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Double π^0 photoproduction on the neutron at GRAAL

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Abstract

The photoproduction of double π^0 on the neutron is studied in the beam energy range of 0.6 up to 1.5 GeV, using a liquid deuterium target. The cross section and the beam asymmetry are extracted and compared to those previously obtained on a proton target. The theoretical interpretation of these results is given using different models.

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The double pion photoproduction on the nucleon is now used, as well as the single pion photoproduction, to study the excitation of nucleon resonances [1–10]. Such experiments have become possible with the advent of new accelerators and large acceptance detectors. At GRAAL, a study of the double π^0 photoproduction on the free proton has been performed and showed a prominent peak at the nucleonic resonance mass of 1700 MeV [9]. The interpretation was performed with Valencia Group model and Laget model involving mostly the excitation of P_{11} and D_{13} baryon resonances. The double π^0 photoproduction on the neutron is another fundamental channel which is accessible at GRAAL with a deuterium target. The study of this channel is interesting to see if there is also a prominent peak in the total cross section at the resonance mass of 1700 MeV. The question is particularly important since, according to a chiral soliton model [11], the 1700 MeV mass location happens to be that of the nonstrange member of the baryon antidecuplet. Furthermore, the authors of the soliton model proposed to disentangle between octet and antidecuplet baryon components by studying simultaneously the photoproduction of π^0, $2\pi^0$ and η mesons on both the proton and the neutron [12]. So, the aim of the present Letter is to study the double π^0 photoproduction

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on the neutron as a fundamental channel and also to find some difference with the double π^0 photoproduction on the proton by comparing their respective observables of cross section and beam asymmetry.

The data have been obtained with the GRAAL setup using a tagged and linearly polarized photon beam, a liquid deuterium target 6 cm thick, and a large acceptance detector [13]. The photon beam of 0.6 up to 1.5 GeV is produced by backscattering a laser beam on the electron beam of 6.04 GeV in the ring of the European Synchrotron Radiation Facility (ESRF) at Grenoble. The energy spectrum of this type of beam is flat and the degree of polarization is close to 100% at maximum energy. In the beam energy range considered here the degree of polarization varies from 0.6 to 0.98, using the green or the UV lines of the laser.

When a laser photon is backscattered on an electron in the ring, the scattered electron is deflected by a magnet of the ring towards a position sensitive detector (tagging detector) allowing to deduce its energy with a resolution of 16 MeV (full width at half maximum). As to the backscattered photons of high energy and small angular divergence, they constitute the photon beam which hits the target and continues in air until reaching first a thin monitor then a full absorption lead-scintillator detector. A flux intensity close to $1.0 \times 10^6 \gamma/s$ was used.

The large acceptance detector consists of three layers: wire chambers, scintillators and calorimeters. In the central part ($25° \leqslant \theta \leqslant 155°$), a bismuth germanate (BGO) calorimeter covering 90% of 4π, centered on the target and vetoed by a barrel of scintillators, detects with a good resolution the γ's [14]. In the forward direction ($\theta \leqslant 25°$), a double wall of scintillators and a shower wall measure the time of flight of the proton and the neutron respectively [15].

Here, we study the reaction $\gamma n \to n\pi^0\pi^0$, using a deuterium target. We select the events of the reaction $\gamma d \to n\pi^0\pi^0 p$ where the γ interacts, in a quasi-free process, with the neutron weakly bound inside the deuterium nucleus while leaving the partner proton as spectator. In such a process, the neutron target has a given Fermi momentum and the proton keeps, in the final state, a momentum of opposite value. Consequently, we propose to select the quasi-free events as those for which the proton in the final state has a characteristic Fermi kinetic energy E_p of a few MeV, which is below the energy threshold for charged particle detection in the GRAAL setup (≈20 MeV). In the analysis, the experimental events with five neutral particles detected in the final state were selected, in order to reconstruct two π^0's and a neutron, the π^0 being detected through its decay into 2γ's. A further selection is imposed by requiring the detection of the two π^0's in the central detector (BGO). This condition ensures good angular and energy measurements of the γ's and consequently of the two π^0's. The neutron is detected either in the central detector or in the forward detector and its angles θ and ϕ are measured through the cellular structure of the detector. In the forward directions, the neutron is discriminated from the γ's by the time of flight given by the shower wall. In the central detector, the neutron is taken as the neutral particle left when the four others give the best reconstruction of two π^0's. The use of the four energy and momentum conservation laws allows to deduce the energy of the neutron and the angles and the energy of the undetected proton. The plot on Fig. 1 shows the invariant masses for the best combination of two pairs of γ's to reconstruct a double π^0. The resolution (full width at half maximum) of the reconstructed invariant mass of π^0 is 25 MeV. In Fig. 2, the plot with a thick line displays the energy spectrum of the undetected proton, where the peak close to zero originates from the quasi-free process and the background visible at higher energy comes from other processes.

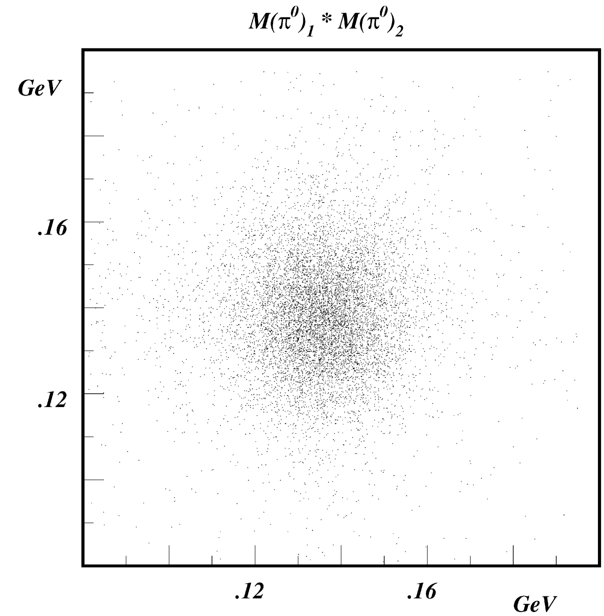

Fig. 1. Bidimensional plot of the invariant masses of two pairs of γ's corresponding to the best combination (see text). For this plot, events of the reaction $\gamma d \to n\pi^0\pi^0 p_{sp}$, with the energy of the undetected proton lower than 50 MeV, were selected.

In parallel to the analysis of the experimental data, a simulation was carried out using the code LAGGEN of GRAAL built on an event generator and on the GEANT3 code from the CERN library. The generator was used to produce events for the reaction $\gamma d \to \Delta^0\pi^0 p \to n\pi^0\pi^0 p$, where the gamma interacts with a neutron bound inside the deuterium and having a Fermi motion. The GEANT3 code provides the tracking of the produced particles in the detector. The results of the simulation were used for two purposes: to check the event selection criteria and to determine the acceptance. In the simulation the events were analyzed as those corresponding to the experimental data. The energy spectrum of the undetected proton is shown as a thin line in Fig. 2. A pronounced peak is obvious at $E_p \approx 0$ and a flat and low background at higher energy. The comparison of the experiment and simulation curves in Fig. 2 suggests that the desired events can be selected by: (i) keeping events with $E_p \leqslant 0.05$ GeV, (ii) rejecting events with $E_p \geqslant 0.10$ GeV and (iii) subtracting events with $0.05 \leqslant E_p \leqslant 0.10$ GeV. This filter was applied for both the experimental and simulated data, in order to correct for the part of true events cut in these operations. In the inset of Fig. 2, the resulting spectra are shown. A good consistency in shape and width is observed between the experiment and simulation spectra. In the experimental spectra, the

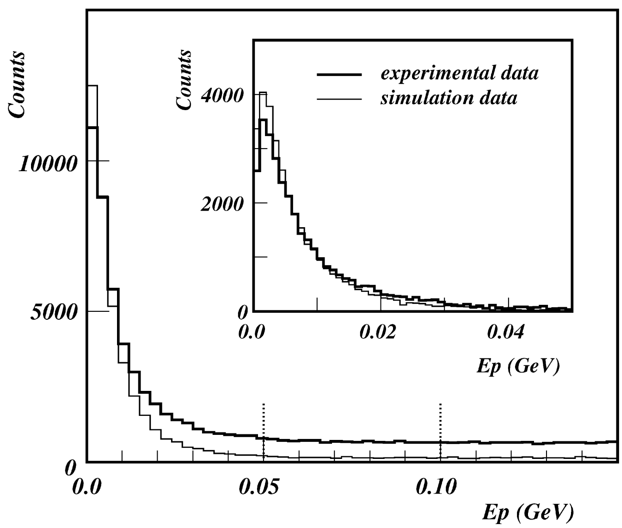

Fig. 2. The kinetic energy spectrum of spectator protons in the reaction $\gamma d \to n\pi^0\pi^0 p$. In thick line, for the experimental data and in thin line for the simulation data. In the inset, the same spectra after background subtraction. For this figure, events are selected within a radius of 35 MeV around the centre of the spot of Fig. 1.

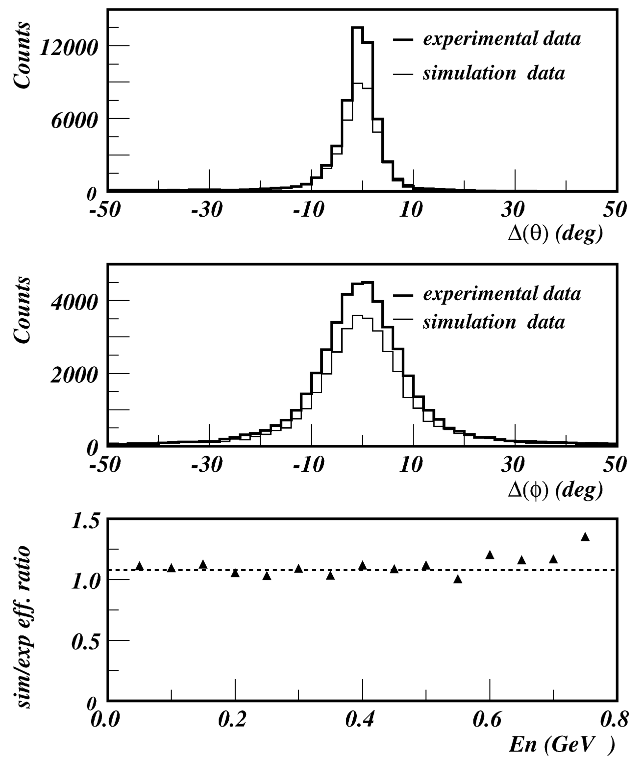

Fig. 3. Spectra relevant to the neutron detection efficiency in the BGO ball obtained from the reaction $\gamma p \to n\pi^0\pi^+$ on a free proton target. The upper two spectra are for the angular difference between measured and expected values in θ and ϕ of the neutron. The lower one is the efficiency ratio (simulation/experiment) for $|\Delta(\theta)| \leqslant 7^0$ and $|\Delta(\phi)| \leqslant 20°$. See text.

background to peak ratio is about 20% and the error resulting from the background subtraction is estimated to be 5%. The contamination from the various three pions photoproduction channels was studied using the simulation code. With the realistic values of the cross sections used in the GRAAL generator and with the filtering conditions of the analysis they were controlled to contribute only to the flat background without peaking near $E_p \approx 0$ and so they are subtracted within the background. For the determination of the acceptance, the simulation used, as in Ref. [9], three kinematical variables: the photon beam energy, and the momentum and the θ-angle of the $2\pi^0$ system. This choice of variables attenuates the model-dependence of the calculated acceptance. When extracting the cross section, the invariant mass or the beam asymmetry, each experimental event will be weighted according to the acceptance. Average efficiencies of 30% on the quasi-free proton and of 8% on the quasi-free neutron were found. An extrapolation for the uncovered phase space (less than 8% at any photon beam energy) was needed. The error on the total cross section originating from the extrapolation does not exceed 4%. There is a systematic error of about 6% on the acceptance originating from the choice of a simple phase space by lack of a more realistic one and this error is not drawn on the results of the present Letter.

The neutron detection efficiency was extracted from the analysis of experimental events of the reaction $\gamma p \to n\pi^0\pi^+$ on the free proton. The analysis requires the identification of such events and the determination of the efficiency as the fraction of events for which the neutron is detected. First, the events with π^0 and low energy π^+, both detected in the BGO, are selected. The restriction to low energy π^+ ($\leqslant$200 MeV) is done to allow a good particle identification by the barrel and BGO detectors. Second, the kinematics is used to deduce the θ_{expected} and ϕ_{expected} angles and the energy E_n of the neutron. Third, a comparison of the expected angles of the neutron to the measured ones, θ_{measured} and ϕ_{measured}, is performed when the neutron is detected either in the BGO ball or in the shower wall. Then the efficiency is extracted in terms of E_n for cuts on $\Delta\theta = \theta_{\text{measured}} - \theta_{\text{expected}}$ and $\Delta\phi = \phi_{\text{measured}} - \phi_{\text{expected}}$. The efficiency is of the order of 26% in the BGO ball and of 20% in the shower wall. In parallel, the same procedure is performed for events obtained by simulation for the reaction $\gamma p \to n\pi^0\pi^+$ assuming a 3-body phase space in the final state. In Fig. 3, are given the $\Delta\theta$ and $\Delta\phi$ spectra. Also, in the same figure the efficiencies ratio obtained from the simulation and the experimental data is plotted as a function of the neutron energy. The ratio is approximately constant ($\approx$1.08), the neutron being detected either in the BGO ball or in the shower wall, and is independent of realistic cuts on $\Delta\theta$ and $\Delta\phi$. Accordingly, the acceptance determined by simulation was divided by 1.08. The resulting acceptance error is of the order of 4%.

The reaction $\gamma d \to p\pi^0\pi^0 n$, where the gamma interacts with a quasi-free proton, bound in the deuterium, was also analyzed in the same experimental data used for the quasi-free neutron, with as much as possible the same algorithms. This allows to get rid of most of the systematic errors on the cross section ratio R (quasi-free neutron/quasi-free proton). Around 800 000 pure events were analyzed on bound protons and 230 000 on bound neutrons.

In Fig. 4, the total cross sections on the quasi-free neutron and the quasi-free proton are plotted with solid and open circles respectively. They show two peaks at 750 and 1100 MeV, the

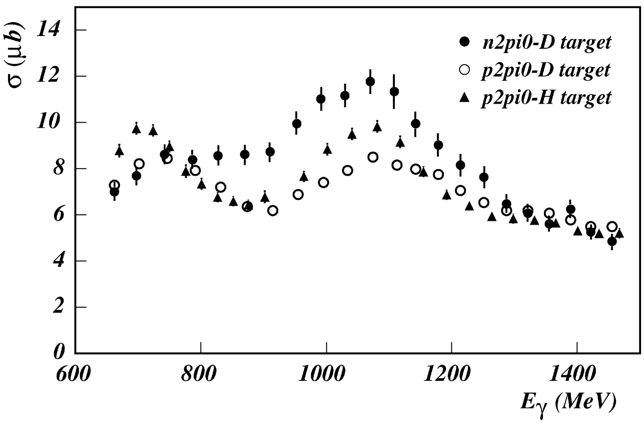

Fig. 4. The total cross sections of double π^0 photoproduction on the quasi-free neutron (with solid circles) and quasi-free proton (with open circles), compared to the one on the free proton (with triangles).

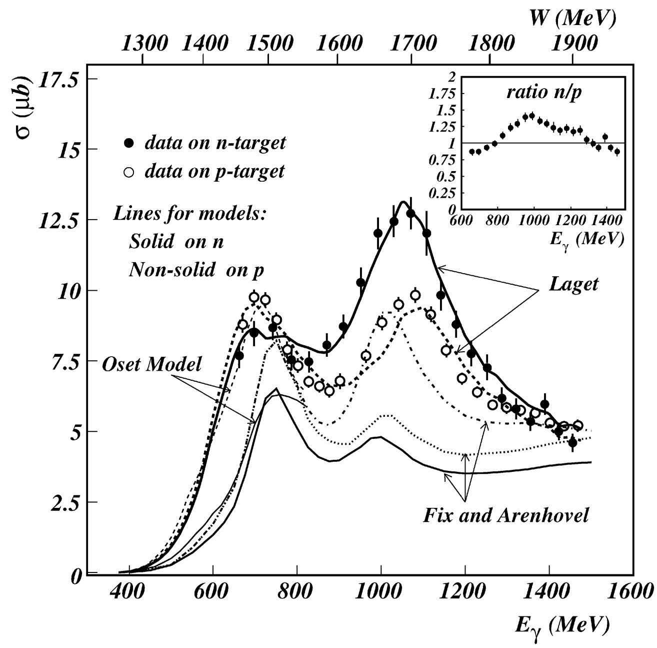

Fig. 5. Total cross sections for double π^0 photoproduction on the nucleon as a function of the beam energy. In dots, are the results of the present work for $\gamma n \to n\pi^0\pi^0$ on free neutron. In circles, the results previously published for the free proton [9]. The error bars ($\approx$8%) for neutron results are total errors coming from statistics, background subtraction, neutron efficiency calculation, and phase space extrapolation. An additional systematic error of $\approx$6% not drawn originates from our use in the acceptance calculation the phase space of $\gamma d \to \Delta^0\pi^0 p \to n\pi^0\pi^0 p$ reaction by lack of a more realistic one. The lines show the results of models, the solid lines being on neutron and the non-solid ones on proton. The dotted and dashed lines of Fix and Arenhövel model are for positive and negative sign of $F_{15}\pi\Delta$ coupling respectively. In the inset, on the upper right side, the quasi-free neutron to quasi-free proton cross section ratio.

one at the 1100 MeV being higher on the neutron. The systematic error on these results is estimated to be about 7%. The cross section on the quasi-free proton is also compared to the cross section on the free proton (plotted with triangles), showing a flattening of the peaks and a shifting towards higher incident energy.

Since the Fermi motions of the neutron and the proton inside a deuterium target are identical, it is expected that the total cross section σ_t scales in an identical way, when one passes from quasi-free proton to free proton and from quasi-free neutron to free neutron. So, using the ratio R (quasi-free neutron/quasi-free proton) measured here and the cross section on free protons obtained in Ref. [9], we deduced σ_t on a free neutron as plotted with dots in Fig. 5, which is compared with σ_t on a free proton plotted with empty circles. Both cross sections are dominated by two peaks at 1500 and 1700 MeV in the centre of mass. The peak at 1700 MeV is more important on the neutron, as also illustrated by the ratio R, plotted in the inset of the figure.

For the interpretation of our present results on the neutron, the model of J.M. Laget was used to fit the total cross section results and to predict the beam asymmetry ones [16,17]. The parameters of the resonances are the same as on the proton [9], except: (i) the mass of $D_{13}(1650)$ was shifted to 1675 MeV and that of $P_{11}(1720)$ to 1710 MeV, (ii) the radiative couplings have been adjusted to fit the data ($\Gamma_\gamma = 0.075$ MeV for $D_{13}(1675)$, 0.27 for $P_{11}(1500)$ and 0.01 for $P_{11}(1710)$), and (iii) the sign of the radiative coupling of the neutron to the $D_{13}(1675)$ is opposite to the one in the proton case. In Fig. 5, the results of the Laget model on the free neutron are plotted by a continuous line while those on the free proton, taken from Ref. [9] are shown by a dotted line. The model reproduces the two peaks which dominate the total cross section, relying on the interference between the direct emission of the σ meson and the decay of the P_{11} resonances into the σN channel.

The Valencia group model includes a large number of diagrams and was used to calculate the various observables in double pion photoproduction on the nucleon for beam energy from threshold up to 800 MeV [2,3]. When applied to the double π^0 photoproduction on the nucleon it reproduces the peak at 800 MeV in the total cross section on the free proton but underestimates the one on the free neutron. The model includes $P_{33}(1232)$, $P_{11}(1440)$ and $D_{13}(1520)$ as intermediate baryonic states and gives the main contribution from $D_{13}(1520)$. Recently the model was applied to interpret the helicity dependence of the total cross section of $\vec{\gamma}\vec{p} \to \pi^0\pi^0 p$ reaction [10] and its results were consistent with the dominance of the $\sigma_{3/2}$.

More recently, Fix and Arenhövel calculated the double photoproduction on the nucleon for photon energies from threshold up to 1.5 GeV, using an effective Lagrangian approach with resonance and Born terms contributions [4]. A satisfactory description of the total cross section of double pions on the protons for various charge channels was obtained but the total cross section of double π^0 was underestimated. Nevertheless, the model gives a consistent result with the Valencia group model in explaining the peak at 800 MeV as due to the $D_{13}(1520)$ resonance. The calculation predicts a second peak at 1 GeV on both the proton and the neutron target mostly coming from the excitation of the $F_{15}(1680)$. The magnitude of the peak is higher on proton target and then close to the experimental data when the coupling of the $F_{15}\pi\Delta$ is taken with a negative sign.

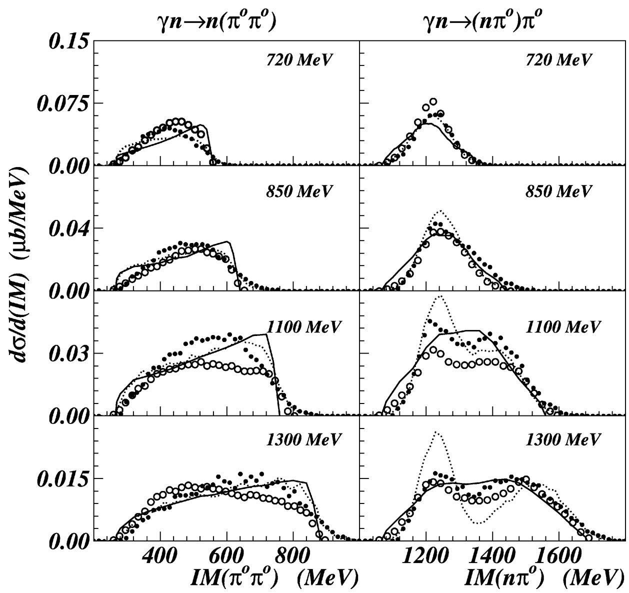

Fig. 6. Invariant mass (IM) spectra of the quasi-free $\gamma n \to n\pi^0\pi^0$ at four beam energy bins, 100 MeV wide and centered at 720, 850, 1100 and 1300 MeV. On the left, spectra of the IM of the system $(\pi^0\pi^0)$ and on the right of the IM of $(n\pi^0)$. Present results on the quasi-free $\gamma n \to n\pi^0\pi^0$ are given in dots. Our previous results of $\gamma p \to p\pi^0\pi^0$ on free protons are given in circles. The dotted line is the phase space of the reaction $\gamma n \to \Delta^0\pi^0$, and the continuous line the Laget model calculation on the neutron [17].

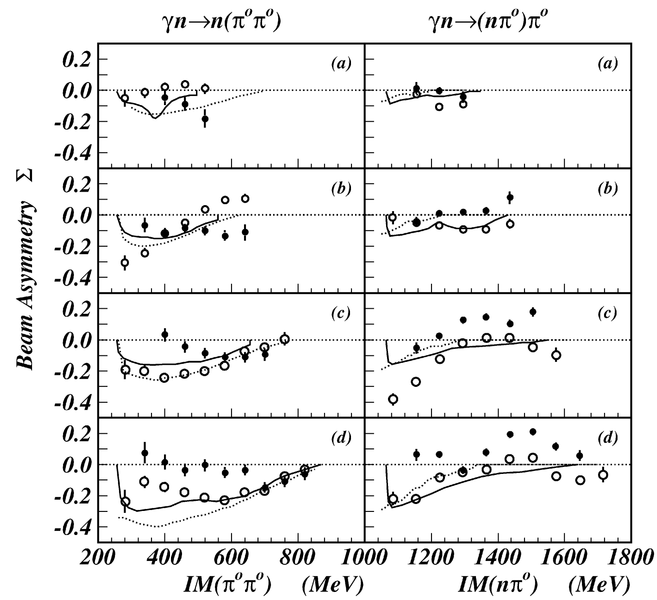

Fig. 7. The beam asymmetry Σ of the double π^0 photoproduction on the nucleon at four beam energies: (a) 650–780 MeV, (b) 780–970 MeV, (c) 970–1200 MeV, and (d) 1200–1450 MeV. On the left, Σ as a function of the IM of the system $(\pi^0\pi^0)$ and on the right of the IM of $(n\pi^0)$. The results of the present work on the quasi-free $\gamma n \to n\pi^0\pi^0$ are given in dots. In circles, the results of $\gamma p \to p\pi^0\pi^0$ on free protons. The continuous and dashed lines give the Laget model calculation on the neutron and the proton respectively. 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 total momentum of the $2\pi^0$ system, and on the right, the plane of the incident photon and any one of the two outgoing π^0's.

In Fig. 6, the differential cross sections are presented as a function of the invariant mass of the two π^0's on the left-hand side, and of the invariant mass of the neutron and any one of the two π^0's on the right-hand side, for four bins of beam energy. The results of the quasi-free $\gamma n \to n\pi^0\pi^0$ are plotted with dots and those of $\gamma p \to p\pi^0\pi^0$ on a free proton with circles. The results of the simulation calculation of the reaction $\gamma n \to \Delta^0\pi^0$ are drawn with dotted lines and the results of the Laget model calculation on a free neutron target with continuous lines. Similar shapes are seen in both experimental results on the neutron and the proton. The two bumps seen in the IM$(n\pi^0)$ spectra at beam energies of 1100 and 1300 MeV are roughly reproduced by simulation calculation relying on the production of Δ^0 in the final state. The Laget model calculation is consistent with the overall width, but has several deviations in shape.

The beam asymmetry Σ was extracted for the photoproduction of double π^0 on quasi-free neutrons and quasi-free protons, through the fitting of the $\cos(2\phi)$ dependence of the angular distributions, in the same way as described for free protons in Ref. [9]. Let us notice that with a linear polarization of the beam, for the reaction $\gamma n \to n\pi^0\pi^0$, the recent reference [18] gives the expression $A\cos(2\phi) + B\sin(2\phi)$ to extract two observables A and B of beam asymmetry which are functions of 5 variables of the 3-body reaction. However, we have reduced the reaction to $\gamma n \to nX$ or $\gamma n \to \pi^0 Y$. Doing this we have integrated over the internal variables $(\theta_{\rm cm}, \phi_{\rm cm})$ of $X \to \pi^0\pi^0$ and $Y \to n\pi^0$. After the integration, the term B vanishes because it is odd under the transformation $\phi_{\rm cm} = 2\pi - \phi_{\rm cm}$. It remains the part $A\cos(2\phi)$ where A depends on the variables of the 2-body reactions $\gamma n \to nX$ and $\gamma n \to \pi^0 Y$.

The Σ results on a quasi-free nucleon and on a free nucleon should not differ significantly, since the widening of beam energy by the Fermi motion of the quasi-free nucleon is hidden by the significant width of the beam energy bins. In a global check, the values extracted on a quasi-free proton were compared with those previously obtained for the free proton ones [9]. A good consistency was found. All data points agree within $|\Sigma_{\rm free} - \Sigma_{q\rm free}| \leqslant 0.05$. In Fig. 7, the beam asymmetry results for $\gamma n \to n\pi^0\pi^0$ on a quasi-free neutron are presented with dots, together with the previous results of $\gamma p \to p\pi^0\pi^0$ from a free proton target (circles). The abscissa variables were taken to be the same as those used for the differential cross sections. The errors originate from the statistics and the fitting procedure on the ϕ distributions to extract the asymmetry Σ. The systematic error from the polarization determination not drawn is of ≈3%. Strictly speaking, the beam asymmetry has only been extracted within the 5-dimensional phase space covered by the GRAAL setup, but we expect the influence on Σ from uncovered phase space regions to be small. The asymmetry analysis was performed with and without weighting each event by the acceptance deduced from the simulation calculation. the asymmetry results remained stable within the error bars. The Laget model results for free neutrons and protons are given with continuous and dotted lines respectively. The experimental and theoretical values of the asymmetry are both small either for the neutron or for the proton. The theoretical curves have a regular shape and are similar for the neutron and the proton at a given beam energy. The experimental results display a less regular shape, especially for the neutron target, probably resulting from the contribution of several diagrams not used in the model.

To summarize, the total cross section of the double π^0 photoproduction on the neutron shows a very characteristic pattern dominated by two peaks at 1500 and 1700 MeV in the centre of mass. The Laget model built on a few diagrams favoring the excitation of P_{11} resonances could fit the experimental data. Both of the models of Valencia group and Fix and Arenhövel successfully predicted the peak at 1500 MeV due mainly to D_{13} excitation. The peak at 1700 MeV was predicted by Fix and Arenhövel as originating from F_{15} excitation. Both of the experimental and Laget model amplitudes of the beam asymmetry are small ($\leqslant 0.3$).

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