Double π^0 Photoproduction on the Proton at GRAAL

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The double π^0 photoproduction off the proton has been measured in the beam energy range of 0.65–1.5 GeV. The total and differential cross sections and the Σ beam asymmetry were extracted. The total cross section measured for the first time in the third resonance region of the nucleon shows a prominent peak. The interpretation of these results by two independent theoretical models infers mostly the selective excitation of P_{11}- and D_{13}-nucleon resonances.

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The study of nucleon resonances is a long-standing challenge of hadronic physics. Up to now, they have been mainly observed through πN scattering and π photoproduction on the nucleon [1]. A more recent method is the double pion photoproduction which gives complementary information, particularly on resonances that couple weakly to a single pion.

Among the three channels of the 2π photoproduction on the proton ($\gamma p \rightarrow p\pi^0\pi^0$, $\gamma p \rightarrow p\pi^+\pi^-$, $\gamma p \rightarrow n\pi^+\pi^0$) the $2\pi^0$ channel is the most selective one. Because of the vanishing charge of the π^0, Born terms associated with pion exchange are suppressed and since the ρ meson cannot decay into $\pi^0\pi^0$, its production is forbidden. Compared to the η photoproduction channel, which is almost exclusively sensitive to the $S_{11}(1535)$ resonance [2], the $2\pi^0$ channel appeared to be mainly sensitive to $P_{11}(1440)$ and $D_{13}(1520)$ resonances, below $E_\gamma = 0.8$ GeV [3].

The precise study of the $2\pi^0$ photoproduction on the proton has become possible with the advent of the new generation of continuous wave electron accelerators and large acceptance detectors. Three successive sets of data from MAMI (Mainz Microtron) have covered the cross section measurements up to 800 MeV [3–5]. The present data measured at GRAAL (Grenoble Anneau Accélérateur Laser) extend the cross section results up to $E_\gamma = 1.5$ GeV and provide invariant mass spectra and beam asymmetry observables which strongly constrain the theoretical models.

A theoretical model taking into account a large number of diagrams has been developed by the Valencia group [6–8], to study the general problem of the photoproduction of two pions, neutral or charged, on the proton and the neutron. They satisfactorily explained the data obtained at the MAMI accelerator [3–5] by allowing the excitation not only of $P_{11}(1440)$ and $D_{13}(1520)$ but also of $D_{33}(1700)$.

Another model [9], which we refer to as the Laget model, is the extension to higher energies of the Laget-Murphy model [10]. Besides Born terms, it involves the excitation of P_{11}, D_{13}, and D_{33} resonances, allowing the P_{11} resonance to decay via the $N\sigma$ channel as well as the $\Delta\pi$ channel. Indeed, the pair of π^0's has the quantum numbers of the σ meson and could be considered as originating from the photoproduction of this meson and its subsequent decay into two π^0's.

The present data have been obtained with the GRAAL setup, using a tagged and linearly polarized photon beam and a large acceptance detector [2,11–13]. The photon beam of 0.6 to 1.5 GeV is produced by backscattering a laser beam on the electron beam of 6.04 GeV of the ESRF (European Synchrotron Radiation Facility). The detector consists of three layers: wire chambers, scintillators, and calorimeters. In the central part, a bismuth germanate (BGO) calorimeter of 90% of 4π, covered from the target side with a barrel of scintillators, measures with a good resolution the neutral mesons, π^0 and η, through their decays into γ's [14]. In the forward direction ($\theta \leq 25°$) a double wall of scintillators and a shower wall [15] measure the time of flight of the proton and of the neutron. On the backward side, a large part of the hole is closed by a disk of scintillators. A liquid H_2 target, 6 cm thick, was used.

The energy spectrum of the photon beam is flat and has a high degree of polarization in its upper part. For a given measurement, there are choices of either the green line of the laser giving an energy range from 0.6 up to 1.1 GeV or the UV line giving an energy range from 0.8 up to 1.5 GeV. We made two experimental runs with both laser lines in order to cover the full energy range (0.65–1.5 GeV) with a degree of polarization between 0.6 and 0.98, and, consequently, we could compare the results in the overlap region. The GRAAL experiment is well adapted to measuring the beam asymmetry Σ. We applied the method which was previously used for the photoproduction of a single pseudoscalar meson [2,11–13].

The measurement and monitoring of the photon beam flux ($\approx 1.0 \times 10^6 \gamma/\mathrm{s}$) were carried out with two independent detectors: one thin scintillator sensitive to 2.7% of the intensity of the beam and a full absorption lead-scintillator sandwich detector. The incident energy is measured by the tagging system with an energy resolution of 16 MeV (FWHM) (full width at half maximum).

For the reaction $\gamma p \to p\pi^0\pi^0$, the θ and ϕ angles of the proton were measured at large θ angles by the BGO-barrel assembly and in the forward direction by the double wall of scintillators. The energy and the angles of the four γ's are measured by the BGO calorimeter or by the forward shower wall. The energy loss and the time spectra given by the barrel and the forward double wall of scintillators serve for the identification of the proton and the monitoring of random events.

Two types of events were selected, one with four γ's detected in the BGO calorimeter ($\approx 440\,000$ events, with UV line), and the other allowing for only one among the four γ's to be detected in the forward shower wall ($\approx 220\,000$ events, with UV line). In the latter case, only the angles could be measured and the energy is deduced from the momentum and energy balance of the reaction. The resolution (FWHM) of the reconstructed invariant mass of π^0 is 23 MeV when the two γ's are seen in the BGO and 30 MeV when only one γ is in the BGO and the other in the shower wall.

Since a fivefold coincidence was required between the four γ's and the proton, and since the random rate was less than 1.5%, the background was less than 1%. The contamination from the $\gamma p \to p\eta$ where the η can decay into three π^0's is less than 1% in any bin of the beam energy.

The acceptance correction, which was deduced with the simulation code LAGGEN built on the GEANT3 code from the CERN library, uses three kinematical variables: the photon beam energy, and the momentum and the angle of the $2\pi^0$ system. The acceptance correction involved an average efficiency of 30% and an extrapolation for the uncovered phase space of less than 3% at any photon energy. Two types of event generators for the simulation were used, based on phase space distributions of either the $\gamma p \to \Delta^+\pi^0$ reaction or the $\gamma p \to p\pi^0\pi^0$ reaction. Both distributions produced compatible outputs for the total cross section, the invariant mass spectra, and the beam asymmetry.

The total cross section for the reaction $\gamma p \to p\pi^0\pi^0$ is shown in Fig. 1 for an incident energy going from the threshold to 1.5 GeV. At 0.7 GeV there is a peak confirming the previous data sets from MAMI [3,5]. This peak is mainly attributed to the excitation of $P_{11}(1440)$ and $D_{13}(1520)$ resonances. However, the GRAAL peak is narrower than the one in the recent set of MAMI which shows an excess at the high energy side. At high energy, the GRAAL data show a new feature not seen before, a peak located at 1.1 GeV.

We show in the same figure the calculations of Oset (Valencia group) [6,7] covering the low energy part and the calculation of Laget covering the whole range

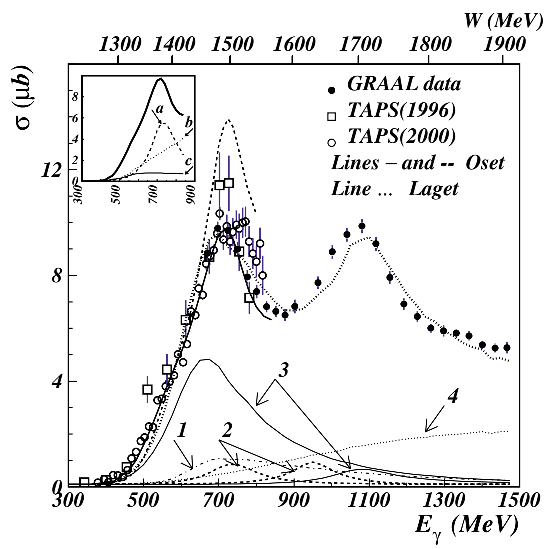

FIG. 1 (color online). Total cross section of the reaction $\gamma p \to p\pi^0\pi^0$. GRAAL data together with previous data from MAMI, TAPS(1996) and TAPS(2000) and theoretical calculation from Oset and Laget models. The GRAAL data are shown with statistical error bars only and the systematical error is estimated to be 3%. In the lower part the partial contributions of the different diagrams of Laget model are given, labeled with numbers: label 1 associated with the dash-dotted line corresponds to $\gamma p \to P_{11}(1440) \to \Delta\pi$; label 2, dashed lines, $\gamma p \to D_{13}(1520), D_{13}(1700) \to \Delta\pi$; label 3, continuous line, $\gamma p \to P_{11}(1440), P_{11}(1710) \to \sigma p$; label 4, dotted line $\gamma p \to \sigma p$. The contribution of $D_{33}(1700)$ is too small to be seen. In the inset, the main contributions of the Oset calculation are given [6]: thick solid line, full calculation; lines (a), (b), and (c) for $D_{13}(1520)$, Δ, and $P_{11}(1440)$ intermediate states, respectively.

of energy. The calculations of Oset for two different parametrizations, drawn in continuous and dashed lines, include N, $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, and $D_{33}(1700)$ as intermediate baryonic states. They give a peak at 700 MeV with a width compatible with GRAAL data. The Laget model takes into account three mechanisms in the $2\pi^0$ channel: (i) the excitation of $P_{11}(1440)$, $D_{13}(1520)$, $P_{11}(1710)$, $D_{13}(1700)$, and $D_{33}(1700)$ resonances which decay into a Δ^+ and π^0, followed by the decay of the Δ^+ into a proton and π^0, (ii) the excitation of $P_{11}(1440)$ and $P_{11}(1710)$ followed by a direct decay to the proton with the emission of a σ meson which decays into $\pi^0\pi^0$, and (iii) the direct emission of the σ meson via ρ exchange between the incoming photon and the target nucleon. The parameters of the resonances taken by Laget are given in Table I. They have been adjusted in order to fit the total cross section and lie in the range of previously determined values [1]. The mass of $P_{11}(1440)$ resonance is at the edge, but it is so wide that a precise determination is meaningless. The result is drawn as the dotted line and the contributions of the different diagrams are plotted in the lower part of the figure. The model reproduces quite satisfactorily the two peaks which dominate the cross section. In both cases, the key to the success is the interference between the direct emission of the σ meson and the decay of the relevant P_{11} resonance into the σN channel: this is the only way to get the magnitude of the cross section with reasonable resonance parameters (see Table I), compatible with Particle Data Group data [1]. It is worth noting that both models reproduce the total cross section at low energy with different combinations of resonances: the $D_{13}(1520)$ dominates the Valencia model, while the $P_{11}(1440)$ dominates the Laget model. Comparisons with experimental differential cross sections and spin observables are clearly needed.

The differential cross sections were evaluated as a function of the invariant mass of any group of two particles in the final state. In Fig. 2 the experimental results of GRAAL are presented with dots, on the left-hand side in terms of the invariant mass of the two π^0's and on the right-hand side in terms of the invariant mass (IM) of the proton and any one of the two π^0's, for four narrow bins (40 MeV) of beam energy centered at 720, 850, 1100, and 1300 MeV. The corresponding differential cross sections predicted by the Laget model are plotted as a continuous line, while the empty circles on the 720 MeV spectra are experimental data from MAMI. The phase space results are also shown as a dashed line for the $\gamma p \to \Delta^+\pi^0$ reaction and as a dotted line for the three-body final state reaction $\gamma p \to p\pi^0\pi^0$. The overall trends are similar for the GRAAL data and for the Laget predictions. At the two lower energies the structures are better reproduced than at the higher ones. At high energy, the experimental data show a stronger peaking in the IM($p\pi^0$) plot at the Δ mass position with a complementary bump on its right. Looking at the phase space results, the shape of GRAAL data is roughly intermediate between the shapes of $\gamma p \to \Delta^+\pi^0$ and $\gamma p \to p\pi^0\pi^0$.

In Fig. 3, the beam asymmetry Σ results are presented in terms of the invariant mass in a way similar to that in Fig. 2. The error bars originate from the statistics and the fit to the ϕ distribution. The systematical error is 3% and is mainly due to the determination of the polarization. The asymmetries calculated by the Laget model are plotted as continuous lines. At the lowest beam energy [part (a)], the experimental asymmetries are small and hardly reproduced by the Laget calculation. At the other energies [parts (b), (c), and (d)], the asymmetries are sizable and the calculation reproduces the sign and the general trend of the data. Another presentation of the beam asymmetries, in terms of Θ_{CM}, is reported in Fig. 4, where at the lowest energy bin (a) the results of the Valencia group [8] are also plotted and show poor agreement with the data.

TABLE I. Parameters of the resonances used in the Laget model. The decay widths for the ρ channel and "others" are given for completeness but do not contribute to the $\pi^0\pi^0$ channel.

		Widths in MeV						
	Mass	Full	Partial					
Reson.	in MeV	Γ	$\Gamma_{\pi\Delta}$	Γ_γ	$\Gamma_{\rho N}$	$\Gamma_{\sigma N}$	$\Gamma_{\pi N}$	Γ_{others}
D_{13}	1520	120	24	0.3	24	0	72	0
D_{13}	1650	100	85	0.05	5	0	10	0
D_{33}	1700	250	50	0.7	9	0	81	110
P_{11}	1500	350	158	0.3	0	25	167	0
P_{11}	1720	135	76	0.01	0	25	34	0

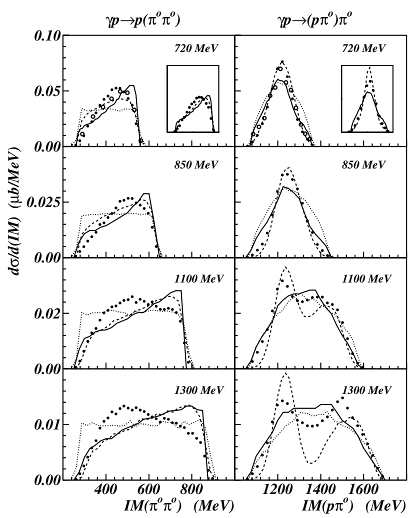

FIG. 2. Invariant mass spectra for the reaction $\gamma p \to p\pi^0\pi^0$ at four beam energies. See explanations in the text. At $E_\gamma =$ 720 MeV the insets compare the Laget (solid line) and Oset [6] (dashed lines) models with the GRAAL data (dots).

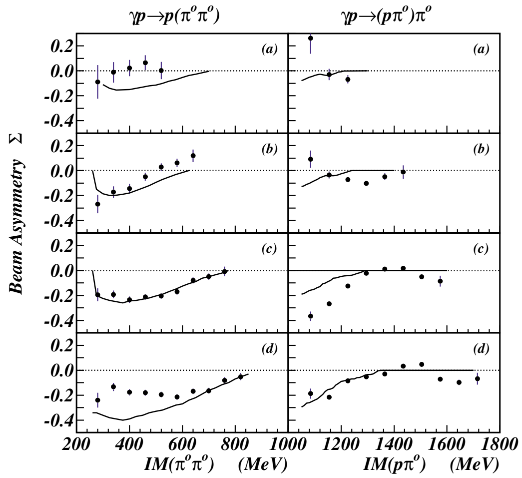

FIG. 3 (color online). The beam asymmetry Σ for the reaction $\gamma p \rightarrow p\pi^0\pi^0$ at four beam energies: (a) 650–780 MeV, (b) 780–970 MeV, (c) 970–1200 MeV, and (d) 1200–1450 MeV. On the left, Σ as a function of the IM of the system ($\pi^0\pi^0$) and on the right, of the IM of the system ($p\pi^0$). The continuous line shows the Laget model results. The reaction plane used to define the ϕ angle in order to extract Σ was, on the left, the plane of the incident photon and the outgoing proton, and on the right, of the incident photon and any one of the two outgoing π^0's .

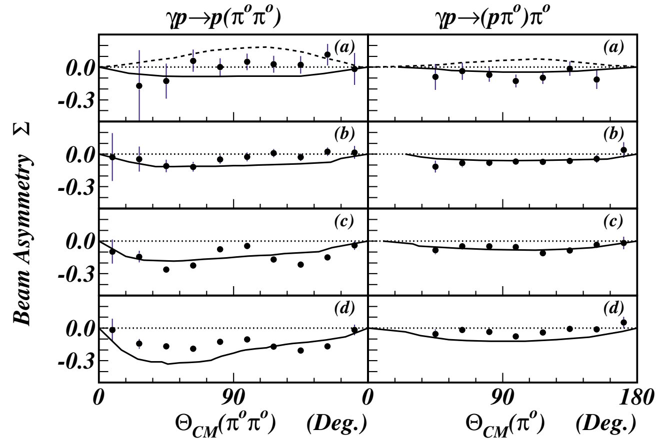

FIG. 4 (color online). The beam asymmetry Σ for the reaction $\gamma p \rightarrow p\pi^0\pi^0$ at for bins of beam energy in terms of $\Theta_{CM}(\pi^0\pi^0)$ (on the left) and of $\Theta_{CM}(\pi^0)$ (on the right). The calculations of Laget (solid line) and the Valencia group (dashed line) are shown. Notations as in Fig. 3.

To summarize, the $2\pi^0$ photoproduction off the proton has been measured from 650 up to 1500 MeV, extending previous data. The total cross section shows evidence of two prominent peaks: one already seen at 700 MeV and corresponding to the excitation of the $P_{11}(1440)$ and $D_{13}(1520)$ resonances and the other at 1100 MeV, seen for the first time and corresponding to the excitation of the $P_{11}(1710)$ and $D_{13}(1700)$ states. The sign of the beam asymmetry and the general trend of the differential cross section and the beam asymmetry were reproduced satisfactorily by the Laget model, where the σ meson was involved in two dominant mechanisms, namely, the excitation of P_{11} resonances which decay by σ emission and the direct emission of the σ meson during the initial ρ exchange. Our interpretation with the Laget model is based on a minimum set of resonances whose parameters lie in the range of accepted values. It has to be confirmed by a full partial wave analysis requiring a large database for which our data would represent a significant input. The $2\pi^0$ channel not only would provide a powerful filter to study P_{11} resonances but also would be an important source of the σ meson. Finally, our conclusions support a dedicated program of $2\pi^0$ photoproduction on heavy targets, in order to study the propagation of the σ meson in hadronic matter [16–19].

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