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Exchange interaction between intermediate $D_{13}(1520)$-hole and $S_{11}(1535)$-hole states in the near-threshold coherent η photoproduction from nuclei

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Abstract. Coherent η-meson photoproduction from nuclei is considered within an extended analogue of the Δ-hole model taking into account the configuration mixing of baryon-hole excitations of different sorts of baryons. Calculated integrated and differential cross-sections for reactions ${}^{12}\mathrm{C}(\gamma,\eta)^{12}\mathrm{C}_{\mathrm{g.s.}}$ and ${}^{16}\mathrm{O}(\gamma,\eta)^{16}\mathrm{O}_{\mathrm{g.s.}}$ demonstrate the important role of the exchange interaction between intermediate $D_{13}(1520)$-hole and $S_{11}(1535)$-hole excitations.

PACS. 14.20.Gk Baryon resonances with $S = 0$ – 14.40.-n Mesons – 25.20.Lj Photoproduction reactions – 27.20.+n $6 \leq A \leq 19$

Intensive theoretical investigations on the coherent η-meson photoproduction from nuclei [1–5] are motivated, to a great extent, by an expectation that, in spite of the dominant coupling of the $S_{11}(1535)$ resonance to the $N+\eta$ channel and very strong evidence of this resonance in the η-photoproduction cross-section on the nucleon, the role of this resonance in the coherent η-meson photoproduction from zero-spin and zero-isospin nuclei is small, due to a strong suppression of the isoscalar photoexcitation amplitude $\gamma+N \to S_{11}(1535)$. This circumstance seems to open a unique possibility to investigate other, resonant and non-resonant, mechanisms of the η-photoproduction under the conditions where they are not masked by intensive excitation and decay of the $S_{11}(1535)$ resonance. Recent MAMI measurements on the near-threshold η-photoproduction from ^{4}He [6] support this expectation.

Contrary to other theoretical studies in the field which are performed within the first-order impulse approximation, we come to the η-photoproduction problem extending the nuclear Δ-hole approach to higher baryon-hole resonances [7]. Earlier we considered on this way the reaction ${}^{12}\mathrm{C}(\gamma,\eta)^{12}\mathrm{C}_{\mathrm{g.s.}}$ and observed considerable enhancement of the coherent η-photoproduction cross-section in the near-threshold region when one takes into account mutual exchange interaction between intermediate $D_{13}(1520)$-hole and $S_{11}(1535)$-hole excitations [8]. To investigate further the role of this specific effect in production and decay of higher baryon resonances in nuclei we extend here our approach to other zero-spin and zero-isospin nuclei.

Formalism

The amplitude and differential cross-section for the coherent η-meson photoproduction

$$\gamma(\vec{k}_\gamma) \,+\, A \,\to\, \eta(\vec{k}_\eta) \,+\, A$$

via excitation of nuclear baryon-hole states $N^*h \equiv xh; x'h'; \ldots$ are given (taking into account possible application of these formulas to a general case of polarized photon beam) as follows:

$$T^J_{\lambda,\vec{k}_\gamma}(\vec{k}_\eta,\omega) = \sum_{xhx'h'} \langle \vec{k}_\eta | \delta H_{\eta N x} | xh \rangle \langle xh | G^J(\omega) | x'h' \rangle \langle x'h' | \delta H_{\gamma N x'} | \lambda, \vec{k}_\gamma \rangle, \quad (1)$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta_\eta,\phi_\eta) = \frac{1}{(4\pi)^2}\frac{k_\eta}{k_\gamma}\frac{1}{2}\sum_\lambda \left| \sum_J T^J_{\lambda,\vec{k}_\gamma}(\vec{k}_\eta,\omega) \right|^2 . \quad (2)$$

Here $\vec{k}_\gamma$, $\vec{k}_\eta$ are the photon and η-meson linear momenta in the initial and final states and λ stands for the photon polarization. J and ω are the total angular momentum of the excited target nucleus and its excitation energy.

The Green function responsible for propagation of the baryon-hole pair in nuclei,

$$G^J_{xh,x'h'}(\omega) = (\omega - \hat{M} - \hat{W})^{-1}_{xh,x'h'}, \quad (3)$$

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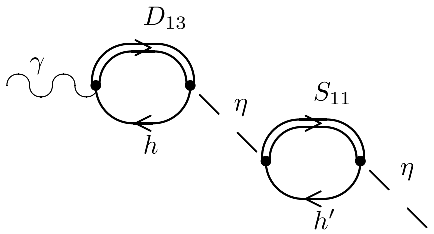
is calculated within the basis

$$|xh\rangle = |n_x l_x j_x, n_h l_h j_h : J\rangle, \quad x = D_{13}(1520),\, S_{11}(1535),$$

taking into consideration the η-exchange baryon-hole interaction $\hat{W}$



with matrix elements

$$W^J_{xh,x'h'} = \int \frac{\mathrm{d}^3\,\vec{q}}{(2\pi)^3} \frac{\langle xh|\delta H_{\eta Nx}|\vec{q}\rangle\langle\vec{q}|\delta H_{\eta Nx'}|x'h'\rangle}{\omega^2 - \vec{q}^2 - m_\eta^2 + i\delta}. \quad (4)$$

Matrix elements of the mass operator $\hat{M}$ contain the baryon and nucleon masses m_{N^*} and m_N, the hole-state energies ϵ_h and depend on the potential of the baryon-nucleus interaction V_{N^*A}. Following [9], the latter can be taken as proportional to the nuclear density $V_{N^*A}(r) = \Big(\rho(r)/\rho(0)\Big)V_0$ with V_0 used as fitting parameters for both resonances $D_{13}(1520)$ and $S_{11}(1535)$. As the first step to the problem and, also, taking into account that no information is available of the character of this interaction, we calculate here the mass operator $\hat{M}$ within the harmonic oscillator approximation

$$M_{xh,x'h'}(\omega) = \delta_{xx'}\delta_{hh'}\left[m_x - m_N + \epsilon_x - \epsilon_h - \frac{\mathrm{i}}{2}\Gamma_x(\omega)\right], \quad (5)$$

with the baryon single-particle energy

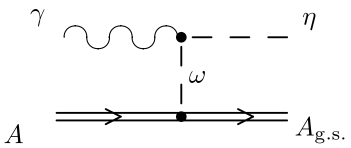
$$\epsilon_x = -V_{0x} + \hbar\omega_x(2n_x + l_x + 3/2), \quad (6)$$

and the free baryon decay width $\Gamma_x(E)$. The depth of the potential of the interaction between the baryons and the hole nucleus in $D_{13}(1520)$-hole and $S_{11}(1535)$-hole states is taken as in the Δ-hole model: $V_{0x} = 55$ MeV.

The total photoproduction amplitude is constructed as a sum of the resonant term (1) and the direct one not related to the production of the baryon-hole states

$$T_{\lambda,\vec{k}_\gamma}(\vec{k}_\eta,\omega) = T^{(\mathrm{res})}_{\lambda,\vec{k}_\gamma}(\vec{k}_\eta,\omega) + T^{(\mathrm{dir})}_{\lambda,\vec{k}_\gamma}(\vec{k}_\eta,\omega). \quad (7)$$

The ω-exchange amplitude



is the dominant direct term. In calculating this term the nuclear matter form factor $F(q)$ is taken corresponding to the standard Fermi distribution of nuclear density. Vertex constants $g^{\mathrm{v}}_{\omega NN} = 10$, $g_{\omega\eta\gamma} = 0.31$ for the diagram above are the same as in papers [3,4].

Mutual interaction and decay parameters of the $D_{13}(1520)$-hole and $S_{11}(1535)$-hole states

We use the effective Lagrangian approach [10] for the elementary processes $N + \gamma \to N^*$ and $N^* \to N + \eta$ exploring the nonrelativistic reduction of the corresponding operators

$$\begin{aligned}
\delta H_{\eta N D_{13}} &= i\frac{g_{\eta N D_{13}}}{2m_\eta M}(\vec{S}^\dagger\cdot\vec{k})(\vec{\sigma}\cdot\vec{k}) + \text{h.c.},\\
\delta H_{\eta N S_{11}} &= i g_{\eta N S_{11}} + \text{h.c.},\\
\delta H^{(1)}_{\gamma N D_{13}} &= -\frac{e g^{(1)}_{\gamma N D_{13}}}{2M}E_\gamma(\vec{S}^\dagger\cdot\vec{\epsilon}_{\lambda\vec{k}})\\
&\quad - i\frac{e g^{(1)}_{\gamma N D_{13}}}{4M^2}(\vec{S}^\dagger\cdot\vec{k})(\vec{\sigma}\times\vec{k})\vec{\epsilon}_{\lambda\vec{k}} + \text{h.c.},\\
\delta H^{(2)}_{\gamma N D_{13}} &= \frac{e g^{(2)}_{\gamma N D_{13}}}{4M}E_\gamma(\vec{S}^\dagger\cdot\vec{\epsilon}_{\lambda\vec{k}}) + \text{h.c.},\\
\delta H_{\gamma N S_{11}} &= -\frac{e g_{\gamma N S_{11}}}{2M}E_\gamma\left(1 + \frac{E_\gamma}{2M}\right)(\vec{\sigma}\cdot\vec{\epsilon}_{\lambda\vec{k}}) + \text{h.c.},
\end{aligned} \quad (8)$$

with the original form of the effective Lagrangians

$$\begin{aligned}
L_{\eta N D_{13}} &= \frac{g_{\eta N D_{13}}}{m_\eta}\bar{\Psi}^\mu_{D_{13}}\gamma_5\Psi_N\partial_\mu\varphi_\eta + \text{h.c.},\\
L_{\eta N S_{11}} &= -i g_{\eta N S_{11}}\bar{\Psi}_N\Psi_{S_{11}}\varphi_\eta + \text{h.c.},\\
L^{(1)}_{\gamma N D_{13}} &= i\frac{e g^{(1)}_{\gamma N D_{13}}}{2M}\bar{\Psi}^\mu_{D_{13}}\gamma^\nu\Psi_N F_{\mu\nu} + \text{h.c.},\\
L^{(2)}_{\gamma N D_{13}} &= \frac{e g^{(2)}_{\gamma N D_{13}}}{4M^2}\bar{\Psi}^\mu_{D_{13}}\partial^\nu\Psi_N F_{\mu\nu} + \text{h.c.},\\
L_{\gamma N S_{11}} &= \frac{e g_{\gamma N S_{11}}}{4M}\bar{\Psi}_{S_{11}}\gamma_5\sigma_{\mu\nu}\Psi_N F^{\nu\mu} + \text{h.c.},
\end{aligned} \quad (9)$$

and vertex constants of strong and electromagnetic interactions

$$\begin{aligned}
&g_{\gamma p S_{11}} = 0.73, \quad g^{(1)}_{\gamma p D_{13}} = 5.46, \quad g^{(2)}_{\gamma p D_{13}} = 5.76\\
&g_{\gamma n S_{11}} = -0.62, \quad g^{(1)}_{\gamma n D_{13}} = -0.97, \quad g^{(2)}_{\gamma n D_{13}} = 0.66\\
&g_{\eta N S_{11}} = 2.1, \quad g_{\eta N D_{13}} = 6.76,
\end{aligned} \quad (10)$$

taken from recent calculations by the Mainz and Giessen groups [3,4]. The mass operators (5) of the baryon resonances are calculated taking into account the specific energy dependence of partial components of their decay widths

$$\Gamma_{D_{13}}(s) = \Gamma^{(0)}_{D_{13}} \times\left(P^{D_{13}}_\eta\frac{q^5_{\eta(\mathrm{c.m.})}(s)}{q^5_{\eta(\mathrm{c.m.})}(m^2_{D_{13}})} + P^{D_{13}}_\pi\frac{q^5_{\pi(\mathrm{c.m.})}(s)}{q^5_{\pi(\mathrm{c.m.})}(m^2_{D_{13}})} + P^{D_{13}}_{\pi\pi}\right). \quad (11)$$

Here $\Gamma^{(0)}_{D_{13}} = \Gamma_{D_{13}}(s = m^2_{D_{13}}) = 120$ MeV is the total decay width of the free resonance D_{13}; $P^{D_{13}}_\pi = 0.6$,

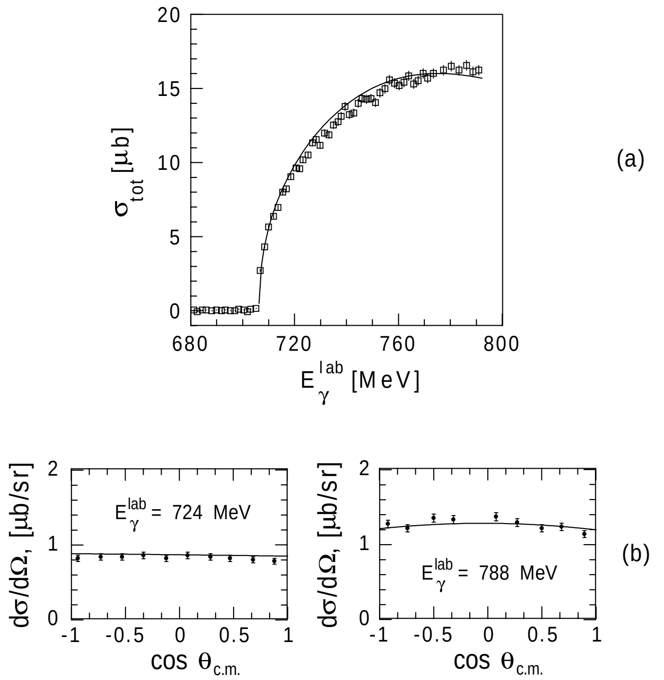


Fig. 1. Calculated integrated (a) and differential (b) cross-sections for the $\gamma p \to \eta p$ reaction on proton; experimental data from [11].

$P_{\eta}^{D_{13}} = 0.001$ and $P_{\pi\pi}^{D_{13}} = 0.4$ are the relative weights of its decay channels taken at $\sqrt{s} = m_{D_{13}} = 1520$ MeV. The similar set of decay parameters is used for the resonance $N(1535)S_{11}$

$$\Gamma_{S_{11}}(s) = \Gamma_{S_{11}}^{(0)} \times \left(P_{\eta}^{S_{11}} \frac{q_{\eta(\text{c.m.})}(s)}{q_{\eta(\text{c.m.})}(m_{S_{11}}^2)} + P_{\pi}^{S_{11}} \frac{q_{\pi(\text{c.m.})}(s)}{q_{\pi(\text{c.m.})}(m_{S_{11}}^2)} + P_{\pi\pi}^{S_{11}} \right), \quad (12)$$

with $\Gamma_{S_{11}}^{(0)} = \Gamma_{S_{11}}(s = m_{S_{11}}^2) = 160$ MeV; $P_{\pi}^{S_{11}} = 0.4$, $P_{\eta}^{S_{11}} = 0.5$ and $P_{\pi\pi}^{S_{11}} = 0.1$, $m_{S_{11}} = 1535$ MeV.

This nonrelativistic approach works quite well in calculating the main characteristics of η-photoproduction from the nucleon (fig. 1).

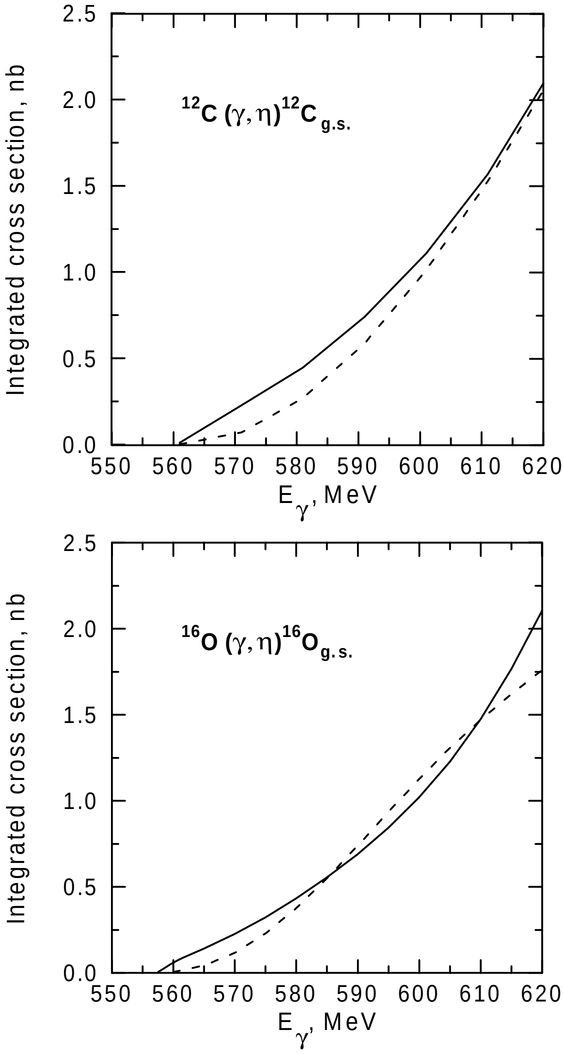


Fig. 2. Integrated cross-sections for reactions $^{12}\mathrm{C}(\gamma,\eta)^{12}\mathrm{C}_{\text{g.s.}}$ and $^{16}\mathrm{O}(\gamma,\eta)^{16}\mathrm{O}_{\text{g.s.}}$ calculated taking into account both the resonant and direct photoproduction processes with (solid line) and without (dashed line) the $D_{13}(1520)$-hole and $S_{11}(1535)$-hole mutual interaction taken into account.

Calculation and discussion

Figure 2 shows the integrated cross-sections for nuclear reactions $^{12}\mathrm{C}(\gamma,\eta)^{12}\mathrm{C}_{\text{g.s.}}$ and $^{16}\mathrm{O}(\gamma,\eta)^{16}\mathrm{O}_{\text{g.s.}}$ calculated with (solid line) and without (dashed line) the mutual exchange interaction between the $D_{13}(1520)$-hole and $S_{11}(1535)$-hole states taken into account. Relative enhancement due to this interaction is considerable although the absolute cross-sections remain small. The effect is more pronounced in special calculations where only the resonant term $T_{\lambda,\vec{k}_\gamma}^{(\text{res})}(\vec{k}_\eta, \omega)$ of the photoproduction amplitude (7) is taken into consideration (fig. 3). The coherent η-photoproduction cross-section via independent intermediate $S_{11}(1535)$-hole and $D_{13}(1520)$-hole states is very small. In the first case the process is strongly forbidden due to the suppression of the isoscalar photoproduction amplitude, but not only for this reason. In totally closed-shell nuclei, such as ^{16}O, the spin-flip character of the Hamiltonian $\delta H_{\gamma N S_{11}}$ contradicts to the nonspin-flip character of the Hamiltonian $\delta H_{\eta N S_{11}}$. In the case of pure $D_{13}(1520)$-hole states the cross-section in the near-threshold region is suppressed because of the very small η-meson partial width of the these states. And, again, specific selection rules concerning spin variables play their important role in this case. Namely, tensor character of the spin part of the Hamiltonian $\delta H_{\eta N D_{13}}$ contradicts the axial character of that of the Hamiltonian $\delta H_{\gamma N D_{13}}^{(2)}$ (and, of course, of the first term of the Hamiltonian $\delta H_{\gamma N D_{13}}^{(1)}$). That means that, in such nuclei as ^{16}O, coherent η-

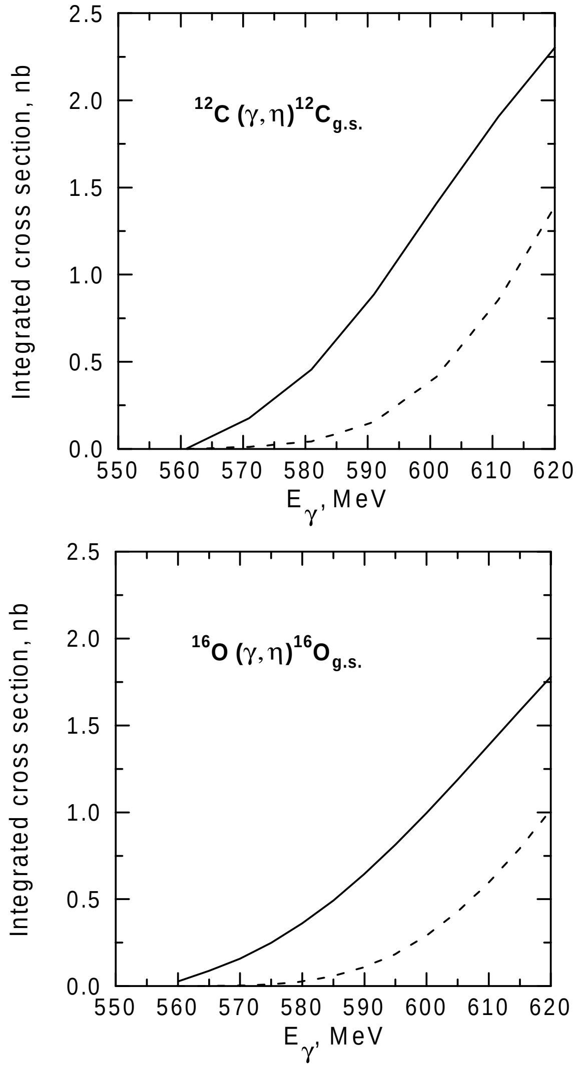


Fig. 3. The same as in fig. 2 calculated for the resonant photoproduction process only.

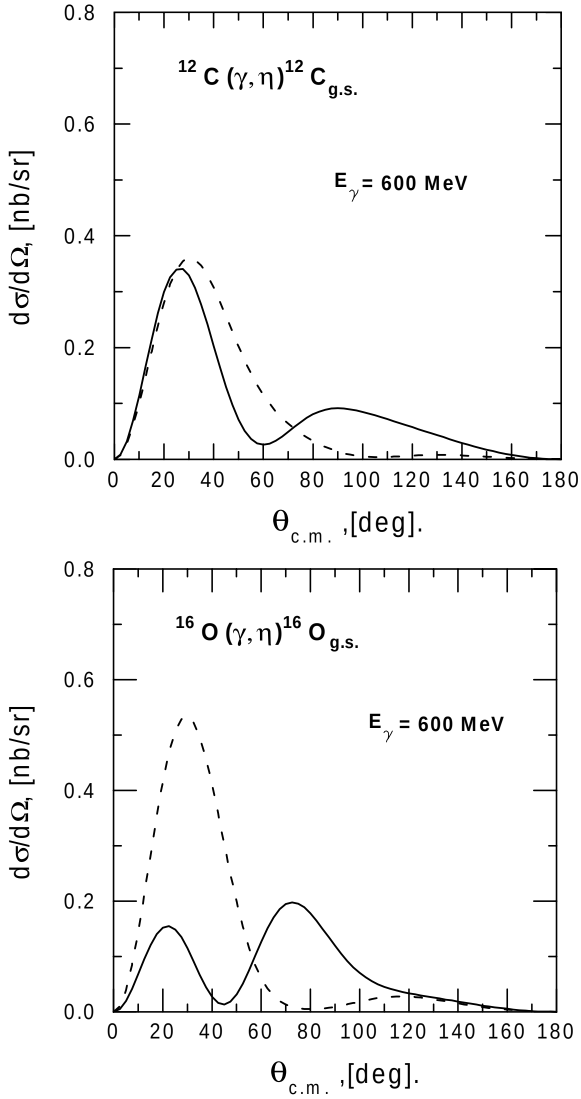


Fig. 4. Differential cross-sections for reactions $^{12}\mathrm{C}(\gamma,\eta)^{12}\mathrm{C}_{\mathrm{g.s.}}$ and $^{16}\mathrm{O}(\gamma,\eta)^{16}\mathrm{O}_{\mathrm{g.s.}}$ at $E_\gamma = 600$ MeV calculated taking into account both the resonant and direct photoproduction processes with (solid line) and without (dashed line) the $D_{13}(1520)$-hole and $S_{11}(1535)$-hole mutual interaction taken into account.

photoproduction via the $D_{13}(1520)$-hole states takes place only due to the second term of the Hamiltonian $\delta H^{(1)}_{\gamma N D_{13}}$.

The mutual exchange interaction between the two sorts of baryon-hole excitations —$D_{13}(1520)$-hole and $S_{11}(1535)$-hole— changes the situation qualitatively. Schematically the mechanism of the enhancement looks as if the photon absorption takes place in the $D_{13}(1520)$-hole channel, then this excitation is transferred into the $S_{11}(1535)$-hole states, from which the excited nucleus decays to the coherent η-production channel. Being impossible in the elementary photoproduction process on an isolated nucleon, this, in a sense, two-step mechanism turns out to work actively in nuclei.

Calculated differential cross-sections for both reactions $^{12}\mathrm{C}(\gamma,\eta)^{12}\mathrm{C}_{\mathrm{g.s.}}$ and $^{16}\mathrm{O}(\gamma,\eta)^{16}\mathrm{O}_{\mathrm{g.s.}}$ demonstrate the importance of the mechanism under consideration from the other point of view (fig. 4).

Conclusion

Calculations presented here for two zero-spin and zero-isospin nuclei confirm the general conclusion of our earlier calculations [8] on the important role of the exchange interaction between baryon-hole states of different sorts in the coherent η-photoproduction process. Looking forward, much work must be done to develop further the extended baryon-hole approach to make possible to suggest on its ground reliable quantitative predictions concerning the processes under consideration. On the other hand, the very idea of mixing different baryon excitations, which was demonstrated here within the extended baryon-hole model, seems to be even more important from the conceptual point of view than as a specific instrument of a specific model. On this connection one can see a similarity between our "two-step" concept and that concerning the role of the baryon-nucleon rescattering on the intermediate stage of the process of coherent η photoproduction from deuteron [12,13]. To understand the depth of this similarity one must investigate what contribution to the differential and integrated cross-sections of the reaction $d(\gamma,\eta)d$ comes from the transformation of the dominating entrance state $D_{13}(1520)$-nucleon of this reaction into the $S_{11}(1535)$-nucleon state directly coupled with the final $d\eta$ state. It is within our plans to investigate this question.

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References

1. C. Bennhold, H. Tanabe, Nucl. Phys. A **550**, 625 (1991).
2. L.J. Abu-Raddad, J. Piekarewicz, A.J. Sarty, M. Benmerrouche, Phys. Rev. C **57**, 2053 (1998).
3. A. Fix, H. Arenhovel, Nucl. Phys. A **620**, 457 (1997).
4. W. Peters, H. Lenske, U. Mosel, Nucl. Phys. A **642**, 506 (1998).
5. A.I. Lebedev, V.A. Triasutchev, V.H. Fetisov, Yad. Fis. **27**, 1584 (1978).
6. V. Hejny *et al.*, Eur. Phys. J. A **6**, 83 (1999).
7. V.V. Balashov, A.V. Bibikov, V.K. Dolinov, *16th European Conference on Few Body Problems in Physics, Autrans, France, 1-6 June 1998* (Abstracts Booklet, Grenoble, 1998) p. 34.
8. V.V. Balashov, A.V. Bibikov, V.K. Dolinov, M.M. Kaskulov, in *Proceedings of the 7th International Conference CIPANP 2000, Quebec City, Canada, May 2000* (*AIP Conf. Proc.* Vol. **549**, Melville, New York, 2000) p. 475.
9. H.C. Chiang, E. Oset, L.C. Liu, Phys. Rev. C **44**, 738 (1991).
10. M. Benmerrouche, N.C. Mukhopadhyay, J.F. Zhang, Phys. Rev. D **57**, 3237 (1995).
11. B. Krusche *et al.*, Phys. Rev. Lett. **74**, 3736 (1995).
12. S.S. Kamalov, L. Tiator, C. Benhold, Phys. Rev. C **55**, 98 (1997).
13. F. Ritz, H. Arenhovel, arXiv: nucl-th/0011089.