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PHOTOPRODUCTION OF PIONS OFF NUCLEONS AND NUCLEI

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1. Studies of pion photoproduction off nucleons and nuclei are now an extensive branch in the intermediate energy nuclear physics. Photopion nuclear physics combines two of the most active areas of the intermediate energy nuclear physics research. The first one is electromagnetic phenomena and the second one is mesonic effects in nuclei. In general, of interest here is the use of the electromagnetic interaction to study the pionic properties of nuclei.

The initial pion production stage involves knowledge of photoproduction of pions off single nucleons, the final stage requires understanding of the way pions scatter off nuclei, while the transition of a nucleus between initial and final states is the subject of the electron scattering studies. Each of these three stages is a subject of an independent and extensive investigation. A great deal of information is accumulated at each stage and they are well enough understood. Thus, when combined together they should describe the pion photoproduction off nuclei.

How the matter is going on in reality is just the subject of the present report. The most developed area in studies of the pion photoproduction off nuclei is transitions to discrete states of residual nuclei in the energy range of photons up to 350 MeV. For this reason our discussion will be concentrated on this topic.

2.1. For a long time elementary reactions $\gamma N \to \pi N$ have been an active area of research in the particle physics. In the Δ_{33}-resonance region multipoles have been accurately determined and their analysis in the framework of dispersive relations led to a fair understanding of the basic mechanisms rulling this reaction. Energy independent multipole analysis of experimental data performed by several groups leads to comparable sets of multipoles differing only in details.

For photon energies from the threshold through about 400 MeV only s- and p-pionic waves are important and the dominant multipoles are the electric dipole (E_{0+}) corresponding to the s-wave in the πN system and the magnetic dipole (M_{1+}) corresponding to the p-wave.

The multipole analyses are consistent with the prediction of dispersive relation calculations two of which are very popular, CGLN /1/ and BDW /2/. Both versions describe well enough the experimental (γ,π^+) data on free proton starting from the threshold up to 350 MeV.

An alternative way to treat the pion photoproduction off nucleons is to expand the amplitude in terms of few relevant diagrams and to use effective Lagrangians to describe the coupling of the photon with the pion, the nucleons and the nucleonic resonances. This line has been developed in Refs. /3,4/. Corresponding amplitude (BL) well enough reproduces the cross-section on proton, too.

The CGLN,BDW and BL amplitudes were a success in reproducing the (γ,π^0)-cross section in the Δ_{33} resonance region. However, the situation in the threshold region remains unclear until now. Let us discuss this point in some detail. The one--pion exchange diagram occurs only for the charge pion; the same is true for the seagull one. The nucleonic diagrams can-

cel each other for the neutral pions. As a result, the contribution of the Born terms to the $\pi^\pm$ photoproduction is large. For π^0 it gives only small correction terms. Thus the pion photoproduction amplitudes can schematically be written down as

$$\gamma + N \to N + \pi^\pm \qquad : \text{Born} + \Delta_{33}$$

$$\gamma + N \to N + \pi^0 \qquad : \Delta_{33} + \text{small non-resonant multipoles} + \omega^0\text{-exchange.}$$

2.2. So at the threshold the E_{0+} multipole is dominant for the $\pi^\pm$ photoproduction and very small for π^0 . For the threshold region, one has explicit expressions for the E_{0+} amplitudes derived from the Low Energy Theorem, namely Kroll--Ruderman one and PCAC

$$E_{0+}^{\pi^+}(q_\pi \to 0) \approx \sqrt{2}\,\frac{eg}{8\pi M_N}\left(1 - \frac{3}{2}\,\frac{m_\pi}{M_N}\right), \tag{1}$$

$$E_{0+}^{\pi^-}(q_\pi \to 0) \approx \sqrt{2}\,\frac{eg}{8\pi M_N}\left(-1 + \frac{1}{2}\,\frac{m_\pi}{M_N}\right), \tag{2}$$

$$E_{0+}^{\pi^0}(q_\pi \to 0) \approx \frac{eg}{8\pi M_N}\left(-\frac{m_\pi}{M_N} + \frac{\mu_p + 2}{2}\left(\frac{m_\pi}{M_N}\right)^2\right). \tag{3}$$

The numerical value of $E_{0+}^{\pi^0}$ from (3) is 2.4; from BL, 2.4; from the dispersive relations with non-resonant amplitudes, 1.52 /5/; from the Pade approximation, 0.88 /5/; and from BDW, 0.1. Experiments give the values -0.5 $\pm$ 0.3 /6/ and -0.2$\pm$0.1 /7/ (preliminary). So for π^0 there is a serious discrepancy between the experimental value and the predictions based on the Low Energy Theorems (LET).

What is the reason for violation of LET?

i) It could be that the contribution of pion charge-exchange diagram is not negligible .

According to Ref. /8/, the effective Lagrangian model can still be used for π^0 production at the threshold region, provided that near the threshold the $\vec{\sigma}\cdot\vec{\varepsilon}$ term in the amplitude for neutral pions is multiplied by the factor

$$1+\frac{i}{\sqrt{2}\, m_{\pi^+}}\sqrt{\beta^2(m_{\pi^\pm})}\; I^{\pm}, \qquad (4)$$

where $I^+ = 8.0$ ($\gamma p \to p\pi^0$) and $I^- = 8.5$ ($\gamma n \to n\pi^0$) and

$$\beta(m_{\pi^\pm}) = 2M_N m_\pi(\omega - M_N - m_\pi)/(M_N + m_\pi) \qquad (5)$$

is on-shell (in c.m. frame) momentum of the intermediate pion. So one needs a numerical estimation of this effect.

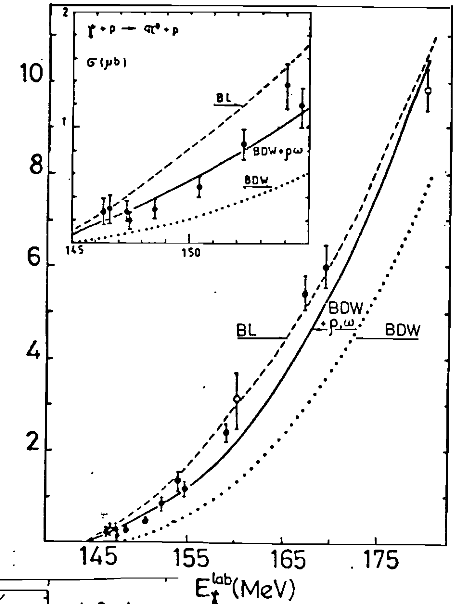
ii) Certainly, there is a contribution of ρ_0- and ω_0 mesons to the s-wave amplitude of the π^0 photoproduction. According to Ref. /9/, taking into account their contribution through a pole term in the dispersive relations at a fixed value of t, one gets

$$E_{0+}^{\pi^0}(V)=\frac{e}{8\pi\omega}\sum_{\alpha=\rho_0,\omega_0}\frac{g_{\alpha\pi\gamma}}{m_\alpha^2+m_{\pi^0}^2}\left(m_\alpha^2 G_\alpha^T - m_{\pi^0}^2 G_\alpha^V\right), \qquad (6)$$

where $g_{V\pi\gamma}$ is the $V\to\pi\gamma$ decay constant, G_α^V and G_α^T are the vector and tensor coupling constants. For reasonable values of coupling constants the vector meson contribution to $E_{0+}^{\pi^0}$ becomes of the same order of magnitude as due to LET.

In Fig. 1 the cross-sections of the (γ,π^0) reaction on a proton are calculated with the BL (Boisted-Laget) /4/, standard BDW /2/ and modified BDW /9/ amplitudes. Note that i) the BL amplitude does not contain the factor (4) and ii) the contribution of the vector mesons in the modified BDW-amplitude is

Fig.1. The π^0-photoproduction cross sections on the proton calculated in Ref./9/ using the BL /4/, BDW /2/ and (BDW+ω,ρ) /9/ amplitudes. Experimental data from Ref./6/ (♦) and Ref./10/ (ϕ).



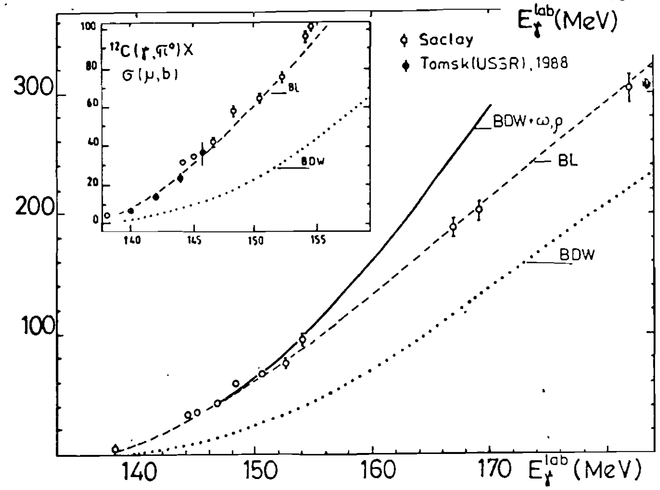


Fig.2. Coherent π^0-photoproduction of ^{12}C at the threshold. DWIA calculations are based on the BL, BDW and (BDW+ω,ρ) amplitudes. Experimental points are from Ref./12/ (ϕ) and Ref. /13/ (♦).

included with the following set of coupling constants: $G_\omega^V=15$, $G_\omega^T=0$; $G_\rho^V=2.6$, $G_\rho^T=15.9$. The BL-results overestimate the experimental data at the threshold whereas the modified BDW one reproduces it well. To clearify this problem one needs a thorough analysis of the threshold region including experimental data for the angular distribution too.

2.3. Much information on the elementary process has recently been added when the inverse reaction $\pi^- p \to n\gamma$ has been measured /11/. The BL amplitude gives an adequate fit to the data but there are deviations up to 15%. It means that an improved set of amplitudes is to be produced and all the new results should be taken into account simultaneously.

3. Exciting results obtained for the π^0-photoproduction on the proton stimulated further investigations of this reaction on complex nuclei. The most accurate measurements have been performed on nuclei with an equal number of protons and neutrons, ^{12}C and ^{40}Ca /7,12-13/. The coherent transition cuts out the isoscalar spin-independent part from the full amplitude. This part does not contribute to the E_{0+} multipole and is determined completely by the magnetic multipoles M_{1+} and M_{1-}.

The BDW cross-sections underestimate the data, the (BDW+ +ρ,ω) results are in agreement with experiment at $E_\gamma < 155$ MeV (see Fig. 2). The BL (Bosted-Laget version) leads to a nice agreement. The calculations for ^{12}C have been done with the half-off-shell extrapolation of the elementary photoproduction amplitude (see Ref. /14/ and section 4 of this paper for details). The results are presented in Fig. 2. Note that in contrast with Ref. /15/ the present calculations have been performed

with the full unitary version of the BL-amplitude /3,4/ (Bosted--Laget version).

All nucleons in a nucleus are involved in the process of the coherent π^0-photoproduction. For this reason the reaction is to be sensitive to the behaviour of the pionic wave function inside the nucleus. So a possibility of obtaining information on the low-energy π^0 interaction with nuclei opens through the (γ, π^0)-reaction.

4. DWIA is the general method of calculating the (γ, π) reaction cross-sections for complex nuclei. In this method one neglects any dynamical modifications of the elementary operator by the nuclear medium. Full momentum space techniques are clearly preferred despite the difficulties with the Coulomb interaction since the full momentum dependence of the basic photopion operator can be included.

There are several techniques for momentum space calculations /16-18/. To our mind, the most consistent approach is that where both the pion scattering and the photoproduction are considered in the momentum space simultaneously, as it has been done in /16/ and /15/. In this case, starting from the Lippmann--Schwinger equations one obtains the following expression for the pion photoproduction amplitude:

$$F_{\pi\gamma}(\vec{q}_0,\vec{k}\lambda)=V_{\pi\gamma}(\vec{q}_0,\vec{k}\lambda)-\frac{A-1}{A}\frac{1}{(2\pi)^2}\int\frac{d\vec{q}}{m(q)}\frac{F_{\pi\pi}(\vec{q}_0,\vec{q})V_{\pi\gamma}(\vec{q},\vec{k}\lambda)}{\mathcal{E}(q_0)-\mathcal{E}(q)+i\varepsilon}. \quad (7)$$

The first term is the plane wave part of the amplitude. The pion-nucleus interaction in the final state is given by the second term through the pion-nuclear amplitude $F_{\pi\pi}(\vec{q},\vec{q}_0)$ which satisfies the integral equation

$$F'_{\pi\pi}(\vec{q},\vec{q}_0)=U_{opt}(\vec{q},\vec{q}_0)-\frac{1}{(2\pi)^2}\int\frac{d\vec{q}\,'}{m(q')}\;\frac{U_{opt}(\vec{q},\vec{q}\,')\,F'_{\pi\pi}(\vec{q}\,',\vec{q}_0)}{\mathcal{E}(q_0)-\mathcal{E}(q')+i\varepsilon}, \tag{8}$$

where

$$F'_{\pi\pi}(\vec{q},\vec{q}_0)=\frac{A-1}{A}\,F_{\pi\pi}(\vec{q},\vec{q}_0).$$

The details of the optical potential construction are discussed in Ref. /19,20/. U_{opt} contains the so-called first order optical potential constructed on the t-matrix of the πN-scattering. The second order optical potential is added to take into account the effects of true pion absorption.

According to the impulse approximation the plane wave part can be expressed through the elementary (on free nucleon) $t_{\pi\gamma}$ matrix and nuclear transition density $\rho_{no}(\vec{p}\,',\vec{p})$:

$$V_{\pi\gamma}(\vec{q},\vec{k}\lambda)=\int\rho_{no}(\vec{p}\,',\vec{p})\langle\vec{q},\vec{p}\,'|\,t^{\lambda}_{\pi\gamma}(\omega)\,|\vec{k},\vec{p}\rangle d\vec{p}\,d\vec{p}\,', \tag{9}$$

where ω is the reaction energy and is equal to the full energy of the πN system in the c.m. frame for the free nucleon

$$\omega=E_{\pi}(\vec{q}_{c.m.})+E_N(\vec{q}_{c.m.}). \tag{10}$$

For the photoproduction off nucleus one needs already to know the off shell behaviour of $t_{\pi\gamma}$. Very often it is given by the relation

$$t_\ell(\omega)=t_\ell(z)\,g^{(\ell)}_{\pi N}(q_{c.m.})/g^{(\ell)}_{\pi N}(q_z), \tag{11}$$

where q_z and $q_{c.m.}$ are the pion momenta in the c.m. frame, which correspond to the total energy z and ω, respectively, and $g^{(\ell)}_{\pi N}(q)=q^\ell/(1+\alpha q^2)^2$ with $\alpha=0.224\ \mathrm{fm}^2$.

Using the extrapolation given by (11) we arrive at a new free parameter $z(q_z)$. It is not clear how this parameter is

coupled to the pion-nuclear energy. There are different suggestions

$$\begin{aligned} z_0&\equiv\omega_i=\left[(E_\gamma+E_N(\vec{p}))^2-(\vec{k}+\vec{p})^2\right]^{1/2},\\ z_1&=\left[m_\pi^2+M_N^2+2E_\pi(\vec{q}_0)E_N(\vec{p}\,')-2\vec{q}\cdot\vec{p}\,'\right]^{1/2},\\ z_2&\equiv\omega_f=\left[(E_\pi(\vec{q})+E_N(\vec{p}\,'))^2-(\vec{q}+\vec{p}\,')^2\right]^{1/2}. \end{aligned} \tag{12}$$

A large effect due to this ambiguous situation arises when t_ℓ is strongly energy-dependent. This is a case for the M_{1+} amplitude in the resonance region.

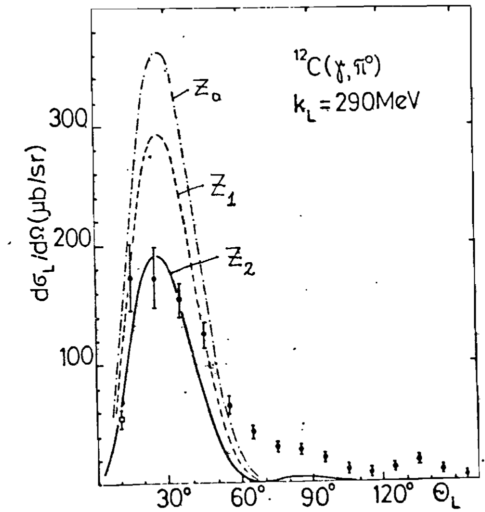
Different possibilities of choosing z have been investigated for the pion elastic scattering in Ref. /21,22/ and for the (γ,π^0)-reaction in Ref. /14/. The best agreement with experimental data has been achieved when $z=z_2=\omega_f$ (the so-called half-of-shell extrapolation, see Fig. 3).

It is necessary to say that due to the strong energy dependence of the multipoles in the Δ_{33}-region the correct inclusion of the nucleon Fermi-motion becomes of great importance. This motion has been taken into account by the factorization approximation when the nucleonic momenta in the elementary t-matrix are substituted by their effective values according to

$$\vec{p}=-\frac{\vec{k}}{A}-\frac{A-1}{2A}(\vec{k}-\vec{q}) \quad\text{and}\quad \vec{p}\,'=-\frac{\vec{q}}{A}+\frac{A-1}{2A}(\vec{k}-\vec{q}). \tag{13}$$

The corresponding DWIA method is usually called the "<u>local DWIA</u>". The approximation (13) works well in general but nucleon non-localities may manifest themselves in some specific transition /17/ (for example in the $^{14}N\,(\gamma,\pi^+)\,^{14}C_{g.s.}$ reaction).

Fig. 3. Angular distribution for coherent $^{12}C(\gamma,\pi^0)$ reaction at E_γ^L = =290 MeV. DWIA-calculations /14/ have been done with the BD-amplitude /23/ and with the reaction energies using eq.(12). Experimental points are from Ref./24/.



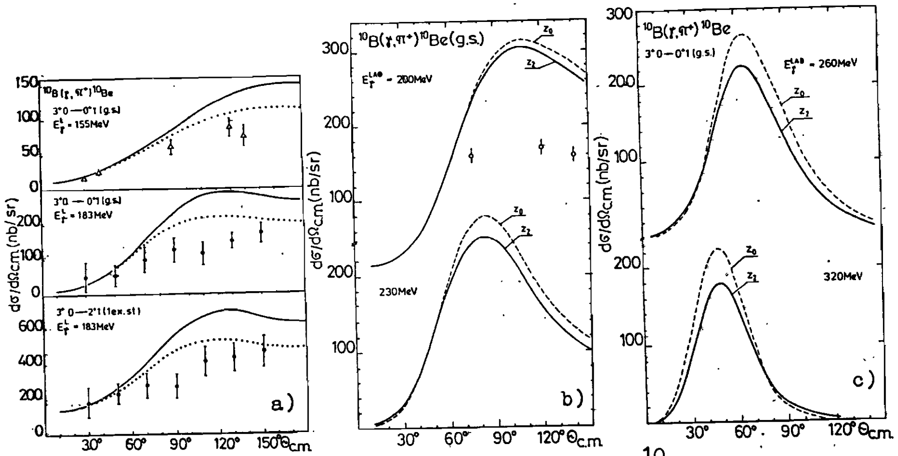


Fig. 4. Angular distribution for the $^{10}B(\gamma,\pi^+)^{10}Be$ reaction. Local DWIA calculations have been done with the BD-amplitude. Different reaction energies are used: (solid and dashed lines). Dotted lines - calculations with the Δ -excitation omitted. Experimental points are from Refs. /25/ (⍖), /26/ (⍿) and Ref. /27/ (⍗).

5. We have discussed all ingredients of the problem of pion photoproduction off nuclei and in some cases have checked them by comparing with experimental data. Now we will discuss some examples illustrating how a matter is going on.

5.1. The situation with transition to the ground state ^{10}Be in the (γ,π^+) reaction on ^{10}B is very simple, only one nuclear matrix element contributes which can be taken from the electron scattering data. The cross-sections calculated in the framework of our local DWIA method are shown in Fig. 4 for two versions of Z. As comes from the preliminary experimental data obtained by J.A.Nelson and A.M.Bernstein (MIT/RPI) Z_2 is preferable just as in the (γ,π^0)-reaction at $E_\gamma^L \gtrsim 230$ MeV. Boyarkina's wave functions have been used (r_0 = 1.64 fm) in the calculation of matrix elements.

However, at the same time the calculated cross-sections at $E_\gamma^L \lesssim 200$ MeV overestimate the measured ones (Fig. 4a,b). The same situation takes place in the case of more complicated (due to the contribution of several matrix elements) transition on the first excited state of ^{10}Be. If one suppresses the Δ - contribution, the agreement with experimental data will be improved. Maybe, some kind of medium modification of the Δ - isobar in nuclei arises in accordance with the isobar-hole /28/ and isobar-doorway /30/ models. This topic is very interesting and needs careful study.

5.2. Charged pion photoproduction on ^{16}O is a more complicated case because it combines transitions on four bound states simultaneously. Let us mention one peculiar situation: on shell version of DWIA /16/, where all kinds of shell effects are excluded (the so-called K-matrix approximation when one neglects the principal value of the integral in exp. (7)), gives the best agreement with experimental data both at high and low energies (see Fig. 5). In this case the partial nuclear photoproduction amplitude $F^{L_\pi}_{\pi\gamma}(q_0,\kappa\lambda)$ has the same structure, as follows from the Fermi-Vatson theorem

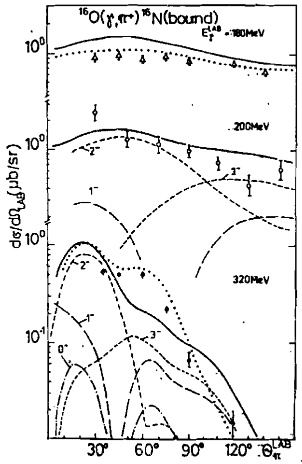
$$F^{L_\pi}_{\pi\gamma}(q_0,\kappa\lambda)=V^{L_\pi}_{\pi\gamma}(q_0,\kappa\lambda)\,e^{i\delta_{L_\pi}}\cos(\delta_{L_\pi}), \qquad (14)$$

where $\delta_{L_\pi}=\delta^{S}_{L_\pi}+\delta^{C}_{L_\pi}$ is the sum of the strong and Coulomb nuclear phase shifts. All calculations of the matrix elements have been done using the wave functions of Ref. /36/ (r_0 = 1.77 fm).

5.3. At present, the transition to the ground state of ^{14}C in the (γ,π^+) reaction on ^{14}N is discussed very intensively /17,33-35/. The matrix element of the $\sigma\tau$ operator is suppressed here /34/. So the weak terms of the amplitude become important. It could be that their estimation needs precise knowledge of nuclear wave functions. At the same time, this transition is very sensitive to different descriptions of the pion-nucleus interaction /33/. Therefore, a lot must be done to understand the situation in this reaction.

5.4. The contradictory situation appears when interpreting nuclear transitions to the ground states in the π^--production off ^{13}C and ^{15}N. In both the cases, one can expect that at forward angles nuclear E0 form factor is dominant whereas at larger angles M1 dominates. The situation is very similar to the free neutron case. Indeed, in the first approximation one can consider ^{13}C as a neutron above the ^{12}C core and ^{15}N as

Fig.5. Angular distribution for the $^{16}O(\gamma,\pi^+)^{16}N$ (bound) reaction. Solid lines - local DWIA calculations with BD-amplitude and with the reaction energy $\mathcal{E}=\mathcal{E}_{2}(\vec{q})$ from exp. (14). Dotted line - on-shell DWIA calculations by exp.(13). Experimental points are from Refs. /30/ (ɸ), /31/ (ɸ) and Ref./32/ (ɸ).



a proton hole in the ^{16}O core. So their response has to be more or less the same. However, in the experiment E0 multipole is seen only in the last nucleus. This is unexpected and the reason for such a different response is unclear.

6. We have discussed different aspects of pion photoproduction off nucleons and nuclei. More deep understanding of the elementary process came after a series of new measurements. It seems that theory succeeds in describing coherent processes realized in the π^0 photoproduction on nuclei. The same is true for charged pion photoproduction off ^{10}B in the resonance region. However, there are some other transitions of a more complicated nature which cannot be reproduced in the theory.

Both theoretical and experimental activities in this field seem to result in accumulating new information to resolve the existing problems.

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