, 055202 (2009).

[22] M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 045213 (2009).

[23] E. F. McNicoll *et al.* [Crystal Ball at MAMI Collaboration], Phys. Rev. C **82**, 035208 (2010) [Erratum-ibid. C **84**, 029901 (2011)].

[24] J. Muller [CBELSA/TAPS Collaboration], Ph. D. Thesis in preparation. University of Bonn: Germany.

[25] W. -T. Chiang *et al.*, Phys. Rev. C **68**, 045202 (2003).

[26] A. Wilson *et al.* [CBELSA/TAPS Collaboration], Paper in preparation.

[27] H. Eberhardt *et al.* [CBELSA/TAPS Collaboration], Paper in preparation.

[28] F. Klein *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. D **78**, 117101 (2008).

[29] U. Thoma *et al.* [CB-ELSA Collaboration], Phys. Lett. B **659**, 87 (2008).

[30] T. Seifen [CBELSA/TAPS Collaboration], Ph. D. Thesis in preparation. University of Bonn: Germany.

[31] A. V. Sarantsev *et al.*, Phys. Lett. B **659**, 94 (2008) [arXiv:0707.3591 [hep-ph]].

[32] J. Beringer *et al.* [Particle Data Group Collaboration], Phys. Rev. D **86**, 010001 (2012).