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Latest results of meson photoproduction off the deuteron at GrAAL

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Abstract: A preliminary investigation of the coherent $\eta\pi^0$ and double π^0 photoproduction channels on deuterium was conducted at GrAAL, including a comparison with the corresponding spectra from the BGOOD experiment. The center-of-mass energy distribution from GrAAL for the coherent η π^0 photoproduction channel on deuterium is well described by a fit consisting of a Breit-Wigner function added to a second-degree polynomial, which effectively reproduces the shape of the BGOOD cross-section spectrum. This behavior aligns with a model involving Δ, π^+ quasi-free photoproduction on the nucleon, followed by pion rescattering and the formation of the $N^*(1535)$ resonance, culminating in neutron-proton coalescence. The invariant mass distributions of the $\pi^0 d$ and ηd systems exhibit a resonant structure consistent with a Breit-Wigner profile. The BGOOD differential cross-section spectra are reasonably described by a model describing the process as a quasi-free reaction with an excitation of a Δ or a N*(1535) resonance on proton or neutron, rescattering of a charged pion on the other nucleon and coalescence of the two nucleons to a deuteron.

For the $\gamma d \rightarrow \pi^0\pi^0 d$ channel, the center-of-mass energy distribution measured at GrAAL can be fitted with an incoherent sum of two Breit-Wigner functions. In contrast, the cross-section spectra from BGOOD and FOREST require the sum of three Breit-Wigner components for a good fit. The resonance masses and widths extracted from the BGOOD and FOREST data are consistent with those obtained from the GrAAL fit.

Keywords: Calorimeters; dE/dx detectors

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Contents

1 Introduction and motivations of the research

The study of nucleon excited states remains an active research area, primarily conducted via meson electro- and photoproduction reactions. These processes probe a wide spectrum of resonances and can help resolve the "missing resonance" puzzle, consisting of such predicted excited states never observed in pion-nucleon scattering reactions [1]. The investigation of the experimental hadron excitation spectrum is essential for understanding the nonperturbative regime of strong interactions, where QCD cannot be treated perturbatively, and for probing the internal structure of nucleons. Recently, there has been an increasing interest in exotic resonances with a complex structure, like tetraquarks or pentaquarks, which are structures predicted by the quark constituent model. Further, baryons can bind together, producing dibaryon systems.

The deuteron pn(I=0, J=1) is the lightest dibaryon state. There is some experimental evidence of a state d*(2380)(I=0, J=3, P=+) [2], which was first observed in proton-neutron fusion reactions as a low-mass enhancement in the squared invariant mass distribution of double π^0 and a peak in the $\sqrt{(s)}$ distribution, and later observed in a multitude of final states (here some references in literature [3, 4, 10]). This state is predicted as a compact structure from the chiral quark constituent model, and its compact nature is supported by beam asymmetry measurements of the deuteron photodisintegration [5].

A preliminary study of coherent $\eta\ \pi^0$ d and double π^0 photoproduction channels on the deuteron is presented in this work by analyzing the GrAAL experiment data. The results of the investigation show a good agreement with those of the BGOOD collaboration [6, 11], in particular, the spectra of the invariant mass distributions of the π^0-d and η-d systems evidence two resonant structures compatible with a model of coherent photoproduction process by an intermediate state. Two resonant structures are observed in the GrAAL center-of-mass energy distribution for the double π^0 photoproduction channel on deuterium. These resonances agree with the two highest states observed in the cross-section spectra of BGOOD and FOREST. The structure of this article is as follows. In the "GrAAL Experiment Setup" section, we provide an overview of the GrAAL apparatus and the Lagranγe detection system, and describe the event-reconstruction procedure for the two reaction channels. The "Analysis and

Results" section details the data-analysis methods and presents the obtained results. Finally, the "Conclusion" section summarizes the key findings and their significance.

2 GrAAL experiment setup

The GrAAL apparatus operated at the ESRF facility in Grenoble (France), collecting data of meson photoproduction reactions until the end of 2008. A γ-ray beam was produced by Compton backscattering of a 100 % polarized laser beam against the ultrarelativistic electrons (6 GeV energy) circulating in the storage ring of the ESRF. The energy of the γ photons was provided by a tagging system measuring the position of the scattered electron, providing an energy resolution of the beam of about 16 MeV. Because electrons were relativistic, their helicity was conserved in the collision with laser photons, resulting in a minimal exchange of the angular momentum from the electron to the γ photon. However an exchange of spin degrees of freedom from laser photons to γ photons could occur and the polarization of the laser beam was transferred to the gamma beam, which tended to retain the same polarization. The polarization increased with energy, reaching a value very close to 100 % at the maximum energy, as shown in the figure 7 of the article [8]. The laser beam, operating in the range of UV or VIS lines, could be circularly and linearly polarized and a rotating polarizer could change its polarization. The polarizer could change the orientation of the linear polarization from vertical to horizontal and it could switch the state of polarization from linear to circular. The gamma beam achieved higher energies using UV lines compared VIS lines [8].

The gamma photons impacted on a liquid hydrogen or deuterium target. Meson photoproduction reactions took place by the interactions of gamma photons with nucleons or deuterons inside the target. The particles produced in these reactions were detected by the Lagranγe detection system, composed of a central region covering the polar angles between 25° and 155° with a BGO electromagnetic calorimeter, a plastic scintillator barrel and two cylindrical MWPCs, and a forward part covering polar angles lower than 25° equipped with planar MWPCs, a plastic scintillator wall (Hodoscope) and a shower wall (lead-plastic scintillator detector). A general description of the apparatus is provided in the GrAAL article [8].

3 Events identification

The $\gamma d \rightarrow \eta\pi^0 d$ or $\gamma d \rightarrow \pi^0\pi^0 d$ reactions are investigated by detecting and identifying the recoil deuteron in the forward direction by using the Time-of-Flight and the energy loss in the hodoscope detector, while the mesons are reconstructed with their e.m. decays in the central BGO electromagnetic calorimeter. A particle in the forward part of the apparatus was recognized as charged if detected in coincidence by the three charged particle sensitive detectors (planar MWPCs-Hodoscope-Shower Wall) or almost the first two detectors (charged particles which are too slow stop in the Hodoscope) [9]. If, instead, the particle produced a hit only in the Shower Wall, sensitive to both charged and neutral particles, it was identified as neutral. The energy loss (Δ E) and time of flight measurements (TOF) for charged particles were provided by the wall of plastic scintillators called Hodoscope [9], necessary to distinguish charged pions, protons, and deuterons. Charged particles were identified in the TOF vs ΔE spectrum of the hit clusters (see figure 1). Events like protons belong to the central cluster, so deuterons must belong to the cluster more to the right, which is associated with longer Time-of-Flights and higher energy loss events. Pions are relativistic, so their time of flight is close to that of light

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and their energy loss is practically constant; for this reason, they are identified by a small cluster in the spectrum. The figure 1 shows a typical TOF vs ΔE spectrum obtained during a run taken using a deuteron target. Once a charged particle was identified, its energy was calculated by its time of flight, and the two planar MWPC provided its angles [9]. Therefore, the four-momenta of deuterons used in our analysis were then reconstructed.

Central photons were detected by the BGO calorimeter [7], placed in the central part of the apparatus and covering a polar angle between 25° and 155°. It was composed by 480 BGO crystals, providing high detection efficiency and energy resolution lower than 3% for γ photons. The position of the photons was calculated as the energy-weighted average of the crystal cluster interested in the electromagnetic shower. Resolutions on the angles were 6° for θ angle and 7° for the ϕ angle [9]. Four-momenta of detected photons were, therefore, reconstructed.

Our investigation of the channels $\gamma d \to \eta\pi^0 d$ and $\gamma d \to \pi^0\pi^0 d$ was conducted by analyzing all data collected using a deuterium target and UV and VIS laser lines.

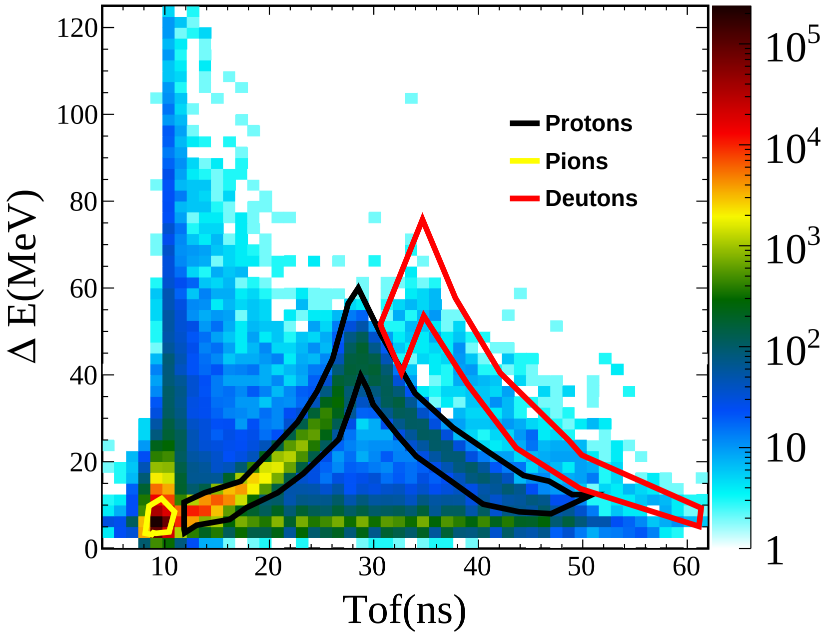

Figure 1. ΔE vs. ToF spectrum of charged particles detected by hodoscope detector in deuterium target data. Graphical cuts identifying protons, pions, and deuterons events are superimposed to the distribution.

4 Analysis and results

4.1 GrAAL results on the coherent $\eta\pi^0$ photoproduction reaction on deuterium

Coherent $\eta\pi^0$ photoproduction events on deuterium were selected by requiring a forward-going deuteron ($\theta \leq 21°$) and four photons detected in the central region by the BGO calorimeter. The mesons were reconstructed by selecting the photon pair combinations that minimized the deviation from the nominal η and π^0 invariant masses. Residual background contributions were subtracted via a fit to the invariant mass spectra of the reconstructed mesons.

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The resulting invariant mass distributions for the η and π^0 candidates, with the identification of signal and background, are presented in the left and right panels of figure 2, respectively. The product of signal-background ratios obtained by the fit reported in figure 2 for the identification of π^0 and η mesons are used to weight the yield distribution of the center of mass energy distribution of the reaction $\gamma d \rightarrow \pi^0 \eta d$, reported in figure 3. The same procedure has been used for figures 4, 5, and 6. The GrAAL distribution of the figure 3 was fitted with a function composed of a Breit-Wigner distribution and a second-order polynomial function.

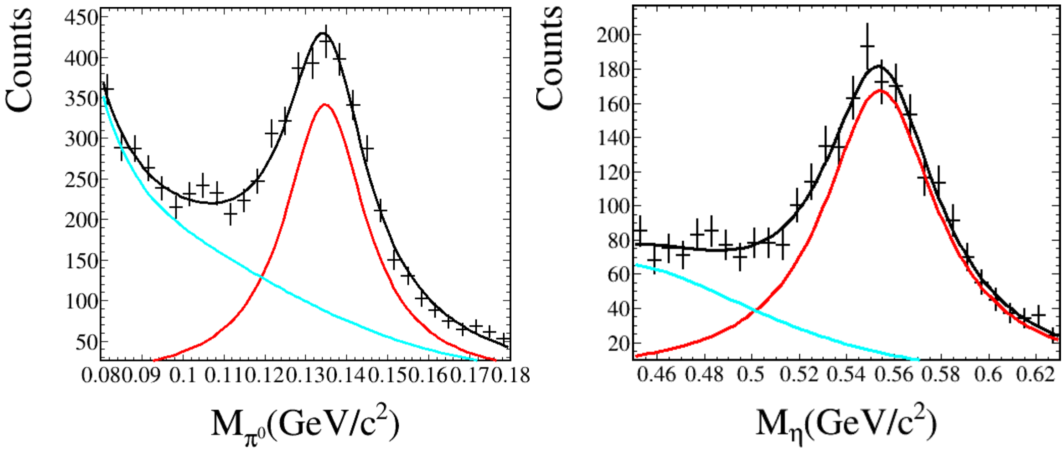

Figure 2. Fit on the invariant mass distribution of reconstructed π^0 and η mesons, left and right panel respectively. The signal was fitted with a Breit-Wigner function (red line), while the background was fitted with a third-degree polynomial multiplied by an exponential(cyan line). The mass and the width of the Breit-Wigner distributions provided by the fit are M=0.134 GeV/c^2 and Γ=0.02 GeV/c^2 for π^0, M=0.55 GeV/c^2 and Γ=0.05 Gev/c^2 for η, while the reduced chi-square is close to 1 for both fits.

A qualitative comparison with the results of the BGOOD experiment reported in figure 3 of ref. [11] shows agreement in determining the peak position. GrAAL and BGOOD experiments used the same detectors in the central part, 25°-155°. In the forward direction, GrAAL identified the deuteron with energy loss vs time-of-flight measured by the hodoscope, while BGOOD with the mass spectrometer of the forward region of the apparatus [13]. The peak measured at GrAAL seems better defined, probably because of the Compton Backscattering gamma beam which is more intense in the investigated invariant mass region.

The cross section of the BGOOD collaboration was fitted by a sum of two models, describing the process as a quasi-free reaction with an excitation of a Δ or N^* resonance on proton or neutron, rescattering of a charged pion on the other nucleon and coalescence of the two nucleons to a deuteron [11].

In the figure 4, the invariant mass distribution of the GrAAL π^0-d system in the interval 2703 MeV≤ W ≤ 2799 MeV, where W is the energy available in the center of mass reference frame, is shown with a function fit (Breit-Wigner distribution + a third degree polynomial). The result shows agreement in comparison with the differential cross section spectrum from BGOOD in the same energy interval and for $\cos(\theta_d^{C.M.})$>0.8 presented in figure 5 of ref. [11]. All GrAAL distributions were taken in the overall range of the polar angle of the detected deuteron in the center-of-mass reference frame. The distribution at GrAAL shows a peak with a Breit-Wigner behaviour centered at 2.13 GeV/c^2 and a width Γ = 0.05 GeV/c^2. The Breit-Wigner profile is compatible with a coherent

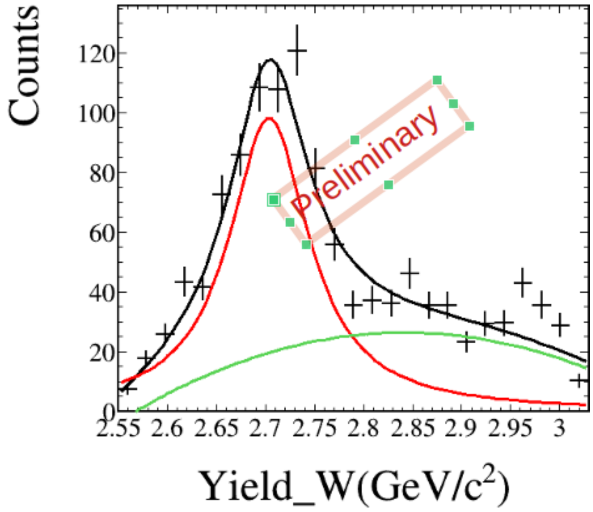

Figure 3. Center of mass energy distribution for the coherent photoproduction channel of η and π^0 on deuterium at GRAAL: the black line is the fit, which is a composition of a Breit-Wigner distribution(red line) and a parabola(green line). The reduced chi-square is χ^2/dof=4. The mass and width of the Breit-Wigner given by the fit are: M=2.70 GeV/c^2 and Γ=0.103 GeV/c^2.

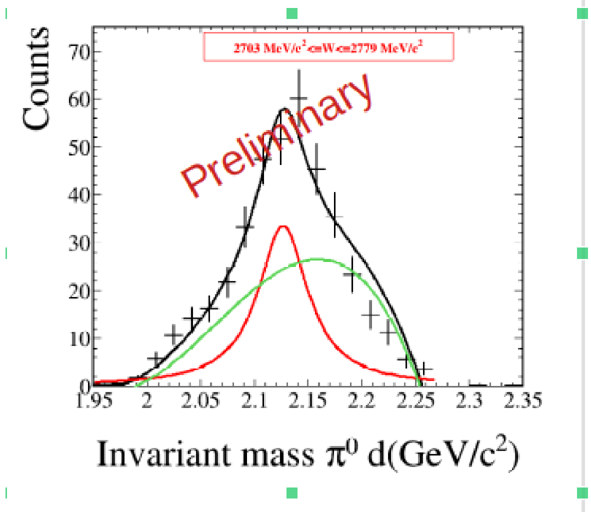

Figure 4. Fitted invariant mass distribution for the π^0d system from GrAAL data in the interval 2703 MeV/c^2 $\leq$ W $\leq$ 2799 MeV/c^2. The mass and width of the Breit-Wigner given by the fit are: M= 2.13 GeV/c^2 and Γ=0.05 GeV/c^2. The reduced chi-square of the fit is χ^2/dof=3.

photoproduction process with the excitation of an intermediate dibaryon. GrAAL distribution can be compared with the BGOOD cross-section distribution (ref. [11] left-top panel of figure 5), which is reasonably described by the cited “Toy model”.

In the figure 5, the fitted invariant mass distribution of the η d system at GrAAL is shown. This distribution can be compared with the spectrum of differential cross section from BGOOD as a function of the invariant mass of the η d system in the interval 2661 MeV $\leq W \leq$ 2703 MeV and for $\cos(\theta^d_{CM}) > 0.8$ (central-top panel of figure 5 ref. [11]). The function fit used in the GrAAL distribution is a Gaussian. There is an agreement between the peaks of the two distributions. The

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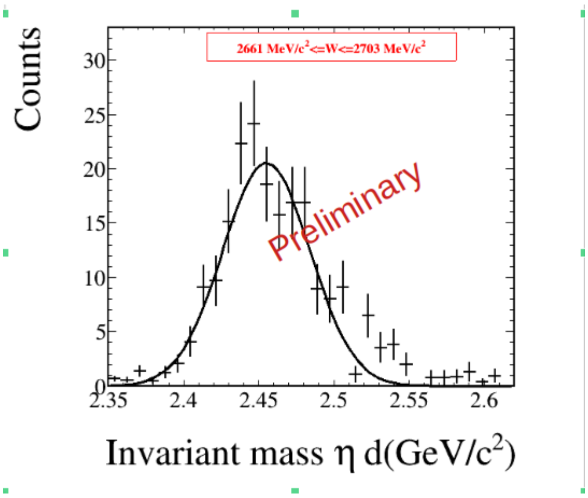

Figure 5. Fitted invariant mass distribution for the ηd system from GrAAL data in the interval 2661 MeV/c^2 $\leq$ W $\leq$ 2703 MeV/c^2. The function fit is a Gaussian: the center and the width parameters given by the fit are: M=2.45 GeV/c^2 and Γ=0.08 GeV/c^2. The reduced chi-square is χ^2/dof=1.72.

center and the width of the Gaussian given by the fit are: M =2.45 GeV/c^2 and Γ=0.08 GeV/c^2. The BGOOD cross-section spectrum is again in reasonable agreement with the "Toy model" already mentioned.

4.2 GrAAL results on the coherent double π^0 photoproduction reaction on deuterium

Events of the coherent double π^0 photoproduction channel on deuterium were selected by requiring the presence of at least 4 photons detected in the central region of the apparatus, reconstructing two π^0 mesons and a deuterium detected in the forward part of the apparatus as described in the η-π^0 analysis. Then, we have considered the best combinations of 4 photons, with two pairs of photons having the closest invariant mass to π^0 meson, and removed the background by a fitting procedure on the invariant mass distributions of the two best reconstructed π^0 mesons.

Additionally, two selection criteria were applied to the events: the difference between the missing energy of the $\pi^0-\pi^0$ system and the measured deuteron energy was required to lie within ±0.05 GeV/c^2; similarly, the difference between the polar angle θ of the detected deuteron and the missing angle reconstructed from the two π^0 mesons was constrained within ±20°.

From the selected events, the distribution of the center-of-mass energy was extracted. The resulting spectrum can be compared with the cross-section as a function of the center-of-mass energy published by BGOOD [6] and FOREST [10]. The GrAAL center-of-mass distribution was fitted with an incoherent sum of two Breit-Wigner functions (see figure 6), showing good agreement with the results of BGOOD and FOREST. Due to limitations of the GrAAL tagging system, the lowest-mass resonance centered at 2380 MeV, commonly associated with the $d^*(2380)$, cannot be fully resolved. These findings are preliminary, and further analyses are ongoing to refine the results.

The parameters of the two resonances are reported in the caption together with the reduced chi-square of the fit.

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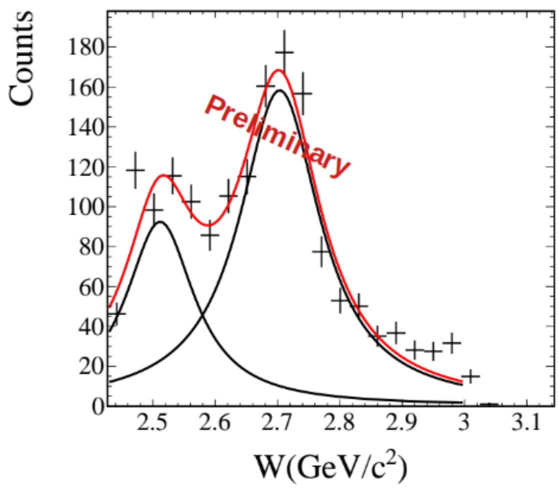

Figure 6. Center of mass energy distribution from GrAAL on the events of the coherent double π^0 photoproduction reaction on deuterium. The distribution was fitted with an incoherent sum of two Breit-Wigner functions. The mass and widths of the two resonances are M_1=2.50 GeV/c^2, Γ_1=0.08 GeV/c^2, M_2=2.70 GeV/c^2, Γ_2=0.17 GeV/c^2. The reduced chi-square is χ^2/dof=3.

5 Conclusions

A study of the coherent $\eta\pi^0$ and double π^0 photoproduction channels on deuterium was carried out at GrAAL. Resonant structures are observed in the center-of-mass energy distribution and invariant mass spectra of the ηd and $\pi^0 d$ systems for the coherent $\eta\pi^0$ channel. The center-of-mass energy cross section of BGOOD is an order of magnitude higher than expected from a single photoproduction reaction on a nucleon, and this behaviour is caused by complex photoproduction models involving deuterons. In the case of double π^0 photoproduction, the center-of-mass energy distribution measured at GrAAL is well described by an incoherent sum of two Breit-Wigner functions, with fit parameters in agreement with the two higher-mass resonances obtained from fits to the spectra measured by the BGOOD and FOREST collaborations. Due to limitations in the GrAAL tagging system, the lowest-mass resonance at 2380 MeV, linked to the d*(2380), cannot be fully resolved. All these results are still preliminary, and further analysis is underway to improve them.

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