Quasi-free $\pi^0$ Photoproduction from the Bound Nucleon

K. Kossert$^{1,a,b}$, M. Camen$^{1,a}$, F. Wissmann$^{1,b}$, J. Ahrens$^2$, J.R.M. Annand$^3$, H.-J. Arends$^2$, R. Beck$^2$, G. Caselotti$^2$, P. Grabmayr$^4$, O. Jahn$^2$, P. Jennewein$^2$, M.I. Levchuk$^5$, A.I. L’vov$^6$, J.C. McGeorge$^3$, A. Natter$^4$, V. Olmos de León$^2$, V.A. Petrun’kin$^8$, G. Rosner$^3$, M. Schumacher$^{1,c}$, B. Seitz$^{1,d}$, F. Smend$^1$, A. Thomas$^2$, W. Weihofen$^1$, and F. Zapadtkają

1 II. Physikalisches Institut, Universität Göttingen, D-37073 Göttingen, Germany
2 Institut für Kernphysik, Universität Mainz, D-55099 Mainz, Germany
3 Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QK, UK
4 Physikalisches Institut, Universität Tübingen, D-72076 Tübingen, Germany
5 B.I. Stepanov Institute of Physics, Belarussian Academy of Sciences, 220072 Minsk, Belarus
6 P.N. Lebedev Physical Institute, 119991 Moscow, Russia

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Abstract. Differential cross-sections for quasi-free $\pi^0$ photoproduction from the proton and neutron bound in the deuteron have been measured for $E_\gamma = 200 - 400$ MeV at $\theta_{lab} = 136.2^\circ$ using the Glasgow photon tagger at MAMI, the Mainz 48 cm $\Theta \times 64$ cm NaI(Tl) photon detector and the Göttingen SENECA recoil detector. For the proton measurements made with both liquid deuterium and liquid hydrogen targets allow direct comparison of “free” $\pi^0$ photoproduction cross-sections as extracted from the bound proton data with experimental free cross sections which are found to be in reasonable agreement below 320 MeV. At higher energies the “free” cross sections extracted from quasifree data are significantly smaller than the experimental free cross sections and theoretical predictions based on multipole analysis. For the first time, “free” neutron cross section have been extracted from quasi-free data are significantly smaller than the experimental free cross sections and theoretical predictions based on multipole analysis. For the first time, “free” neutron cross section have been extracted in the $\Delta$-region. They are also in agreement with the predictions from multipole analysis up to 320 MeV and significantly smaller at higher photon energies.

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1 Introduction

Single-pion photoproduction has been a subject of extensive experimental and theoretical investigation for many decades. This reaction is one of the main sources of information on nucleon structure. It allows investigation of resonance excitations of the nucleon, especially the $\Delta(1232)$ excitation, and their photo-decay amplitudes. The pion photoproduction amplitude is used as an input when calculating pion photoproduction from heavier nuclei and in the dispersion analysis of nucleon Compton scattering. This reaction also serves as a test of our understanding of the chiral pion-nucleon dynamics. A well-known example is the demonstration that chiral perturbation theory accurately describes the very precise data on the $S$-wave multipole $E_0^+$ and the $P$-wave amplitudes of $\pi^0$ photoproduction on the nucleon in the threshold region $^{1,2}$.

Experimental investigation of pion photoproduction on the nucleon has a long history. More than seventeen thousand data points form the modern data base of pion photoproduction at energies up to 2 GeV. Almost all of them are data on the charged channels on both nucleons and on the $\gamma p \rightarrow \pi^0 p$ channel. The contribution of the $\gamma n \rightarrow \pi^0 n$ reaction to this base amounts to only 120 data points at energies up to 905 MeV obtained in 1970’s at the Frascati synchrotron $^3$ and at the Tokyo synchrotron $^4,5$. However, no direct measurements of quasi-free $\pi^0$ photoproduction on the neutron using a deuterium target have been carried out. Instead, the ratio $R = d\sigma(\gamma d \rightarrow \pi^0 p)/d\sigma(\gamma d \rightarrow \pi^0 n)$ was measured where $p_s$ and $n_s$ are the spectator proton and neutron, respectively, and used to obtain the free-neutron cross-section based on the assumption that $R$ is a good approximation also for the ratio of the free cross-sections $d\sigma(\gamma n \rightarrow \pi^0 n)/d\sigma(\gamma p \rightarrow \pi^0 p)$. Though the method may be reasonable in principle, the data points obtained from those works are of very limited precision.

Following a proposal made in Ref. $^7$ (see also Ref. $^8$) an experiment has been carried out at the 855 MeV microtron MAMI-B, where the primary goal was to measure differential cross-sections for neutron Compton scattering...
in quasi-free kinematics using a deuterium target \cite{9,10,11}. For that experiment the incident photon energy was chosen to be in the region from 200 MeV to 400 MeV. For the Compton scattering experiment the produced $\pi^0$ mesons are a source of background photons due to their 2 $\gamma$ decay, which has to be eliminated in the analysis. In the present paper these events were used to obtain differential cross sections for $\pi^0$ photoproduction from the proton and neutron bound in the deuteron. By replacing the deuterium target by a hydrogen target $\pi^0$ photoproduction from the free proton was also measured under the same kinematic conditions. It should be noted that the present data are the first where the quasi-free events were identified through a coincidence between one of the $\pi^0$ decay photons and the recoiling nucleon.

2 Experiment

The experimental arrangement installed at the Glasgow photon tagger at MAMI \cite{12}, and outlined in Fig. 1 has been described previously \cite{9,10,11}. This allows us to give here only a short description. The large Mainz 48 cm $\varnothing \times 64$ cm NaI(Tl) detector \cite{13,14} was positioned at a scattering angle of $\theta_{\text{lab}} = 136.2^\circ$ (nominally $135^\circ$). The energy resolution of this detector is 1.5% in the $\Delta$ energy region and its detection efficiency 100%. The recoil nucleons were detected with the Göttingen SENECA detector \cite{15} positioned at an average emission angle of $\theta_N = -18^\circ$, thus covering the angular range corresponding to quasi-free kinematics. This angle was optimized for Compton scattering but sufficiently covers also the range required for $\pi^0$ photoproduction where the average emission angle is $\theta_N = -15^\circ$. Effects of the variation of the emission angle are precisely taken into account by computer simulation. A target to recoil detector distance of 250 cm was chosen as a compromise between the energy resolution for the time-of-flight measurement, $\Delta E_n/E_n \approx 10\%$, and the geometrical acceptance $\Delta\Omega_n \approx 90$ msr. As target a 5 cm $\varnothing \times 15$ cm Kapton cell filled with liquid deuterium was used. By filling the same cell with liquid hydrogen it was possible to investigate quasi-free and free $\pi^0$ photoproduction on the proton under identical kinematic conditions. SENECA consists of 30 hexagonally shaped cells filled with NE213 liquid scintillator (15 cm in diameter and 20 cm in length) mounted in a honeycomb structure. Veto-detectors in front of SENECA provided the possibility to identify charged background particles and to discriminate between neutrons and protons. This allowed clean separation between quasi-free Compton scattering and $\pi^0$ photoproduction from the proton and neutron detected in the same experiment. The detection efficiency of the veto-detectors for protons was implemented in the Monte Carlo program \cite{16}. The detection efficiency for neutrons was measured \textit{in situ} by analysing events from the $p(\gamma, \pi^+ n)$ reaction leading to $\epsilon_n = 18\%$ \cite{11} on the average. The new data for $\epsilon_n$ being valid on a few percent level of precision are used to correct the results of computer simulations. For further details see \cite{11}. The momenta of the recoil nucleons were measured using the time-of-flight (TOF) technique with the NaI(Tl) detector providing the start signal and the SENECA modules providing the stop signals.

Data were collected during 238 h of beam time with a deuterium target and 35 h with a hydrogen target. The tagging efficiency, being 55%, was measured several times during the runs by means of a Pb-glass detector moved into the direct photon beam, and otherwise monitored by a P2 type ionization chamber positioned at the end of the photon beam line.

3 Data analysis

Before analysing the data obtained with the deuterium target the corresponding analysis of data obtained with the hydrogen target was carried out. In this case the separation of events from Compton scattering and $\pi^0$ photoproduction can be achieved by the NaI(Tl) detector alone, but the detection of the recoiling proton improves the separation, especially for energies near the peak of the $\Delta$ resonance. A typical spectrum is shown in panel a of Fig. 2. The data obtained for the free proton have been used to optimize the analysis procedure for the bound nucleon.

For the separation of events from Compton scattering and $\pi^0$ photoproduction it is convenient to use two-dimensional scatter plots of events with the missing nu-
The benefits of this procedure are illustrated in Fig. 2. Panel a shows numbers of proton events from a proton target versus the measured missing energy of the scattered photon, given for a narrow energy interval close to the maximum of the $\Delta$ resonance. In this case we find very good separation between the two types of events as in previous experiments carried out with proton targets. The good separation disappears when proton events of the same type are taken from a deuteron target. These data are shown in panel b where it can clearly be seen that the effects of binding destroy the separation of the two types of events which was visible in panel a. The separation can be partly restored when the rotation procedure is applied as is shown in panel d. This panel contains as a solid line the same data as the scatter plot of events shown in panel c but projected on to the abscissa after rotation. For comparison the broken line shows the same data before rotation. The comparison of these two lines clearly demonstrates that the rotation procedure improves the separation of the two types of events.

Fig. 3 shows typical spectra obtained with the deuteron target shown for the recoil proton (left panels) and recoil neutrons (right panels). The data from the two dimensional plot have been projected on to the abscissa after the rotation described in the caption of Fig. 2 and in the text. The solid curves are the results of a Monte Carlo simulation scaled to the Compton events and the ($\gamma, \pi^0$) events, respectively.
the grey areas in case of the Compton scattering events and to the white areas in case of the $\pi^0$ events.

The number of ($\gamma, \pi^0$) events which is the number of events given by the adjusted curves, corresponds to the integral of the triple differential cross-section in the region of the quasi-free peak. The following relation has been used to determine the final triple differential cross-section in the center of the nucleon quasi-free peak (NQFP):

$$\left( \frac{d^3\sigma}{d\Omega_{\gamma}d\Omega_{\pi}dE_N} \right)_{\text{NQFP}} = \frac{N_{\gamma\pi N}}{N_\gamma N_T \epsilon_N R_{\text{NQFP}}^{\pi^0}}.$$  \hspace{1cm} (1)

where $N_{\gamma\pi N}$ is the number of coincident $\pi^0$-nucleon events as extracted from the missing energy spectra, $N_\gamma$ is the number of incident photons, $N_T$ is the number of target nuclei, $\epsilon_N$ is the nucleon detection efficiency and $R_{\text{NQFP}}^{\pi^0}$ is a factor obtained by Monte Carlo simulation which relates the number ($\gamma, \pi^0$) events integrated over the distribution of events to the triple differential cross-section in the center of the nucleon quasi-free peak.

### 4 Theory

In our analysis of the data we used the theoretical model proposed in Refs. 17, 18 and developed subsequently in Refs. 19, 20, 21, 22, 23 (see also Refs. 24, 25, 26). The model is based on the diagrams relevant for the reaction on the kinematic conditions under consideration. The main graphs contributing to the reaction amplitude in the quasi-free region are displayed in Fig. 3. Graph 4a) describes quasi-free photoproduction from the nucleon $N_1$. It is expected to be dominant when the momentum of the nucleon $N_2$ is sufficiently small ($\lesssim \sqrt{mE_0}$ where $E_0 = 2.2246$ MeV is the deuteron binding energy and $m$ the nucleon mass). This corresponds to the so-called nucleon quasi-free peak (NQFP) region. The non-interacting nucleon $N_2$ in this graph is often referred to as a spectator.

The final nucleons can interact with each other through the mechanism displayed in graph 4b), describing the so-called final state interaction (FSI). This graph was found to be of great importance for many processes involving deuteron disintegration, including the reaction $\gamma d \rightarrow \pi N N$ (see Refs. 17, 18, 19, 20, 21, 22, 23). The big effect of FSI is mainly caused by $NN$-interaction in the s-wave at small relative momenta ($\lesssim 200$ MeV/c) of the $NN$-pair. Such small relative momentum is provided under the kinematic conditions of small incident energies and/or forward angles of a third particle in the final state, which is the pion in our case. Of the two s-wave final-states, $^1S_0$ and $^3S_1$, the repulsive isosinglet np-wave $^3S_1$ proved to be the more important one, leading to a decrease of the cross-section due to FSI. Experiments on semi-inclusive $\pi^0$ photoproduction in the reaction $d(\gamma, \pi^0)np$ clearly confirm these properties of FSI. Since our experiment covers the kinematic region where the relative momentum of the np-pair ranges from 140 to 270 MeV/c we expect that FSI gives a noticeable contribution at the beginning of the energy interval and decreases in importance with increasing photon energy.

Fig. 4. Graphs contributing to the reaction $\gamma d \rightarrow \pi^0 np$. The set of graphs where $N_1 \leftrightarrow N_2$ is not shown in the figure.

The pion (neutral or charged) produced in the $\gamma N \rightarrow \pi N N$-vertex can be scattered by the spectator nucleon as displayed in graph 4c). Although the detailed investigation of the reaction $\gamma d \rightarrow \pi^- pp$ performed in Refs. 17, 18 has shown that there exists a kinematic region where the diagram 4c) can give a noticeable contribution to the amplitude in the $\Delta$ region, usually the effect of $NN$-rescattering is smaller than that of $NN$-rescattering. In our previous paper 19, we found the contribution of graph 4c) in the NQFP region to be of minor importance at energies from 250 to 400 MeV.

It is known that two-loop diagrams can be important for the description of the reaction $\gamma d \rightarrow \pi N N$ under certain kinematic conditions. For instance, the graph 4d) proved to give a big contribution to the inclusive process $d(\gamma, \pi^0)np$ in the threshold region (see Ref. 20). This result can be easily understood if one takes into account that the threshold electric dipole amplitude $E_0+$ of charged pion photoproduction which is contained in the upper block of this graph, is about 30 times larger in absolute numbers than those for neutral channels. With increasing photon energy this effect is expected to decrease in importance. Nevertheless, we will take it into account.

A significant modification of the reaction amplitude through s-wave interaction of the NN-pair may not occur in the final state but also in the intermediate state by the mechanism displayed in graph 4e). This was previously demonstrated in Refs. 17, 18 in the analysis of the reaction $\gamma d \rightarrow \pi^- pp$ where it was shown that of the two possible s-wave interactions, $^1S_0$ and $^3S_1$, the isosinglet...


\[ F(\pi^+) = (A_1^2 + A_2^2) / (A_1^2 + A_2^2)^2 \]

with \( q_{on}, q_{off} \) being the on-shell (off-shell) momentum of the intermediate pion. Introducing the form factor ensures also the convergence of the integrals over the pion off-shell momentum \( q_{off} \) which emerge in the evaluations of graphs (a)-(d). The value of the cut-off parameter \( \Lambda_\pi \) is usually treated as a free parameter which is adjusted to provide the best description of the reaction under consideration. It is not surprising that in the literature there exists a great variety of numerical values for \( \Lambda_\pi \). We use two different choices for it. The first one is a very soft form-factor (\( \Lambda_\pi = 440 \text{ MeV} \)) which was used in Refs. [37, 38] to give the best fits to the \( \pi^0 \) photo and electroproduction data in the threshold region as well as to the \( \Delta(1232) \) resonance multipole \( M^{(3/2)}_{1+} \) over a wide energy range. The second one is a very hard form-factor (\( \Lambda_\pi = 1720 \text{ MeV} \)) used in Ref. [34] for the construction of the CD-Bonn potential. We found, however, that the variation of \( \Lambda_\pi \) from 1000 MeV to 1720 MeV practically does not change the results. Moreover, for \( \Lambda_\pi > 1000 \text{ MeV} \) one can safely put the form factor \( F_\pi(q_{on}, q_{off}) \) to be equal to 1. In actual calculations, the upper limit of the integrals was taken to be \( p_{\text{max}}^{\pi^+} = 1000 \text{ MeV/c} \) but its replacement by \( p_{\text{max}}^{\pi^+} = 500 \text{ MeV/c} \) changed the cross-sections by less than 3%.

Contributions of separate diagrams to the triple differential cross-section of the reaction \( \gamma d \to \pi^0 np \) are shown in Fig. 5. The effect of FSI manifests itself in a noticeable reduction of the cross-section. The size of this reduction ranges from 20% at 200 MeV, and 5% at 300 MeV, to 2% at 400 MeV in the center of the proton quasi-free peak (CpQFP). In the center of the neutron quasi-free peak (CnQFP) one has the same numbers. It is interesting to note that the numbers given above were also obtained by us for the relative FSI contribution in the case of the reaction \( \gamma d \to \pi^+ np \) [11]. The effect of \( \pi N \)-rescattering (graph...
does not exceed 1% and is not shown in Fig. 6. The inclusion of graph (4f) leads to a decrease of the cross-section by 6% at 200 MeV, 2% at 300 MeV, and 0.5% at 400 MeV. These numbers are practically independent of the $\Lambda_{\pi}$ value. A further reduction of the cross-section below 320 MeV is due to the contribution of diagram (4e). The reduction is quite visible, being about 15% from 200 to 260 MeV and reducing further to 8% at 300 MeV. These numbers are obtained for $\Lambda_{\pi} = 1720$ MeV. For $\Lambda_{\pi} = 440$ MeV they are 12% and 2%, respectively. Above 320 MeV one observes some increase of the cross-section after inclusion of graph (4e). The total contribution of one-loop and two-loop diagrams is −30%, −15%, and +6% at 200, 300, and 400 MeV, respectively, if one takes $1720$ MeV and two-loop diagrams is −30%, −15%, and +6% at 200, 300, and 400 MeV, respectively, if one takes $1720$ MeV

\[ \frac{d\sigma}{d\Omega_{\pi}}(\gamma p \rightarrow \pi^0 p) = \frac{(2\pi)^3}{u^2(0)} |P_p|^3 \left( \frac{1}{E_p} \frac{1}{E_\gamma} \right) \frac{d\sigma}{d\Omega_{\pi}}(\gamma d \rightarrow \pi^0 n) \frac{d\sigma}{d\Omega_{\pi}}(\gamma n \rightarrow \pi^0 p), \] 

where $u(0)$ is the S-wave amplitude of the DWF at zero momentum (the D-wave component of this function does not contribute at zero momentum), $q_\pi$ is the pion 4-momentum, $\mu$ is the pion mass, $p_p$ is the proton 4-momentum. $E'_\gamma$ is the lab photon energy corresponding to free-pion photoproduction

\[ E'_\gamma = \frac{(p_p + q_\pi)^2 - m^2}{2m} = E_\gamma - \frac{E_\gamma - E_b}{m}. \] 

In the case of quasi-free pion photoproduction on the neutron, one has a formula analogous to that of Eqs. 2 and 3 but with the replacement $p \leftrightarrow n$.

Equation 2 is valid for the pole diagram contribution (Fig. 4a) only. Therefore, in order to make Eq. 2 valid for practical applications the r.h.s. of this equation has to be multiplied by a factor $f(E_\gamma, \theta_\gamma) = d^3\sigma_{pol}/d^3\sigma_{tot}$ (see analogous discussion in Ref. 11). Here, $d^3\sigma_{pol}$ stands for the contribution of the pole (proton or neutron) diagram to the total differential cross-section $d^3\sigma_{tot}$ for which all the diagrams a)-f) have been taken into account.

5 Discussion of the Results

Results for the triple differential cross-section of the reaction $d(\gamma, \pi^0 p)n$ and $d(\gamma, \pi^0 n)p$ in CqPFP and CuQFP at $\theta^{lab}_{\pi} = 136.2^\circ$ are given in Tables 4 and 5 and displayed in Fig. 6. Also in this figure we show theoretical predictions in the framework of the model described above. The area filled by the curves gives the size of uncertainties of the theoretical model. One can see good agreement between the experimental data and theoretical predictions below 320 MeV. This agreement, however, vanishes above the $\Delta$-peak. At present we do not know the reasons responsible for the disagreement. For instance, the effect of $N\Delta$-interaction omitted in our theoretical model was shown in Ref. 49 to be of no importance in the $\Delta$-region at backward angles. Further theoretical efforts are needed to shed light on the above situation.

Using Eq. 2 with the correction factor $f(E_\gamma, \theta_\gamma)$ included, we can extract the free-nucleon cross-sections from the corresponding quasi-free data. It should be noted that the extracted free values are practically independent of the choice of the multipole analysis of pion photoproduction so that the only model dependence in these values stems from their sensitivity to the cut-off parameter $\Lambda_{\pi}$. After averaging over two sets of results for $\Lambda_{\pi} = 440$ and 1720 MeV we obtain the central numbers given in Tables 4 and 5 and displayed in Fig. 6 to which an uncertainty of about 4% due to the conversion from quasi-free to “free” according to Eq. 2 should be attributed. In Fig. 6 we also show the cross-sections measured with the hydrogen target (see
The CM differential cross-section of the free proton (upper figure) and free neutron (lower figure) at $\theta_{cm}^{\pi} = 147.5^\circ$. The present free data measured with hydrogen or deuterium targets are shown as filled circles. Data from Refs. [40] (□), [41] (△), and [42] (♦) are shown as empty circles. Solid and dashed curves represent results obtained from the MAID2001 and SM02K solutions, respectively.

Table 5 and compare them with the data obtained in other experiments [40, 41, 42] and with the predictions of the multipole analyses. Reasonable agreement between all data sets is seen up to the $\Delta$-peak. All of them fairly well correspond to the SM02K solution and are slightly above the predictions of the MAID2001 solution. However, above 320 MeV our quasi-free data points for the proton lie significantly below both all the free data and the multipole predictions. Of course, this has to be expected from the unsatisfactory description of the quasi-free data above 320 MeV mentioned above. The free-neutron cross-sections are consistent with the multipole predictions at all energies except for 377 MeV where the measured value is noticeably smaller than the predicted one.

As has been mentioned in the introduction, the experimental information on the $\gamma n \rightarrow \pi^0 n$ channel is very sparse. Up to now there has been only one measurement of the differential cross-section in the $\Delta$-region [6] which covered the angular region from 70° to 130°. In Fig. 8 we show the angular distribution of the cross-section at 300 MeV. One can see that the data from [6] and from the present paper are consistent with each other in the sense that they are in agreement with the predictions of the same multipole analyses. But a significant improvement in the accuracy of the present experiment in comparison with that of Ref. [6] is evident.

6 Conclusion

The energy dependence of the triple differential cross-section for $\pi^0$ photoproduction from the proton and neutron in deuterium and the free photoproduction cross-section from the proton have been measured in the same kinematics at $\theta_{lab} = 136.2^\circ$. For the first time accurate “free” cross-sections have been extracted for the proton and the neutron from the quasi-free data in the $\Delta$ region, using an extended model for the conversion developed in the present work. Applying this model to the proton “free” cross-sections are found to be in good agreement with the present and previously measured free cross-sections and in reasonable agreement with theoretical predictions based on multipole analyses below 320 MeV. For the neutron no previous data are available to compare with. The “free” neutron cross-sections obtained here also reasonably agree with theory up to 320 MeV. At higher energies there is significant disagreement for both proton and neutron which is not presently understood.

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Table 1. The energy dependence of the triple differential cross-
section of the reaction \(d(\gamma, \pi^0)p\) in CpQFP at \(\theta_{\text{lab}}^\gamma = 136.2^\circ\). The statistical error is given. The systematic experimental error amounts to 4.4%.

| \(E_{\gamma}, \text{MeV}\) | \(\frac{d^3\sigma}{d\Omega_{\pi^0}dE_{\pi^0}}\) CpQFP | \(\frac{\mu b}{\text{MeV sr}^2}\) |
|-------------------------|----------------|------------------|
| 254.3                  | 3.61 ± 0.04    |                  |
| 273.5                  | 5.42 ± 0.05    |                  |
| 292.7                  | 7.88 ± 0.05    |                  |
| 312.0                  | 9.67 ± 0.06    |                  |
| 331.2                  | 9.78 ± 0.07    |                  |
| 350.4                  | 8.66 ± 0.09    |                  |
| 369.4                  | 8.68 ± 0.09    |                  |
| 388.5                  | 5.27 ± 0.08    |                  |

Table 2. The energy dependence of the triple differential cross-
section of the reaction \(d(\gamma, \pi^0)n\)p in CnQFP at \(\theta_{\text{lab}}^\gamma = 136.2^\circ\). The statistical error is given. The systematic experimental error amounts to 9.0%.

| \(E_{\gamma}, \text{MeV}\) | \(\frac{d^3\sigma}{d\Omega_{\pi^0}dE_{\pi^0}}\) CnQFP | \(\frac{\mu b}{\text{MeV sr}^2}\) |
|-------------------------|----------------|------------------|
| 211.1                  | 0.33 ± 0.02    |                  |
| 230.2                  | 0.87 ± 0.03    |                  |
| 249.4                  | 1.80 ± 0.04    |                  |
| 268.7                  | 3.15 ± 0.06    |                  |
| 287.9                  | 5.64 ± 0.08    |                  |
| 307.2                  | 7.67 ± 0.10    |                  |
| 326.4                  | 8.96 ± 0.12    |                  |
| 345.6                  | 8.65 ± 0.15    |                  |
| 376.5                  | 6.50 ± 0.11    |                  |

Table 3. The energy dependence of the differential cross-
section of “free” proton \(\pi^0\) photoproduction extracted from quasi-free data at \(\theta_{\text{cm}}^\pi = 136.2^\circ\). The statistical error is given. The systematic experimental error amounts to 4.4%. The error of the conversion of quasi-free cross sections to “free” cross sections amounts to 4%.

| \(E_{\gamma}^f, \text{MeV}\) | \(\frac{d\sigma}{dE_{\pi^0}}\) \(\frac{\mu b}{\text{sr}}\) | \(\theta_{\text{cm}}^\pi\) [deg] | \(\frac{d\sigma}{d\Omega_{\pi^0}}\) \(\frac{\mu b}{\text{sr}}\) |
|-------------------------|----------------|----------------|----------------|
| 254.3                  | 5.32 ± 0.08    | 146.7          | 8.38 ± 0.13   |
| 273.5                  | 7.62 ± 0.11    | 146.9          | 12.13 ± 0.18  |
| 292.7                  | 9.79 ± 0.10    | 147.1          | 15.77 ± 0.16  |
| 312.0                  | 11.06 ± 0.12   | 147.3          | 18.07 ± 0.20  |
| 331.3                  | 9.89 ± 0.10    | 147.6          | 16.39 ± 0.17  |
| 350.4                  | 7.91 ± 0.09    | 147.9          | 13.31 ± 0.15  |
| 369.4                  | 5.70 ± 0.08    | 148.1          | 9.74 ± 0.14   |
| 388.5                  | 4.08 ± 0.07    | 148.4          | 7.08 ± 0.12   |
| 407.4                  | 2.96 ± 0.06    | 148.7          | 5.22 ± 0.11   |
| 427.3                  | 2.10 ± 0.05    | 149.0          | 3.76 ± 0.09   |
| 448.3                  | 1.46 ± 0.04    | 149.3          | 2.66 ± 0.07   |
| 469.0                  | 1.11 ± 0.04    | 149.5          | 2.06 ± 0.07   |
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