Spectator isobar production in the $A(\gamma,\pi NN)B$ reaction

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Abstract

We present an analysis of the spectator mechanism of $\Delta$-isobar production in the pion photoproduction on nuclei with the emission of two nucleons. The reaction mechanism is studied within the framework of the $\Delta N$-correlation model, which considers the isobar and nucleon of the $\Delta N$-system produced in the nucleus at the virtual $NN \rightarrow \Delta N$ transition, to be in a dynamic relationship. The two-particle transition operator for nuclei is obtained by the $S$-matrix approach. We consider the properties of the spectator mechanism of isobar production using the example of the reaction $^{16}\text{O}(\gamma, \pi^-pn)^{14}\text{O}$. Numerical estimates of the cross section are obtained in the kinematic region, where it is possible to expect the manifestation of bound isobar-nuclear states.

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1 Introduction

In the impulse approximation the amplitude of the nuclear reaction $A(a,a')bC$, accompanied by the two-particle fragmentation of the nucleus $A$, is the sum of two terms. Each term describes the reaction mechanism, in which the incident particle interacts with one of the fragments and the other nuclear fragment (spectator) does not participate in that interaction. The terms describing the interaction of a particle with light and heavy fragments are usually called the direct and exchange amplitudes, respectively [1]. Data from nuclear reactions of the type $A(e,e'p)B$ and $A(p,2p)B$, measured in the kinematic region where the direct amplitude dominates, are an important source of information on single-particle properties of the nuclear shell structure [2, 3]. The kinematic region of the exchange reaction mechanism is, as a rule, outside the measurement capabilities of experimental setups, in which the identification of the reaction events is carried out by detecting two fast particles. An exception to this rule is the case when the spectator is a nucleon resonance (isobar).

The isobar as spectator is possible in the framework of a model in which the wave function of the nucleus includes both nucleon and isobar configurations. According to this model, some
nucleons in the ground state of the nucleus can experience internal excitation and go through a process $NN \rightarrow \Delta N$ resulting in a virtual isobar state \[4, 5, 6\]. Such isobars can be knocked out of the nucleus by a high-energy particle. The isobar knock-out is possible both in the direct interaction of the incident particle with the isobar, and as a result of the exchange (spectator) reaction mechanism, in which the incident particle interacts with the nucleon core of the nucleus. The isobar, which did not participate in the interaction, goes into a free state as a result of "shaking".

Direct isobar knock-out from the nucleus has been studied both experimentally and theoretically, see for example \[7, 8, 9, 10\]. The spectator mechanism of isobar production has been analysed until recently only in reactions on the lightest nuclei \[8, 11, 12\].

The purpose of studying isobar configurations in the ground state of nuclei is to obtain information, on the one hand, about the high-momentum component of the wave function of the atomic nucleus, and on the other hand, about the behavior of $\Delta$-isobars in a nuclear medium. One interesting aspect of $\Delta$-nuclear physics is the question of the existence of bound isobar-nuclear states, the states of the nucleus in which one of the nucleons is replaced by a "real" isobar (near the mass shell). The excitation energy of such nuclei ($\Delta$-nuclei) can be $\sim 300$ MeV. Decay of a $\Delta$-nuclei is possible by emission of a pion-nucleon pair, or two nucleons as a result of the transition $\Delta N \rightarrow NN$.

One of the manifestations of a $\Delta$-nuclei in the nuclear reaction is the detection of a pion and a nucleon, which fly out in opposite directions with a small total momentum. Based on such features, and assuming the existence of a $\Delta$-nuclei, the data of the reactions measured in experiments on the MAMI microtron in Mainz \[13\] and the Tomsk synchrotron \[11\] were interpreted. Some signs of the $\Delta$-nuclei are also observed in data from other experiments \[15\]. It should be noted that theoretical estimates of the possibility of the existence of a $\Delta$-nuclei are contradictory \[16, 17, 18\].

One of the problems associated with identifying such exotic nuclear states is the determination of the reaction mechanisms that could imitate them. From general physical concepts, it follows that the spectator $\Delta$-isobar production can imitate the excitation of a $\Delta$-nucleus. This mechanism of isobar production was proposed in the Ref. \[19\]. The aim of this paper is to develop further this model for the isobar production and to study its properties in the kinematic region, where it is possible to expect the manifestation of bound isobar-nuclear states.

The paper is arranged as follows: In Sec. 2 the transition matrix for the spectator mechanism of $\Delta$-isobar production in the $A(\gamma, \pi NN)B$ reaction is given. The two-particle transition operator is obtained in Sec. 3. Compared with Ref. \[19\] we start from the relativistic approach for the working-out of the transition operator. The detail analysis of the spectator mechanism of $\Delta$-isobar production in the $^{16}O(\gamma, \pi^-pn)^{14}O$ reaction is made in Sec. 4. The analysis of the reaction mechanism is performed within the framework of the $\Delta N$-correlation model \[10\].

## 2 Nuclear transition matrix

The differential cross section for the $A(\gamma, \pi NN)B$ reaction is written in the laboratory system of coordinates as

$$
\frac{d\sigma}{dE_{\gamma}} = (2\pi)^4 \delta (E_{\gamma} + M_T - E_{\pi} - E_{n1} - E_{n2} - E_B) \delta (p_{\gamma} - p_{\pi} - p_{n1} - p_{n2} - p_B) 
$$

$$
\times |T_{fi}|^2 \frac{d^3p_{\pi} d^3p_{n1} d^3p_{n2} d^3p_B}{(2\pi)^3 (2\pi)^3 (2\pi)^3 (2\pi)^3},
$$

2
where \((E_\gamma, p_\gamma), (E_\pi, p_\pi), (E_{n1}, p_{n1}), (E_{n2}, p_{n2}), (E_B, p_B)\) are 4-momenta of the photon, pion, two free nucleons, and the residual nucleus \(B\), \(M_T\) is the mass of the nucleus \(A\), and \(T_{fi}\) is the transition matrix.

Within the framework of the formalism developed in Ref. [10], the matrix of the transition from the initial state containing the photon and the nucleus \(A\), to the final state including the pion, two free nucleons, and the residual nucleus \(B\), is represented as follows:

\[
T_{fi} = \frac{A(A-1)}{2} \int d\left(\mathbf{X}_1', \mathbf{X}_2' \mathbf{X}_1, \mathbf{X}_2, ..., \mathbf{X}_A\right) \\
\times \Psi_F^*\left(\mathbf{X}_1', \mathbf{X}_2', \mathbf{X}_3, ..., \mathbf{X}_A\right) \langle X_1', X_2' | t_{\gamma\pi} | X_1, X_2 > \Psi_i\left(\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3, ..., \mathbf{X}_A\right).
\]  

(1)

Here, \(\Psi_i\) is the wave function of the nucleus \(A\), in which some of the baryons are in the isobar state, \(\Psi_F\) is the wave functions of the finite nuclear system, which includes the two free nucleons and the residual nucleus \(B\), \(X \equiv (x, m) \equiv (r, s, t, m)\) is the complete set of coordinates characterising the position of the baryon in the ordinary space \((r)\), spin space \((s)\), isotopic space \((t)\), and in the space of internal states \((m)\), \(t_{\gamma\pi}\) is a two-body operator for pion production from nuclei with the emission of two nucleons, and the integral sign denotes integration over space variables and summation over spin and isotopic variables and over the variables of the internal state of baryons.

In the framework of this approach, the wave function of the system of \(A\) baryons is written in the form [20]

\[
\Psi\left(\mathbf{X}_1, ..., \mathbf{X}_A\right) = A_m \phi_{N_1...N_A} (m_1, ..., m_A) \psi_{N_1...N_A} (x_1, ..., x_A),
\]

where \(\phi_{N_1N_2...N_A} (m_1, m_2, ..., m_A)\) is the function describing the internal states of baryons. The state indices take the values \(N\) (nucleon) or \(\Delta\) (isobar). The wave function describing the state of baryons in the space \((r)\) and spin \((s)\) and isotopic \((t)\) spaces is \(\psi_{N_1N_2...N_A} (x_1, x_2, ..., x_A)\), and \(A_m\) is the antisymmetrization operator. The operators of the pion production \(t_{\gamma\pi}\), acting in the spaces of the coordinates \(x\) and \(X\), are related by the equation

\[
\langle x_1', x_2'| t_{\gamma\pi} | x_1, x_2 > = \sum_{m_1', m_2'} \phi_{NN}^* (m_1', m_2') \langle X_1', X_2'| t_{\gamma\pi} | X_1, X_2 > \phi_{NN} (m_1, m_2).
\]

According to the \(\Delta N\)-correlation model, the wave function \(\Psi_i\) of the initial nucleus \(A\) is represented as an antisymmetrized product of the wave function \(\Psi_{\beta_1\beta_2\beta_3...\beta_{12}}\) of the \(\Delta N\) system, which includes the isobar and nucleon produced at the virtual transition \(NN \rightarrow \Delta N\) of two nucleons in states \(\beta_i\) and \(\beta_j\), and the wave function \(\Psi_{(\beta_i\beta_j)^{-1}}\) of the nucleon core [20]:

\[
\Psi_i\left(\mathbf{X}_1, ..., \mathbf{X}_A\right) = A_{123...A} \sum_{ij} \Psi_{\Delta A}^{N\Delta} (X_1, X_2) \Psi_{(\beta_i\beta_j)^{-1}} (X_3, ..., X_A),
\]  

(2)

where \(A_{123...A}\) is an antisymmetrization operator.

The matrix element \(T_{fi}\) [11] with the wave function \(\Psi_i\) [2] is the sum of terms, each of which corresponds to a certain reaction mechanism. Part of the possible mechanisms of the \(A(\gamma, \pi NN)B\) reaction, for which the initiating processes were \(\gamma\Delta \rightarrow N\pi\) and \(\gamma N \rightarrow N\pi\), were analysed in Ref. [10]. We will now consider the mechanisms of the reaction in which a photon is absorbed by a nucleus, with the initiating process being a transition \(\gamma N \rightarrow N\).

We will assume that the operator \(t_{\gamma\pi}\) describes the absorption of a photon by a nucleon 1, and that nucleon 2 appears as a result of the decay of the isobar \(\Delta \rightarrow N\pi\). Then, the spectator mechanism of the isobar production corresponds to the following components of \(T_{fi}\):

\[
T_{sp} = T_1 + T_2 + T_3.
\]
the "active" nucleon passes into a free state with a momentum $p_1$ into two nucleons with an emission of a pion, is written in the interaction representation as

$$\Psi_f^*(X_3, X_4, \ldots, X_A) < X_1', X_2' | t_{\gamma\pi} | X_1, X_2 > \sum_{ij} \Psi_{[\beta_i, \beta_j]}^N (X_1, X_2) \Psi_{(i, \beta_i)}^{-1} (X_1, X_4, \ldots, X_A),$$

where $\varphi_{\alpha_1 \alpha_2}^*$ is the antisymmetric wave function of the two free nucleons in states $\alpha_1$ and $\alpha_2$.

$$T_3 = - \left[ \frac{A(A-1)}{2} \right]^{1/2} (A-2) \int d(X_1', X_2' X_1, X_2, \ldots, X_A) \varphi_{\alpha_1 \alpha_2}^* (X_3, X_2') \times \Psi_{f'}^* (X_1', X_4, \ldots, X_A) < X_1', X_2' | t_{\gamma\pi} | X_1, X_2 > \Psi_{1} (X_1, X_2, X_3, \ldots, X_A),$$

with $\varphi_{\alpha_1 \alpha_2}^*$ the wave function describing the state of the residual nucleus $B$.

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Figure 1: Diagrams illustrating the spectator mechanisms of $\Delta$-isobar production in the $A(\gamma, \pi NN)B$ reaction.

The diagrams in Figs. [1], [11], and [13] illustrate the reaction mechanisms corresponding to the amplitudes $T_1$, $T_2$, and $T_3$. The reaction mechanisms corresponding to these amplitudes differ by the state of the nucleon that absorbed the photon. In $T_1$ and $T_2$ nucleon 1 goes into a free state, and in $T_3$ it remains in the nucleus in the bound state. Regardless of the reaction mechanism for knock-out of a virtual isobar from the nucleus, it is necessary that the incident particle transmit energy to the nucleus of about 300 MeV. This is accompanied by a transfer to the nucleus of momentum, the heavier the incident particle, the greater the magnitude of the momentum transfer. Even in the case of the $A(\gamma, \pi NN)B$ reaction, it is unlikely that the nucleon that absorbed the photon remains in the nucleus in the bound state. Therefore, the amplitude $T_3$ can be neglected. We will not consider also amplitude $T_2$ which value is $\sim (A-2)$ times less than amplitude $T_1$. In the case of amplitude $T_1$, on absorption of the photon by the nucleus, the "active" nucleon passes into a free state with a momentum $p_n$, the nucleon core receives a momentum equal to $p_n - p_n 1$. As a result, the virtual isobar becomes real and decays into a pion and nucleon.

### 3 Transition operator

The two-particle transition operator $t_{\gamma\pi}$ for nuclei was obtained following the $S$-matrix approach developed in Ref. [21]. The matrix element of the $S$-matrix, in the lowest order of perturbation theory, of the elemental process, where the $\Delta$-isobar and nucleon, which absorbs a photon, pass into two nucleons with an emission of a pion, is written in the interaction representation as

$$S_{fi} = < \alpha_x, \alpha_{n1}, \alpha_{n2} | \int d^4r \ A_\mu (r) \ J^\mu (r) | \alpha_\gamma, \alpha_n, \alpha_\Delta > .$$  (3)
Here, \( r \equiv (r, t) \), \( t \) is time, \( \alpha_\gamma, \alpha_\pi, \alpha_n, \alpha_\Delta \) are the state indices of the photon, pion, initial nucleon, and isobar, and \( A_\mu (r) \) is the 4-potential of the electromagnetic field,

\[
J^\mu (r) = i \int d^4r_1 \, d^4r_2 \, T \left( j^\mu (r) \, L_s^1 (r_1) \, L_s^2 (r_2) \right),
\]

where \( j^\mu (r) \) is electromagnetic current of the nucleons, the effective Lagrangian \( L_s^1 (r_1) \) describes the interaction of the nucleon, isobar, and pion, \( L_s^2 (r_2) \) effectively describes the transition of the isobar from the virtual state to the real state, and \( T \) is the time-ordering operator.

The electromagnetic current of the nucleons is written as

\[
j_\mu (r) = - e \, \bar{\psi}_N (r) \, \gamma_\mu \, I_e \, \psi_N (r) + \frac{e}{2M_N} \frac{\partial}{\partial r_\mu} \left( \bar{\psi}_N (r) \, I_m \, \sigma_{\mu \nu} \, \psi_N (r) \right),
\]

where \( e \) is the electron charge, \( \psi_N \) is the nucleon field operator, \( \gamma_\mu \) is Dirac matrix, \( \sigma_{\mu \nu} = (\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu) / 2 \), and

\[
I_e = \frac{1 + \tau_3}{2}, \quad I_m = \frac{\mu_p + \mu_n}{2} + \frac{\mu_p - \mu_n}{2} \tau_3.
\]

Here, \( \mu_p, \mu_n \) are the magnetic moments of the proton and neutron in Bohr magnetons, \( \tau_3 \) is Pauli matrix.

The effective Lagrangian \( L_s^1 (r) \), describes the transition \( \Delta \rightarrow N\pi \)

\[
L_s^1 (r) = g_{\Delta N \pi} \frac{\partial}{\partial r_\mu} \phi_\pi (r) \, \bar{\psi}_N (r) \, \Gamma^\mu \, T^+ \, \psi_\Delta^\mu (r),
\]

where \( g_{\Delta N \pi} \) is the \( \pi N \Delta \) coupling constant, \( \Gamma_{\mu \nu} = (g_{\mu \nu} + C \, \gamma_\mu \gamma_\nu) / 2 \), \( C = -1/4 \), \( T^+ \) is the transition operator between states with isospins \( 3/2 \) and \( 1/2 \), \( \phi_\pi \) is the pion field operator, and \( \psi_\Delta^\mu \) is the field operator of a real isobar with spin and isospin \( 3/2 \). The effective Lagrangian describing the transition of the isobar from the virtual state to the real state is used in the form

\[
L_s^2 (r) = g \left( \bar{V}_\Delta \, (r) \, \psi_\Delta^\mu (r) + \bar{\psi}_\Delta (r) \, V_\Delta^\mu (r) \right),
\]

where \( g \) is the transition constant (equal to unity in the spectator model), and \( V_\Delta^\mu \) is the operator of the virtual isobar field.

Reducing the \( T \)-product of the operators in \( \langle 3 \rangle \) to the normal form, we obtain the sum of the terms whose matrix elements describe definite physical processes. The matrix element of the two-particle transition operator in momentum space, which corresponds to the spectator mechanism of the reaction, is determined by the matrix element of the \( S \) matrix, represented by the Feynman diagram in Fig. \( \langle 2 \rangle \). The representation of the matrix element of the transition operator in configuration space \( S_{sp} \), obtained by doing a Fourier transform on each baryon momentum, is given by

\[
S_{sp} = \delta \left( r'_1 - r_1 \right) \, \delta \left( r'_2 - r_2 \right) \times \\
\sqrt{\frac{M_N}{E_{n_1}}} \, \bar{u}_{m_{n_1}} (p_{n_1}) \, \xi_{m_{n_1}}^+ (p_\gamma) \, \sqrt{\frac{M_N}{E_{n_1}}} \, u_{\bar{m}_{n_1}} (\bar{p}_{n_1}) \, \xi_{\bar{m}_{n_1}} \, e^{iE_{n_1}r_1} \, \epsilon'^\mu (p_\gamma) \times \\
e^{-iE_{\pi}r_2} \frac{\sqrt{M_N}}{E_{n_2}} \, \bar{u}_{m_{n_2}} (p_{n_2}) \, \xi_{m_{n_2}}^+ (p_\gamma) \, \sqrt{\frac{M_N}{E_{n_2}}} \, u_{\bar{m}_{n_2}} (p_{n_2}) \, \xi_{\bar{m}_{n_2}} \, \Gamma^\Delta (p_\gamma, p_\Delta) \, \sqrt{\frac{M_N}{E_{\Delta}}} \, u_{\bar{m}_{\Delta}} (p_\Delta) \, \xi_{\bar{m}_{\Delta}}.
\]
Here, $M_N$ and $M_{\Delta'}$ are the masses of the nucleon and virtual isobar, $u_m(p)$ and $w_n^m(p)$ are Dirac and Rarita-Schwinger spinors normalized as $\bar{u}u = 1$, $\xi_{m+1}^+$ and $\xi_{m-\Delta}$ are isotopic spinors of the nucleons and isobar, $\varepsilon^\mu(p)$ is the photon polarization 4-vector, $p_{\Delta} = p_\pi + p_n2$,

$$\Gamma_\mu^\gamma(p) = -e \left( \gamma_\mu I_e + \frac{i}{2M_N} \not\! p_\nu \sigma_{\mu\nu} I_m \right), \quad \Gamma_{\nu}(p, p_\Delta) = -p_\nu^\phi \Gamma_{\nu}^\mu(p_\Delta) \phi_\pi \cdot T^+, \quad$$

and $S_{\nu}^\mu(p_\Delta)$ is the $\Delta$-isobar propagator \[23\].

![Figure 2: Diagram representing the matrix element of the $S$ matrix corresponding to the spectator mechanism of isobar production.](image)

Passing to the nonrelativistic limit, accurate to terms on the order of $O(p/M)$, the operator $t_{\gamma\pi}$ was obtained in the form

$$t_{\gamma\pi} = \delta \left( \mathbf{r}'_1 - \mathbf{r}_1 \right) \delta \left( \mathbf{r}'_2 - \mathbf{r}_2 \right) \times \frac{e^{-ip_{\pi/2}}}{\sqrt{2E_\pi}} \frac{t_{\Delta N}^S t_{\Delta N}^I}{(E_{n2} + E_\pi)^2 + (p_{n2} + p_\pi)^2 - M_\Delta^2 + i \Gamma_\Delta M_\Delta} \left( t_{\gamma N}^S + \Gamma_{\gamma N}^I + t_{\gamma N}^I t_{\gamma N}^I \right) \frac{e^{ip_{\pi/2}}}{\sqrt{2E_\gamma}},$$

where

$$t_{\gamma N}^S(p, \varepsilon) = \frac{i e}{2M_N} \sigma \cdot p, \quad t_{\gamma N}^I = \frac{1 + \tau_3}{2},$$

$$t_{\gamma N}^{Sm}(p, \varepsilon) = \frac{-i e}{4M_N} \left( \sigma \cdot \varepsilon \sigma \cdot p_\gamma - \frac{1 + E_\gamma}{M_N} \sigma \cdot p_\gamma \sigma \cdot \varepsilon \right),$$

$$t_{\gamma N}^{Im}(p, \varepsilon) = \mu_p \frac{1 + \tau_3}{2} + \mu_n \frac{1 - \tau_3}{2},$$

$$t_{\Delta N}^{N}(p_\pi) = \frac{i f_{\Delta N}}{M_\pi} \left[ p_\pi \cdot S^+ - \frac{1}{3} \left( 1 + C^* \frac{E_\pi}{2M_N} \right) \sigma \cdot p_\pi \sigma \cdot S^+ \right],$$

$$t_{\Delta N}^I = \phi_\pi \cdot T^+. \quad$$

Here, $M_\pi$ is the mass of the pion, $\sigma$ is Pauli matrix, $S^+$ is the operator of the transition between states with spin 3/2 and 1/2.

### 4 Results and discussion

Let us consider the properties of the spectator mechanism of isobar production using as an example the reaction $^{16}\text{O}(\gamma, \pi^- p n)^{14}\text{O}$. The procedure for calculating the amplitude and cross section of the reaction is in many respects similar to that used in Ref. \[10\]. According to the proposed model, in this reaction the production of a negative pion is possible as a result of two processes with production of the isobar $\Delta^0$

$$\gamma + ^{16}\text{O} \rightarrow ^{14}\text{O} + n + \Delta^0 \quad (4)$$

with
and the isobar $\Delta^-$

$$\gamma + ^{16}O \rightarrow ^{14}O + p + \Delta^-. \quad (5)$$

This is followed by the subsequent decays $\Delta^0 \rightarrow p + \pi^-$ and $\Delta^- \rightarrow n + \pi^-$. Fig. 3 shows the differential cross section of the spectator isobar production in the $^{16}O(\gamma, \pi^-pn)^{14}O$ reaction versus the pion polar angle $\theta_\pi$. Solid curves: $\Delta^0$-isobar production. Dashed curve: $\Delta^-$-isobar production. Kinematic conditions: $E_\gamma = 500$ MeV, $p_\pi = 170$ MeV/c, $p_p = 470$ MeV/c, $\theta_n = 0^\circ$, curves 1 and 4: $\theta_p = 0^\circ$, curve 2: $\theta_p = 90^\circ$, curve 3: $\theta_p = 180^\circ$, $\phi_\pi = 0^\circ$, and $\phi_p = 180^\circ$.

The differential cross section of the $^{16}O(\gamma, \pi^-pn)^{14}O$ reaction due to the spectator mechanism of $\Delta$-isobar production as a function of the direction of pion emission. The calculations were performed in the plane wave approximation under the following kinematic conditions: $E_\gamma = 500$ MeV, the neutron emission angle with respect to the photon momentum is equal to $0^\circ$, and the pion and proton momenta are equal to

$$p_\pi = 170 \text{ MeV/c}, \quad p_p = 470 \text{ MeV/c}. \quad (6)$$

The polar angles of proton emission are equal to $0^\circ$ (curves 1 and 4), $90^\circ$ (curve 2), and $180^\circ$ (curve 3). The solid curves are the $\Delta^0$-isobar production cross sections and the dashed curve is the $\Delta^-$-isobar production cross section. As can be seen from the figure, the position of the maximum of the $\Delta^0$-isobar production cross section is correlated with the direction of proton emission. The cross section is maximal when the opening angle of the pion and proton is equal to $180^\circ$. On the other hand, the position of the maximum of the $\Delta^-$-isobar production cross section is correlated with the neutron emission direction. At the proton emission angles equal to $90^\circ$ and $180^\circ$, the cross section of the reaction $^{16}O(\gamma, \pi^-pn)^{14}O$ is almost entirely due to the contribution of the $\Delta^0$-isobar production process (4). The second process (5) is suppressed in connection with the extremely small Fourier component of the wave functions of the bound proton at momentum $\mathbf{p}_n = \mathbf{p}_n - \mathbf{p}_\gamma$ in the kinematic region considered. Thus, the spectator isobar production mechanism reproduces the distribution of the cross section by the opening angle of the pion and proton at the decay of the $\Delta^0$-isobar weakly bound in the $\Delta$-nucleus.

In the framework of a model that takes into account isobar configurations in the ground state of the nucleus [10], pion production is also possible through direct $A(\gamma, \pi NN)B$ reaction mechanisms. Fig. 4 shows diagrams illustrating direct mechanisms of the $^{16}O(\gamma, \pi^-pn)^{14}O$ reaction,
which lead to knockout nucleons with momentum sufficiently large for detection in experiment using standard methods. In Fig. 5 the cross sections of the direct and spectator pion productions, depending on the direction of momentum $p_{\Delta^0} = p_\pi + p_p$, are shown. Unlike the data in Fig. 3, the pion and proton fly in opposite directions: $\theta_\pi = 180^\circ - \theta_p$. In this case, for the momenta values \(6\), the directions of emission of the proton and $\Delta^0$ isobar coincide. Curve 3 in Fig. 5 is the coherent contribution to the cross section of the direct reaction mechanisms corresponding to the diagrams in Fig. 4a and Fig. 4b. Curve 4 is the contribution of the diagram in Fig. 4c. The cross sections of the spectator production of the $\Delta^0$ and $\Delta^-$ isobars are shown in Fig. 5 by curve 1 and curve 2, respectively. As can be seen, in the kinematical region considered, the $\Delta^0$-isobar production cross section is weakly dependent on $\theta_{\Delta^0}$ and dominates at the isobar emission angles, which are large $\sim 40^\circ$.

An important factor determining the identification of the reaction mechanism is the cross section distribution by the invariant mass of the particle system in the final state of the nuclear process under study. Fig. 6 shows the differential cross section of the reaction $^{16}\text{O}(\gamma, \pi^-\text{pn})^{14}\text{O}$
as a function of the energy $E_{ex}$, which is determined by

$$E_{ex} = M_{15OΔ} - M_{15O}. \quad (7)$$

Here, $M_{15OΔ}$ is the invariant mass of the system including the residual nucleus $^{14}O$, the proton and negative pion, and $M_{15O}$ is the mass of the nucleus $^{15}O$. The calculations are performed in the region dominated by the spectator mechanism of $\Delta^0$-isobar production: the neutron emits at an angle $0^\circ$ relative to the photon momentum, the polar angle of the pion emission is $90^\circ$, the proton emission angles are $60^\circ$ (curve 1), $90^\circ$ (curve 2), and $120^\circ$ (curve 3), and the proton momentum is $470$ MeV/$c$. These results can be compared with the empirical data obtained in four experiments.

![Figure 6: Differential cross section of the $^{16}O(\gamma, \pi^-pn)^{14}O$ reaction versus energy $E_{ex}$.](image)

In the experiment described in Ref. [13], the distribution of the cross section by the invariant mass of the pion-nucleon pair and the residual nucleus $^{11}C$, produced in the reaction $^{12}C(\epsilon, \epsilon'\pi^-p)^{11}C$, was measured. Narrow peaks in the cross section distribution were interpreted as manifestations of the $\Delta$-nucleus $^{12}C_{\Delta^0}$ in which one neutron is replaced by the $\Delta^0$-isobar. As a result, the excitation energy of the $\Delta$-nucleus $^{12}C_{\Delta^0}$, determined similarly to (7), was estimated. Based on data from the experiment described in Ref. [14], in which the $^{12}C(\gamma, \pi^-p)$ and $^{12}C(\gamma, \pi^-pp)$ reactions were investigated, the excitation energy of the $\Delta$-nucleus $^{11}B_{\Delta^0}$ was determined. As a result of the analysis of the $^{12}C(\gamma, \pi^+n)$ [24] and $^4\text{He}(\gamma, \pi^-p)$ [25] reaction data, an estimate for the excitation energy of the $\Delta$-nuclei $^{12}C_{\Delta^0}$ and $^4\text{He}_{\Delta^0}$ was obtained [15]. In Fig. 6 an energy interval, in which there are empirical data for the excitation energy of $\Delta$-nuclei, is marked by arrows. As can be seen, the $E_{ex}$ energy distribution of the cross section of the spectator mechanism overlaps with the available data for the $\Delta$-nuclei.

In Fig. 7 the dependence of the differential cross section of the $^{16}O(\gamma, \pi^-pn)^{14}O$ reaction, as a function of the isobar momentum $p_{\Delta^0}$, is shown. Within the framework of the spectator isobar production model, the dependence of the cross section on the momentum $p_{\Delta^0}$ is determined by a number of factors, including the momentum distribution of the virtual isobar in the ground state of the nucleus and the distribution of the phase space volume of the reaction, which limits the
Figure 7: Momentum distributions (right-hand ordinate) of the virtual isobar in the ground state of the nucleus $^{16}\text{O}$ (dash-dotted curve) and the “real” isobar in the $\Delta$-nucleus (dashed curve) and differential cross section of the $^{16}\text{O}(\gamma, \pi^-pn)^{14}\text{O}$ reaction (left-hand ordinate, solid curves) versus the isobar momentum $p_\Delta^0$. Kinematic conditions are the same as in Fig. 6, except for $\theta_p = 90^\circ$ and curve 1: $p_p = 470$ MeV/c, curve 2: $p_p = 570$ MeV/c, curve 3: $p_p = 620$ MeV/c.

From the considered properties of the $^{16}\text{O}(\gamma, \pi^-pn)^{14}\text{O}$ reaction, the dependence of the cross section on $p_\Delta^0$ appears to be the most critical feature, which makes it possible to identify the spectator mechanism of the reaction and the process of the $\Delta$-nucleus production. In Fig. 7, together with the cross sections, the momentum distribution of the virtual isobar in the ground state of the nucleus $^{16}\text{O}$ and the momentum distribution of the “real” isobar in the $\Delta$-nucleus are given. The “real” isobar momentum distribution was obtained under the assumption that the isobar was bound in the harmonic oscillator potential in the $s$-state with an oscillator parameter $\alpha_\Delta = \alpha_N \sqrt{M_\Delta/M_N}$ [26]. Here, $\alpha_N$ is the nucleon oscillator parameter. The virtual transition $NN \rightarrow \Delta N$ occurs in the nucleus with greater probability at large relative momentum of nucleons, while the capture by the nucleus of a real isobar in the bound state is possible at small isobar momentum. These circumstances will lead to essentially different dependences of the cross sections of these two processes on the total momentum of the pion-nucleon pair. It should be noted that the features of the cross section of the $A(\gamma, \pi N)$ reaction, interpreted in Ref. [15] as manifestations of $\Delta$-nuclei, were observed in the kinematic region, where the momentum of the pion-nucleon pair takes its minimum value.

5 Conclusions

The study of exotic states of nuclei, in which other strongly interacting particles besides nucleons are contained in the bound state, is an important source of information on hadron interactions. The hypernuclei (nuclei which include hyperons) are the most studied at present [27]. The study of $\eta$-meson nuclei continues [28], and the $\Delta$-nucleus study is in its infancy [29]. Most of the information that is supposedly related to $\Delta$-nuclei is obtained in experiments, which were performed within the framework of another paradigm. Therefore, the results of these experiments give rise to more
questions than clear answers about the possibility of the existence of exotic nucleus states. Based on the opinion that it is first of all necessary to make full use of the possibilities of previously tested methods for describing nuclear reactions when interpreting experimental data, we considered the reaction model caused by isobar configurations in the ground state of the nucleus. From the general concepts, the angular distributions of the pion-nucleon pairs produced at the decays of the isobar-spectator and the isobar, bound in the $\Delta$-nucleus, can be similar. Therefore, the aim of this work was to develop a model of the spectator isobar production and to study its properties.

An analysis of the spectator mechanism of isobar production is performed within the framework of the $\Delta N$-correlation model, which considers the isobar and nucleon of the $\Delta N$-system, produced in the nucleus at the virtual $NN \to \Delta N$ transition, to be in a dynamic relationship. The two-particle transition operator for nuclei $t_{\gamma\pi}$, was obtained by the $S$-matrix approach. A matrix element of the transition operator in momentum space followed from the Feynman amplitudes. The deduction of the transition operator in configuration space was made with the help of the Fourier transformation of each baryon momentum.

The analysis of the spectator mechanism of isobar production is made in the kinematic region, where the contribution to the cross section of this reaction mechanism is maximal. Numerical estimates of the reaction cross section make it possible to draw the following conclusions:

1. The spectator mechanism of isobar production in the $^{16}\text{O}(\gamma, \pi^{-}pn)^{14}\text{O}$ reaction dominates when the isobar emerges at an angle greater than $40^\circ$ with respect to the photon momentum;
2. The cross section of the spectator isobar production as a function of the opening angle of the pion and nucleon, produced at the isobar decay, has a characteristic maximum at an angle of $180^\circ$. This can imitate the decay of the bound $\Delta$-isobar;
3. The distribution of the cross section of the spectator isobar production over the excitation energy $E_{ex}$ overlaps with the available data for the $\Delta$-nuclei;
4. The dependence of the cross section of the $^{16}\text{O}(\gamma, \pi^{-}pn)^{14}\text{O}$ reaction on the momentum of the pion-proton pair is concentrated in the momentum interval which significantly exceeds the characteristic momentum of nucleons bound in the nucleus.

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