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PHOTOEXCITATION OF N* RESONANCES

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We present an overview of most recent experimental results of photonuclear reactions in the resonance energy region. High precision and polarization observables are the key issues in the study of N^* resonance properties.

1 Introduction

The excited states of the nucleon were observed for the first time in $\pi - N$ scattering experiments, as clear peaks in the cross-section. Partial-wave analysis of $\pi - N$ elastic scattering data and charge exchange reactions have provided quantum numbers, masses and widths of most of the baryonic (N and Δ) resonances [1]. Smaller sets of data are available for pion induced reactions with $N\eta$, ΛK, $\Lambda\Sigma$ or $N\pi\pi$ produced in the final state. They have provided information on the branching fraction for the N^* decaying into different baryon-meson channels. Meson photoproduction reactions have been used to extract the electromagnetic transitions amplitudes (the $A_{1/2}$ and the $A_{3/2}$ helicity amplitudes), providing complementary dynamical information on the composite structure of the baryons.

It is very difficult to eliminate the model dependence in the extraction of baryonic parameters from experimental results. For example a model independent multipole analysis of meson photoproduction would require precise measurements of cross section and polarization observables for a *complete* set of results. These must include a minimum of eight single and double polarization observables, in the case of pseudoscalar meson photoproduction. The minimum number of independent observables increases to 23 in the case of vector meson photoproduction. In lack of such complete information, the extraction of resonance parameters relays on both the choice of a theoretical model and on the quality of data. At energies above the $P_{33}(1232)$ the task is complicated by the overlapping of several broad resonances. Having these resonances fixed quantum numbers, their contribution to a scattering process appears only in specific multipoles. However the values of resonance parameters extracted in a multipole analysis depend on the procedure used to discriminate the resonant from the background contribution.

Recently a new generation of precise data on meson photoproduction, including single and double polarization measurements, has become available. This is due to the advent of high quality, polarized and tagged electron and photon beams (MAMI-B, ELSA, LEGS, GRAAL, LEPS, JLAB, BATES), coupled with large solid angle detectors and, in some cases, also with polarized targets. At the same time these results have stimulated the theoretical community to refine the models and to increase their efforts to understand and quantify the theoretical uncertainties of resonance parameters, by comparing results obtained by different procedures on the same data set. This is the case of the Baryon Resonance Analysis Group (BRAG) that is promoting the collaboration among theoretical and experimental physicists to work towards a commonly accepted review of the resonance parameters, extracted from modern electromagnetic and hadronic facilities.

2 The First Resonance Region and the $\Delta(1232)$ EMR

In the energy region corresponding to masses up to 1400 MeV, the excitation of the $\Delta(1232)$ resonance dominates the reaction mechanisms. It is therefore possible to extract its parameters with high precision, not yet achieved at higher energies. The $\gamma N \to \Delta$ transition proceeds mainly through magnetic dipole (M1 or $M_{1+}^{3/2}$), due to a quark spin flip. The presence of a d-wave admixture in the nucleon wave-function allows for a small contribution from the electric quadrupole (E2 or $E_{1+}^{3/2}$) transition amplitude.

The origin of the d-wave component, that breaks the spherical symmetry of the nucleon, differs in various models of the nucleon. In *constituent quark models* (CQM), inspired to Quantum Cromo-Dynamics (QCD), the d-wave component arises from the introduction of an effective color-magnetic tensor interaction, while in chiral bag models the nucleon deformation is ascribed to the asymmetric coupling of the meson cloud to the nucleon spin. The ratio of resonant E2 to M1 transition strengths (EMR) is the experimental quantity of interest. Its value has been extracted from a large amount of available data, using different analysis procedures. The decomposition of amplitudes into a resonant and a background term is model dependent and not unique. Most analysis do not explicitly calculate the influence of non-resonant mechanisms on the resonance properties, such as interference contributions from Born terms and meson rescattering. It is not the *bare* value of the EMR to be extracted in such analysis, but the value the EMR *dressed* by the meson cloud.

Precise measurements, including polarization observables, on $\vec{\gamma}\, p \to \pi^0\, p$, $\vec{\gamma}\, p \to \pi^+\, n$ and Compton scattering have been provided by the Mainz and Legs laboratories. Because the Δ decays into πN final states with 99.4% branch and back to the γN state with 0.6% branch, the analysis of simul-

Table 1. Values of the *dressed* $\Delta(1232)$ resonance EMR and helicity amplitudes extracted by the most recent multipole analysis by Legs and Mainz groups. Results are compared with the latest edition of the Review of Particle Physics.

	REM (%)	$A_{1/2}$ ($10^{-3}/\sqrt{GeV}$	$A_{1/2}$ ($10^{-3}/\sqrt{GeV}$
Mainz analysis [4]	$-2.5 \pm 0.1 \pm 0.2$	$-(131 \pm 1)$	$-(251 \pm 1)$
Legs analysis [5]	$-3.07 \pm 0.26 \pm 0.24$	$-(135.7 \pm 1.3 \pm 3.7)$	$-(266.9 \pm 1.6 \pm 7.8)$
PDG [1]	-2.5 ± 0.5	$-(135 \pm 6)$	$-(255 \pm 8)$

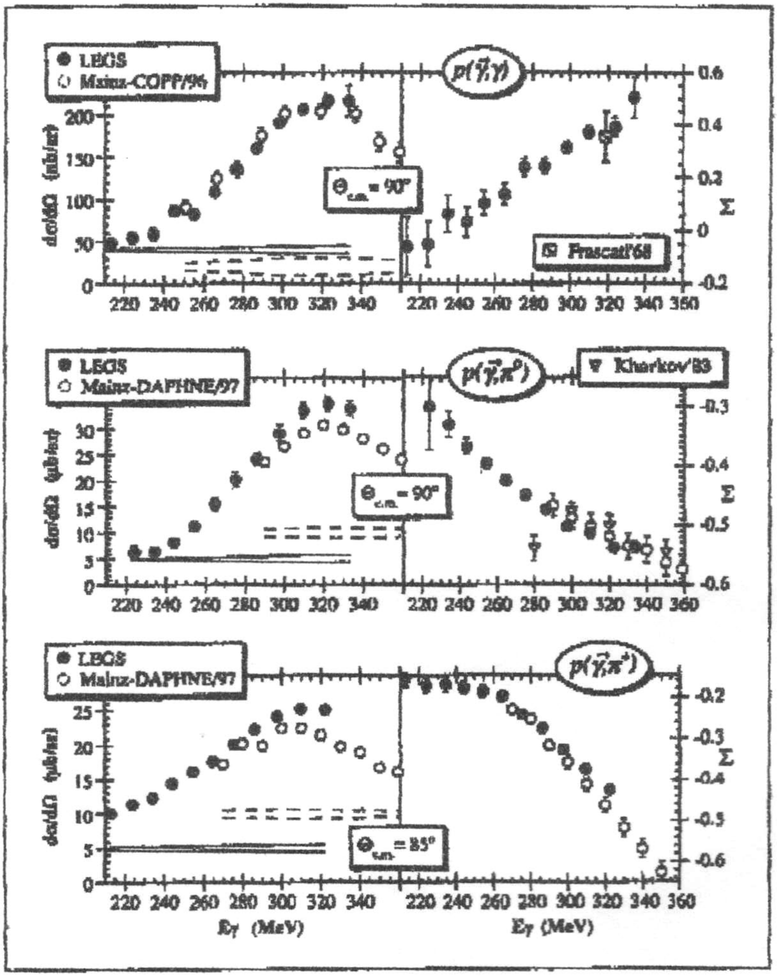

Figure 1. Differential cross sections and beam polarisation asymmetries for the reactions $\vec{\gamma}p \rightarrow \gamma p$, $\vec{\gamma}p \rightarrow \pi^0 p$ and $\vec{\gamma}p \rightarrow \pi^+ n$, measured by the mainz (open circles) [2,4] and the Legs (full circles)[3,5] laboratories.

taneous measurements of previous channels has the potential to extract Δ properties with high accuracy. Figure 1 shows results obtained for the dif-

Table 2. Results for M1, E2 and EMR from the analysis of various groups belonging to BRAG [6,7]. Values for M1 and E2 are expressed in units $(10^{-3}/\sqrt{GeV}$, those for EMR are given in %.

	M1	E2	REM
Effective Lagrangian RPI	286	-7.2	-2.55
Partial wave anal. GWU - SAID	281	-7.2	-2.57
Multipole anal. fixed-t disp. relations HA	281	-6.6	-2.35
Multipole anal. unitary isobar mod. MAID	275	-5.3	-1.93
Dynamical mod. by Yang & Kamalov KY	280	-6.2	-2.24
Fixed-t disp. relations by Asnauryan AZ	278	-6.3	-2.28
Multipole anal. by Omelaenko OM	288	-7.8	-2.77
Average	281.3 ± 4.5	-6.6 ± 0.8	-2.38 ± 0.27

ferential cross section and the beam polarization asymmetries for Compton scattering and π^0 photoproduction, at polar angle equal to 90° in the center of mass. Also data at 85° in the center of mass for the $\pi^+ n$ reaction channel are plotted. Full circles are Legs measurements, empty circles are those from Mainz. Very high precision results and good agreement among data are obtained for the beam polarization asymmetries Σ. While Compton scattering differential cross section data nicely agree, a 10% overall scaling factor is necessary to reconcile the differential cross section results of pion photoproduction reactions.

Table 1 shows results obtained for Δ resonance parameters extracted by multipole analysis performed by the two laboratories on their own measurements. Results are compared with the latest Review of Particle Physics[1] evaluation. The difference between the two laboratories results may be ascribed to the disagreement among measured differential cross sections.

The Baryon Resonance Analysis Group (BRAG) [6,7] has performed the analysis of a "bench-mark" data set of 1287 points on photoreactions and pion induced reactions, not including the latest results from Mainz and Legs, using several theoretical approaches to study the model dependence in the extraction of the *dressed* values of the M1 and E2 strengths. Results were published in [6] and are reported in Table 2. The average result should not be taken as a final value, because it is based on the chosen data set, which does not include all recent experiments. However the results fluctuation is very small and the extraction of a 2% effect may be obtained with a 0.3% percent model dependence.

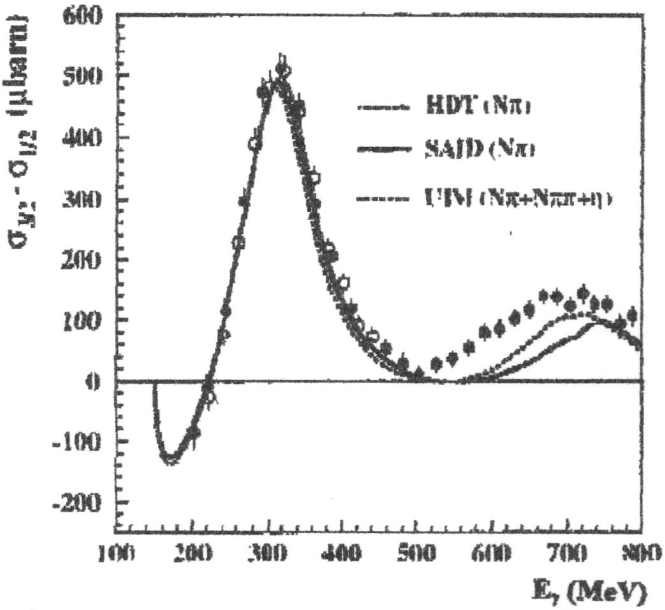

Figure 2. Measured values of the total absorption cross section difference between the two relative helicity states of the proton and the longitudinally polarized photon. Results are from Mainz (open and full circles). Data are compared with predictions by Hanstein *et al.* (dot-dashed curve), multipole analysis by SAID (solid curve) and the Unitary Isobar Model (MAID) (dotted curve).

3 Double polarization measurements and the GDH sum-rule

The first measurements obtained with a polarized photon beam on a polarized target represent an important break through in the study of photonuclear reactions. First data on photoabsorbtion cross sections on the proton have been obtained at Mainz using a longitudinally polarized beam on a frozen spin butanol target [8,9,10] in the energy range $200 < E_\gamma < 800$ MeV. The difference between the total cross section measured in the two relative spin configurations of photons and protons in the initial state, namely $\sigma_{3/2} - \sigma_{1/2}$, is plotted in Figure 2. Open and full circles are experimental results, compared with predictions by Hanstein *et al.*[11] (dot-dashed curve), multipole analysis by SAID[12] (solid curve) and the Mainz Unitary Isobar Model (MAID)[13] (dotted curve). Only the last calculation includes multi-pion and η photoproduction contributions and predictions fail to reproduce the full strength of the cross section difference in the second resonance region.

These first measurements may be used to experimentally verify the GDH[14] sum-rule, defined as follows:

$$\int_{\nu_0}^{\infty} (\sigma_{3/2} - \sigma_{1/2}) \frac{d\nu}{\nu} = \frac{2\pi^2 \alpha}{M^2} \kappa^2 = 204 \mu b \qquad (1)$$

where ν is the photon energy, ν_0 is the pion photoproduction threshold, α is the fine-structure constant, M is the proton mass and κ is the anomalous magnetic moment of the proton.

The experimental contribution to the integral appearing on the left side of the sum-rule, in the measured energy range, is $226 \pm 5 \pm 12 \mu b$. The combination of this result with estimations of the contributions in the missing energy ranges, provides a total result which is consistent with the GDH sum-rule within the experimental errors. The extension of this measurement to higher energies is underway at the Bonn laboratory[15].

First results using a polarized Compton backscattered γ-ray beam on a frozen spin HD target, have been obtained at Legs[16]. Very promising measurements have been obtained in three days of data taking, only. The beam polarization was changed regularly among six states: circular polarization parallel or antiparallel to the proton polarization, linear polarization with the polarization vector oriented vertically, horizontally or at an angle of $\pm 45°$. For the first time it was possible to extract all double polarization asymmetries involving beam and target. More data taking is expected in the near future.

4 Single and double pion photoproduction

New precise results on the differential cross section and Σ have been obtained at GRAAL for the $\vec{\gamma} + p \to \pi^0 + p$ reaction, in the energy range from 600 to 1100 MeV[17], and for the beam asymmetry Σ for the $\vec{\gamma} p \to \pi^+ n$ reaction at energies from 600 to 1500 MeV[18,19]. Comparison with existing well established results provided excellent confidence on the quality of the data. The inclusion of these results in the latest GWU-SAID data base[12] has produced significant modifications in some of the partial cross section of the SAID Partial Wave Analysis. The new solution (FA01) requires a stronger contribution of the $P_{13}(1720)$ resonance and a suppression of the $S_{11}(1620)$, with respect to previous analysis, to reproduce the complex structure of the experimental results.

Important new data have been obtained also on the two-pion photoproduction channels ($\gamma p \to \pi^+ \pi^0 n$ and $\gamma p \to \pi^0 \pi^0 p$) by the Mainz group[20,21].

The resonant excitation mechanisms have been understood to be dominated by the $D_{13}(1520)$ excitation[22], subsequently decaying into $\Delta^0\pi^+$ or $\Delta^0\pi^0$. The model however could not reproduce the full strength of the $\pi^+\pi^0$ channel. The measurement of the invariant mass spectra of the $\pi\pi$ systems[21] was the key to reveal for the first time the direct decay $D_{13}(1520) \to \rho N$ in the $\pi^+\pi^0$ channel.

5 η photo-production

Most of the CQM models predict more states than those experimentally observed. It is possible that the "missing" states have not been observed because they are weekly coupled to πN channels. Evidence of their existence may be observed in other channels, such as ηN, ρN, $K\Lambda$ and ωN.

The study of the η meson photo-production offers the advantage of a reduced complexity for the resonances involved in the reaction. Since η carries isospin $I = 0$, only $I = 1/2$ N^* resonances may be excited and only those having significant ηN branching ratio may contribute. Measurements of the Σ polarization observable add the ability to pin down small contributions from higher multipole resonances through their interference with the main terms. Extraction of the ηN partial widths and photocoupling amplitudes of the corresponding resonances are then possible, even if the ηN branching ratios are very small[27]. Very precise results for the differential cross section have been obtained by the GRAAL collaboration from the reaction threshold up to $E_\gamma = 1.1$ GeV. They cover the full angular range, for a total of 233 data points.[24]. The data are in good agreement with existing Mainz[26] data and confirm the near isotropic behavior of the angular distribution up to $E_\gamma = 0.9$ GeV, arising from the dominance of the $S_{11}(1535)$ excitation. A multipole expansion up to second order shows that deviations from isotropy at higher energies are mainly due to quadrupole terms, associated with the $D_{13}(1520)$ resonance. However, the onset of the P-wave is clear at energies above $E_\gamma = 1.0$ GeV, confirming similar results from η electro-production[31].

Table 3. Values of the $S_{11}(1535)$ resonance parameters extracted from η photo-production.

$\gamma + p \to S_{11}(1535) \to \eta N$					
	IB[29]	CC[30]	Chiral[25]	Krusche[26]	PDG[1]
Mass (MeV)	1541	1556	1542	1544	1536
Γ (MeV)	191	252	162	212	150
$A_{1/2}$ ($10^{-3}\sqrt{GeV}$)	118		64	125±25	90±30
$\Gamma_{\eta N}/\Gamma$		0.50	0.62		0.3 - 0.55

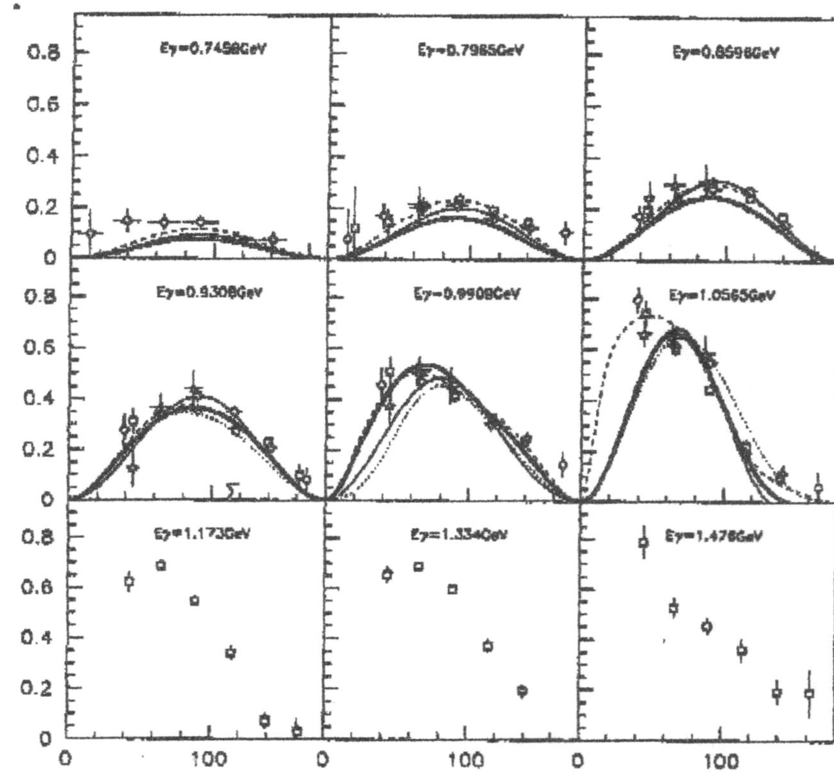

Figure 3. *Preliminary results for the beam polarization asymmetry for the reaction: $\vec{\gamma} + p \rightarrow \eta + p$ from the GRAAL collaboration. Open squares are results obtained with the UV Laser line and a maximum γ-ray energy of 1487 MeV. They are compared with the previous results obtained with a maximum γ-ray energy of 1.1 GeV, shown with open circles. Dashed lines show the latest Partial Wave Analysis of the SAID group[12], including GRAAL data. Bold and dotted lines show the analysis based on the Li and Saghai quark model[25]. Solid lines show a global fit [27] of the GRAAL beam asymmetries [23], the Mainz differential cross sections [26] and the Bonn target asymmetries[28].*

Results for the total cross section are available up to $E_\gamma = 1.1$ GeV. These measures cover the full energy range of the $S_{11}(1535)$ resonance for the first time. Fig. 3 shows published Σ beam asymmetry results[23] together with a sample of preliminary data up to $E_\gamma = 1.48$ GeV. The observable is dominated by the interference of the $D_{13}(1520)$ with the main S-wave.

Deviations from the $sin^2\theta$ distribution are due to contributions from other multipoles. Data are compared with the multipole analysis performed by the GWU group[12] including all GRAAL data (BO12 solution), plotted as a dashed line. Curves from a new analysis based on a chiral constituent quark model[25], that includes all known resonances up to 2 GeV and does not incorporate t-channel exchange terms, are also reported. This model requires the inclusion of a *third* $S_{11}(1730)$ $K\Lambda$ *quasi-bound* state to reproduce the forward peak in the cross section. Bold and dotted curves in Fig. 3 show the results *with* and *without* the third S_{11} "missing" resonance. A global fit[27], combining Mainz differential cross section data[26], published GRAAL asymmetry data[22] and Bonn target asymmetry results[28], is plotted as a solid line. Results have been also included in the MAID 2000 analysis using an isobar model[29] and in a coupled-channel analysis using an Effective Lagrangian model and Bethe-Salpeter equation in K-matrix approximation[30].

The values for the $S_{11}(1535)$ resonance parameters, extracted using these different approaches, are summarized in Table 1 and are compared with the values quoted by the Particle Data Group. Clear discrepancies still remain among the values of the resonance width and of the photocoupling amplitude.

6 K^+ Λ and ω photo-production

New data are available on the $K\lambda$ channel from the SAPHIR collaboration[32]. They show a structure in the differential cross section that has been reproduced[33] using an isobar model which includes a *missing* $D_{13}(1960)$ resonance.

The same model predicts for Σ trends of opposite sign if the missing resonance is included or not. Very preliminary data for the Σ beam asymmetry in the $K^+\Lambda$ reaction channel have been produced by the GRAAL collaboration. They have clearly positive values in the energy range from $E_\gamma = 1050$ MeV to $E_\gamma = 1400$ MeV and confirm the presence of the $D_{13}(1960)$ resonance. More data are expected from the SAPHIR and LEPS collaborations.

Very promising results are expected for the $\gamma p \rightarrow \omega p$ reaction channel. Total and differential cross sections are dominated by the diffractive terms, described by Pomeron and meson (π^0, η) exchange mechanisms in the t-channel, while resonance contributions have some importance at low energies and backward angles. Polarization observables on the contrary are predicted[34,35] to be very sensitive to resonance excitation. Diffractive terms are expected to give very small contribution to the beam polarization asymmetry Σ and large asymmetry values are a direct evidence of resonance excitation contributions. First very preliminary measurements on the Σ asymmetry have been pro-

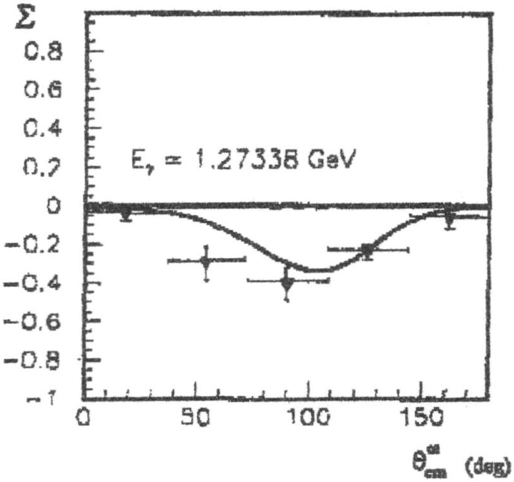

Figure 4. Very preliminary results from the GRAAL collaboration for the beam asymmetry Σ integrated over the ω decay solid angle, for the reaction $\vec{\gamma}p \to \omega p$. Results are compared with prediction from [35]. Dashed curve is the contribution from Pomeron and meson exchange terms alone. Solid curve is the full calculation, including all resonances with masses up to 2 GeV.

duced by the GRAAL collaboration in the energy region from threshold to 1500 MeV. A sample of these data is reported in Figure 4, together with predictions from Q. Zhao[35]. Dashed curve is the calculation including t-exchange terms only, solid curve is the full calculation including all N^* resonances contributions with masses up to 2 GeV. General agreement between data and theoretical predictions is observed and the sizable strength of the Σ observable is expected to be very sensitive to the inclusion of specific resonances, such as the $P_{13}(1720)$.

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