Vol. B12 (1981) ACTA PHYSICA POLONICA No 3

PARTIAL CROSS SECTIONS FOR THE PHOTOPRODUCTION OF π^0-MESONS ON ^{6}Li IN THE RESONANCE ENERGY REGION

By V. A. Tryasuchev

Institute of Nuclear Physics, Tomsk Polytechnical Institute, Tomsk, USSR

A. I. Lebedev and V. N. Fetisov

P. N. Lebedev Physical Institute, USSR Academy of Sciences, Moscow*

(Received July 10, 1980)

Within the framework of the impulse approximation and the intermediate coupling shell model we have calculated the cross sections for the $\gamma^6\text{Li} \to \pi^0\,{}^6\text{Li}^*(\varepsilon)$ partial reactions for the levels of the ^{6}Li nucleus with the excitation energies $\varepsilon = 0.0$, 2.18, 3.56, 4.27 and 5.37 MeV and also for the $\gamma^6\text{Li} \to \pi^0\,{}^6\text{Li}^*(\varepsilon) \to \pi^0\gamma'\,{}^6\text{Li}$ two-step processes at $\varepsilon = 3.56$ and 5.37 MeV. It is shown that the reactions with a change in the nuclear isospin turn out to be suppressed in the energy region of the photoexcitation of the first and second nucleon resonances where the isoscalar amplitudes of photoproduction on a nucleon are small. The possibility of using the described processes to extract an additional information on the single-nucleon photoproduction amplitudes and on the nuclear structure is discussed.

PACS numbers: 13.60.−r, 13.60.Kd, 25.20.+y

1. Introduction

In intermediate-energy physics much attention is given to the investigation of the so-called partial reactions of photoproduction of mesons on nuclei in which the nucleus goes over into a definite final state. Studies on the partial reactions of charged-pion photoproduction on nuclei have made it possible to obtain some information about the partial transitions of nuclei, the single-nucleon photoproduction amplitudes and about the role of the meson–nucleus interaction in the final state [1–7].

The partial photoproduction reactions for neutral pions, unlike the reactions involving the production of charged pions, have been studied less thoroughly [8–10]. At the same time they have some interesting features: (*i*) π^0-mesons are produced coherently on protons and neutrons of the nucleus; (*ii*) the cross sections for these reactions are functions of the nuclear density distribution and (*iii*) in such processes there can occur two types of nuclear partial transitions: both with a change in the isospin and without it. Furthermore, as was

* Address: PN Lebedev Physical Institute, Leninsky prospect 53, Moscow 117924, USSR.

shown in Refs. [10–11], the partial π^0-meson photoproduction cross sections are largely dependent on the intranuclear motion of nucleons and on the mechanism of photoproduction of mesons on nuclei. Studies on the partial π^0-meson photoproduction reactions are therefore important for a deeper understanding of the interaction of elementary particles with atomic nuclei.

A restrictive factor in investigations of the partial neutral-meson photoproduction reactions is the difficulty of their experimental separation. As is known, the method of detection of recoil nuclei can be used to separate out elastic partial reactions only on nuclei with mass number $A \leqslant 4$. In recent years the possibility of studying the inelastic partial reactions of the photoproduction of π and η mesons on nuclei with $A > 4$ by the coincidence detection of a meson and a gamma quantum from the decay of an excited state of the final nucleus was discussed [12–15].

Given below is the impulse approximation treatment of the partial reactions for the photoproduction of mesons on the ^{6}Li nucleus in the excitation energy region of nucleon resonances. ^{6}Li is the lightest stable nucleus having low-lying excited states which decay with the emission of photons. The quantum numbers of the ^{6}Li levels are known and the structure of this nucleus has been fairly well explored in experiments on electron scattering at small momentum transfers [16–18].

2. *Amplitudes and differential cross sections for the partial reactions*

The differential cross section for the reaction

$$\gamma(k, \lambda)+A_i(Q_i) \rightarrow \text{meson } (q)+A_f(Q_f), \tag{2.1}$$

where $k = (k_0, \boldsymbol{k})$, $q = (q_0, \boldsymbol{q})$, $Q_i = (Q_{0i}, \boldsymbol{Q}_i)$, $Q_f = (Q_{0f}, \boldsymbol{Q}_f)$ are the four-momenta of the corresponding particles and λ is the photon polarization index, takes the form

$$d\sigma = (2\pi)^{-2}\delta(q+Q_i-k-Q_f)\,\frac{2k_0Q_{0i}}{s-M_A^2}\,\overline{\sum}\,|\langle\psi_f|\hat{\phi}|\psi_i\rangle|^2 d^3Q_f d^3q. \tag{2.2}$$

Here $s = (k+Q_i)^2$, M_A is the mass of the initial nucleus, $\overline{\sum}$ denotes the summation over the final projections and averaging over the initial projections of the particle spins, ψ_i and ψ_f are the wave functions for the nucleus in the initial and final states, and $\hat{\phi}$ is the operator of the meson photoproduction on the nucleus, which is expressed in the impulse approximation in terms of the sum of the operators of the meson photoproduction on free nucleons: $\hat{\phi} = \sum_{n=1}^{A} \hat{\phi}(n)$. The operator $\hat{\phi}(n)$ was written for a moving nucleon in the rest system of the nucleus in the two-component representation satisfying the relativistic and gradient invariance [19, 20]. For calculating the nuclear matrix elements, it is convenient to represent this operator as a convolution of the tensors of rank ξ, t and κ in the spin, isospin and configuration spaces [14]

$$\hat{\phi}(n) = \sum_{\kappa=0}^{\infty}\,\sum_{m=-\kappa}^{\kappa}\,\sum_{\xi,t=0}^{1}\,\sum_{\nu=-\xi}^{\xi}\,[\mathcal{N}^{\kappa\xi t}_{m\nu\mu}(n)]^*\mathcal{M}^{\kappa\xi t}_{m\nu\mu}(n), \tag{2.3}$$

where

$$\mathcal{N}^{\kappa\xi t}_{m\nu\mu}(n) = (-i)^{\kappa}\sqrt{4\pi}\, Y^{\kappa}_{m}(\hat{p})H^{\xi t}_{\nu\mu}(n),$$

$$\mathcal{M}^{\kappa\xi t}_{m\nu\mu}(n) = \sqrt{4\pi}\, j_{\kappa}(pr_n)Y^{\kappa}_{m}(\hat{r}_n)\sigma^{\xi}_{\nu}(n)\tau^{t}_{\mu}(n). \tag{2.4}$$

$Y^{\kappa}_{m}(\hat{p})$, $Y^{\kappa}_{m}(\hat{r})$ are spherical functions; $j_{\kappa}(x)$ are spherical Bessel functions; $\sigma^0_\nu = I$, $\sigma^1_\nu = \sigma_\nu$, $\tau^0_\mu = I$, $\tau^1_\mu = \tau_\mu$ (I is the unit matrix, σ_ν and τ_μ are the spin and isospin operators of the nucleon); $\boldsymbol{r}$ is the radius vector of a nucleon in the nucleus; $\boldsymbol{p} = \boldsymbol{k}-\boldsymbol{q}$ is the momentum transfer, and $H^{\xi t}_{\nu\mu}(n)$ are the single-nucleon photoproduction amplitudes dependent on k, q, λ and on the nucleon momentum in the nucleus.

According to the intermediate coupling shell model [21], the wave functions for the p-shell nuclei with the excitation energy ε, spin J and isospin T are written as

$$\psi(\varepsilon, JM, T) = \sum_{LM_LSM_S} \langle LM_L, SM_S|JM\rangle \times \alpha_{LS}|(0S)^4, (1P)^{A-4}[f_L]LSTM_LM_S\rangle. \tag{2.5}$$

Harmonic oscillator wave functions in the LS coupling scheme were chosen as single--particle wave functions.

Taking out of the matrix element the amplitudes $H^{\xi t}_{\nu\mu}$ [20] averaged over the momenta of nucleons, we obtain the following expression for the amplitudes of the partial reactions (2.1)

$$\langle\psi_f|\hat{\Phi}|\psi_i\rangle = 2\delta^{M_f}_{M_i}\delta^{L*}_{L}\delta^{S*}_{S}\delta^{T*}_{T}\mathcal{N}^{000}(\lambda)\,\langle 0S\|\mathcal{M}^{000}\|0S\rangle + (A-4)\sum_{L,L^*,j,\kappa,\xi,t} B^{\kappa\xi t}_{LL^*j}(J_iT_i, J_fT_f)$$

$$\times\langle T_iM_{T_i}, t\mu|T_fM_{T_f}\rangle \sum_{\nu}\langle J_iM_i, \xi\nu|jM_j\rangle\,\langle jM_j, \kappa m|J_fM_f\rangle\,[\mathcal{N}^{\kappa\xi t}_{m\nu\mu}(\lambda)]^*$$

$$\times \frac{\alpha_{LL^*}1}{2\sqrt{3}}\langle 1P\|\mathcal{M}^{\kappa\xi t}\|1P\rangle. \tag{2.6}$$

Here

$$B^{\kappa\xi t}_{LL^*j}(J_iT_i, J_fT_f) = (-1)^{L+L^*-J_f+j}\sum_{L',S',T'}\langle(1P)^{A-4}[f_{L^*}]L^*S^*T^*|\,(1P)^{A-5}[f_{L'}]L'S'T'\rangle$$

$$\times\langle(1P)^{A-4}[f_L]LST|\,(1P)^{A-5}[f_{L'}]L'S'T'\rangle U(\kappa LJ_fS^*; L^*j)U(LSj\xi; J_iS^*)$$

$$\times U(L'L^*1\kappa; 1L)U(S'S^*\tfrac{1}{2}\xi; \tfrac{1}{2}S)U(T'T_f\tfrac{1}{2}t; \tfrac{1}{2}T_i), \tag{2.7}$$

$\alpha_{LL^*} = \alpha_L\times\alpha_{L^*}$, the asterisks denote the quantum numbers of the excited nucleus and $\langle(1P)^k[f_L]LST|(1P)^{k-1}[f_{L'}]L'S'T'\rangle$ are the fractional parentage coefficients [22]. The reduced matrix elements $\langle l\|\mathcal{M}^{\kappa\xi t}\|l\rangle$ of the S-shell ($l = 0$) and P-shell ($l = 1$) nucleons are expressed in terms of the corresponding form factors $F_{\kappa l}(p)$ ($\kappa = 0.2$)

$$\langle l\|\mathcal{M}^{\kappa\xi t}\|l\rangle = 2(i)^{\kappa}\left[(2l+1)(2\xi+1)(2t+1)\frac{3\kappa+2}{\kappa+2}\right]^{1/2} F_{\kappa l}(p). \tag{2.8}$$

The form factors $F_{\kappa l}$ are related to the single-particle transition densities $\varrho_l(r)$

$$F_{\kappa l}(p) = \int r^2\varrho_l(r)j_{\kappa}(pr)dr. \tag{2.9}$$

The first term in expression (2.6) is due to the contribution of the S shell nucleons. For the inelastic photoproduction of mesons this term is absent because of the orthogonality of the wave functions ψ_i and ψ_f.

Using the amplitude (2.6), we obtain the following expression for the differential cross sections for the inelastic partial reactions (2.1)

$$\frac{d\sigma}{d\Omega} = K(A-4)^2 \frac{1}{2(2J_i+1)} \sum_{\kappa,\xi,L^*,L,j,t} \sum_{\kappa',\xi',L',L^*,j',t'\lambda} \langle T_i M_{T_i}, t\mu | T_f M_{T_f}\rangle \langle T_i M_{T_i}, t'\mu | T_f M_{T_f}\rangle$$

$$B^{\kappa\xi t}_{LL^*j}(J_iT_i, J_fT_f) B^{\kappa'\xi' t'}_{L'L^*j'}(J_iT_i, J_fT_f)\, |H(\lambda)|^2 \tfrac{1}{12}\, \alpha_{LL^*}\alpha_{L'\bar{L}^*} \langle 1P \| \mathcal{M}^{\kappa\xi t} \| 1P\rangle$$

$$\times \langle 1P \| \mathcal{M}^{\kappa'\xi' t'} \| 1P\rangle, \tag{2.10a}$$

where

$$K = \frac{k_0 Q_{0i}}{2\pi^2(s-M_A^2)} \times \frac{|\boldsymbol{q}|^2 q_0 Q_{0f}}{|\boldsymbol{q}|\,(k_0+Q_{0i}) - k_0 q_0 \cos\theta}, \tag{2.10b}$$

θ is the meson emission angle,

$$|H(\lambda)|^2 = \delta^{\kappa'}_{\kappa}\delta^{\xi'}_{\xi}\delta^{j'}_{j} \frac{2J_f+1}{2\xi+1} \sum_{\nu} [H^{\xi t}_{\nu\mu}(\lambda)]^* H^{\xi t'}_{\nu\mu}(\lambda) + (i)^{\kappa+\kappa'}(2J_f+1)\,[(2\kappa'+1)/2]^{1/2}$$

$$\times \langle \kappa 0, \kappa' 0 | 20\rangle U(1J_i 2j'; j1) U(jJ_f 2\kappa'; \kappa j')\, [h^{tt'}(\lambda) - \tfrac{1}{3}\sum_{\nu} [H^{1t}_{\nu\mu}(\lambda)]^* H^{1t'}_{\nu\mu}(\lambda)], \tag{2.10c}$$

$$h^{tt'}(\lambda) = |\boldsymbol{p}|^{-2} (\boldsymbol{p}\cdot \boldsymbol{H}^{t'}_{\mu})(\boldsymbol{H}^{t}_{\mu}\cdot \boldsymbol{p})^*. \tag{2.10d}$$

The relation similar to (2.10d) was derived also from the treatment of the charged-pion photoproduction on nuclei [23]. The expression for the elastic photoproduction cross section can be easy obtained by taking into account two terms in the formula (2.6).

3. *Partial cross sections for the π^0 photoproduction on ^{6}Li*

The cross sections for the π^0-meson photoproduction on ^{6}Li were calculated using wave functions and transition densities whose parameters are given in Table I for the first five states of the ^{6}Li nucleus [24]. The results of the phenomenological analysis of the elementary process $\gamma N \to \pi N$ [25] were used in calculations for describing the amplitudes $H^{\xi t}_{\nu\mu}$ (2.4).

The integrality of the values of the nuclear isospin ^{6}Li leads to the fact that in separate partial reactions π^0 mesons are produced either by the isoscalar or isovector transitions.

For example, in the reaction

$$\gamma + {}^6\text{Li} \to \pi^0 + {}^6\text{Li}^* \,(2.18) \tag{3.1}$$

mesons are produced by isovector photons. The shape of the angular distribution of pions in this reaction is determined by the form factor F_{21} which has a characteristic maximum

TABLE I

The parameters of the nuclear wave functions and transition densities used in the calculations of the cross sections for the $\gamma^6\mathrm{Li} \to \pi^0\,{}^6\mathrm{Li}^*(\varepsilon)$ reactions

J_f^P, ε [MeV] T_f	Mixing coefficients: initial state	Mixing coefficients: final state	Single-particle transition density $\varrho_l(r)$	References
1^+, 0, 0	a	a	C_l	[17]
3^+, 2.18, 0	a	$a_{D^*} = 1$	C_l	[17]
0^+, 3.56, 1	a	$a_{S^*} = 1.00$, $a_{P^*} = 0.028$	C_l	[17]
0^+, 3.56, 1	a	$a_{S^*} = 1.000$, $a_{P^*} = -0.012$	d_l	[18]
2^+, 4.27, 0	a	$a_{D^*} = 1$	C_l	[17]
2^+, 5.37, 1	b	$a_{P^*} = 0.66$, $a_{D^*} = 0.74$	C_l	[16]

The following notation is used in the table: a is the set of parameters: $a_S = 0.924$, $a_P = 0.369$, $\alpha_D = 0.102$; b — $a_S = 0.997$, $a_P = 0.070$, $a_D = 0.025$.

$C_l = N_l \times r^{2l} \times \exp(-r^2/r_0^2)$, $N_l = \dfrac{2^{2+l}}{\sqrt{\pi}(2l+1) r_0^{3+2l}}$, $r_0 = 2.03$ fm. $d_l = \sum_{n=2,4,6} a_n r^n \times \exp(-r^2/r_0^2)$,
$a_2 = 5.212 \times 10^{-2}\,\mathrm{fm}^{-5}$, $a_4 = -3.79 \times 10^{-3}\,\mathrm{fm}^{-7}$, $a_6 = 8.705 \times 10^{-5}\,\mathrm{fm}^{-9}$, $r_0 = 2.301$ fm.

in the oscillator model when $p \simeq \dfrac{2.2}{r_0}$. The differential cross sections for the reaction (3.1), calculated taking into account the averaging of the single-nucleon amplitudes over the momentum distribution of nucleons in the nucleus [20], are displayed in Figs. 1 and 2 in the photoexcitation energy region of the first and second nucleon resonances, respectively. The cross section for the reaction (3.1) is maximal in the $\Delta(33)$-resonance region where the isovector part of the amplitude of the $\gamma N \to \pi^0 N$ process is of the highest value.

The amplitude of the partial reaction

$$\gamma + {}^6\mathrm{Li} \to \pi^0 + {}^6\mathrm{Li}^*(3.56) \tag{3.2}$$

is expressed in terms of the isoscalar part of the single-nucleon amplitude $\boldsymbol{H}$. As is evident from figures 1, 2, the cross section for this process for angles $\theta > 20°$ is several orders of magnitude smaller than that for the reaction (3.1), which results from the smallness of the isoscalar amplitudes of the elementary process. The shape of the angular distribution of π^0 mesons is characterized by two maxima. In the first maximum corresponding to small momentum transfers ($p < 250$ MeV/c) the cross sections are not critical to the choice of nuclear wave functions. It is expedient, therefore, to use measurements of the cross

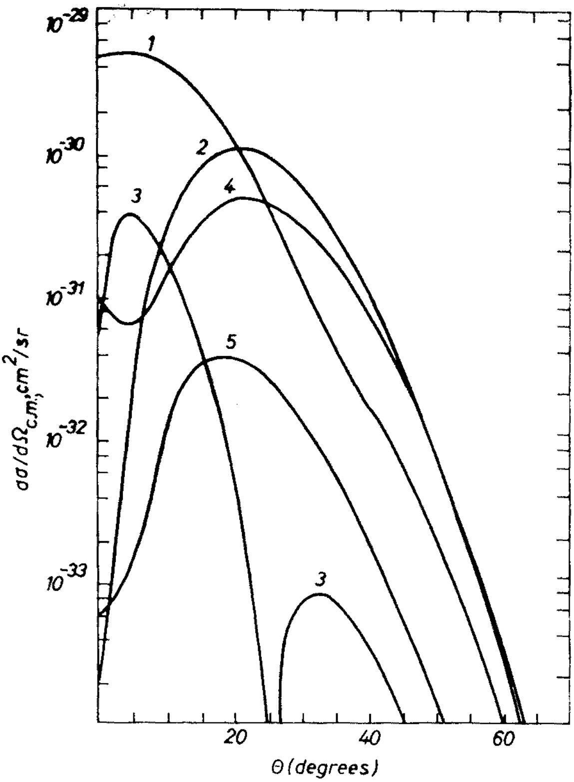

Fig. 1. The cross sections for the $\gamma\, {}^6\text{Li} \to \pi^0\, {}^6\text{Li}^*(\varepsilon)$ reaction in the c.m. system, calculated at the gamma-quantum energy $k_0^{\text{lab}} = 300$ MeV. Curve *1* corresponds to $\varepsilon = 0.0$ MeV (elastic photoproduction); curve *2* to $\varepsilon = 2.18$ MeV; curve *3* to $\varepsilon = 3.56$ MeV; curve *4* to $\varepsilon = 4.27$ MeV and curve *5* to $\varepsilon = 5.37$ MeV. The parameters of wave functions from Table I were used in calculations; the corresponding parameters for the partial transition ${}^6\text{Li} \to {}^6\text{Li}^*$ (3.56) being taken from Ref. [18] (set B)

sections for the process (3.2) in this angular region for refining the isoscalar single-nucleon amplitudes. At larger momentum transfers, where the second maximum in the angular distribution is exhibited, the cross section is significantly dependent on the shape of the transition density (see Fig. 3). In the considered momentum transfer region the intranuclear motion of nucleons has a negligible influence on the cross sections.

The differential cross section for the reaction

$$\gamma + {}^6\text{Li} \to \pi^0 + {}^6\text{Li}^*(4.27) \tag{3.3}$$

and differential cross sections for the reactions (3.1) are rather close together in magnitude for the meson emission angles $\theta > 20°$. In both of these reactions mesons are produced by isovector photons and at large momentum transfers the cross sections are determined by the form factor F_{21}. For the angles $\theta < 20°$, where small momenta are transferred to the nucleus, a significant contribution to the cross section for the reaction (3.3) comes

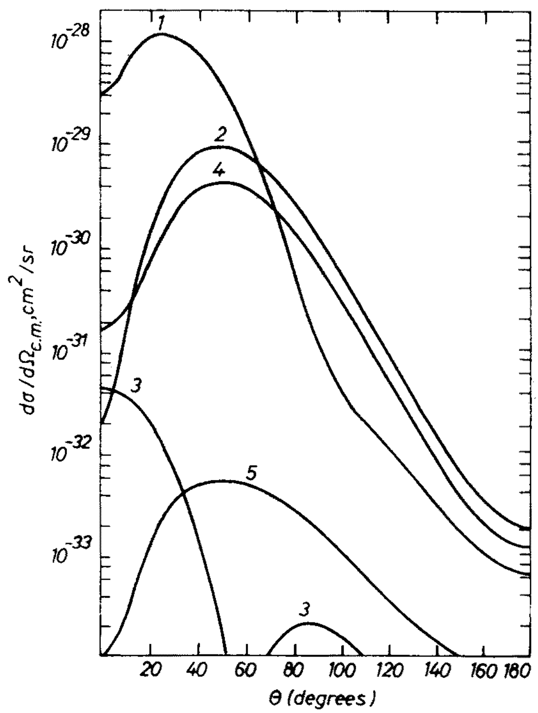

Fig. 2. The cross sections for the $\gamma\ {}^6Li \to \pi^0\ {}^6Li^*(\varepsilon)$ reaction at the gamma-quantum energy $k_0^{lab} = 650$ MeV. The notation is the same as in Fig. 1

from the term comprising the form factor F_{01}, which leads to a difference between the cross sections.

In the reaction

$$\gamma + {}^6Li \to \pi^0 + {}^6Li^*(5.37) \tag{3.4}$$

the nuclear isospin changes; therefore the cross sections are expressed in terms of the isoscalar parts of the single-nucleon amplitudes and turn out to be small, just as in the case of the reaction (3.2). As is evident from Figs. 1 and 2, the angular distributions of mesons in the reactions (3.3) and (3.4) are similar while the cross sections differ by several orders of magnitude.

All nucleons of the nucleus are involved in the reaction of the elastic photoproduction of π^0 mesons on ${}^6Li$

$$\gamma + {}^6Li \to \pi^0 + {}^6Li. \tag{3.5}$$

Since the admixture of the D component in the ^{6}Li ground state is small (see Table I), then, neglecting the term proportional to α_D^n, $n > 1$ in the expression for the differential cross section, one can obtain results presented in Figs. 1 and 2. The differential cross section of the reaction (3.5) is several orders of magnitude larger than the cross sections for the inelastic partial reactions for small meson emission angles, whereas for large angles the

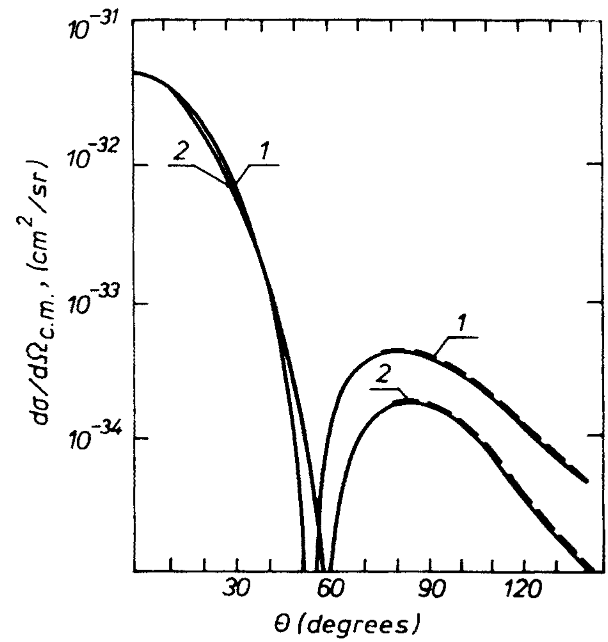

Fig. 3. The cross section for the $\gamma\,^6\mathrm{Li} \to \pi^0\,^6\mathrm{Li}^*$ (3.56) reaction in the c.m. system at the gamma-quantum energy $k_0^{\mathrm{lab}} = 300$ MeV. Used in the calculations for describing the nuclear transition were: *1*, the harmonic oscillator wave functions [17] and *2*, the phenomenological transition density [18] (set B). The solid lines represent the results of calculations taking into account the momentum distribution of nucleons in the nucleus. The corresponding dashed curves are plotted for the "mean" value of the nucleon momentum in the nucleus $\langle p_i \rangle \simeq -\frac{5}{11}p$ [20]

cross sections for some inelastic partial reactions can be much greater than the elastic photoproduction cross section.

It follows from the given analysis of the partial reactions of the photoproduction of π^0 mesons on ^{6}Li that:

— the cross sections for the inelastic partial reactions in the energy interval $k_0 = 300$–-650 MeV are suppressed for the transitions with a change in the nuclear isospin;

— in the region of small momentum transfer, where the nuclear transitions are fairly well known, measurements of the cross sections for the reactions considered on nuclei can give additional information about the single-nucleon amplitudes;

— at large momentum transfer the partial cross sections are critical to the choice of nuclear wave functions.

4. The radiative decay of excited states of nuclei in the partial photoproduction reactions

Data on the inelastic partial reactions of the photoproduction of mesons on nuclei can be obtained from the investigation of the two-step processes

$$\gamma(k,\lambda)+A_i(Q_i) \to \text{meson}\,(q)+A^*(Q^*) \\ \qquad\qquad \hookrightarrow \gamma'(k',\lambda')+A_f(Q_f). \tag{4.1}$$

Using the formalism developed in Ref. [12], the differential cross section for the reaction (4.1) for the radiative transitions of a definite multipolarity will be written as

$$d\sigma = (2\pi)^{-5}\delta(k'+q+Q_f-k-Q_i)\,\frac{8k_0Q_{0i}(Q_0^*)^2}{s-M_A^2}$$
$$\times \overline{\sum} \left| \frac{\sum_{M^*}\langle\gamma', A_f|T_\gamma|A^*(J^*M^*)\rangle\,\langle A^*(J^*M^*)|\hat{\phi}|A_i\rangle}{M_{A^*}^2-s^*-i\Gamma M_{A^*}} \right|^2 d^3Q_f d^3q d^3k', \tag{4.2}$$

where J^* and M^* are the spin and its projection for the excited nucleus with mass M_{A^*}, T_γ is the operator of the radiative decay, Γ is the total width of the decaying state, and $s^* = (k'+Q_f)^2$.

The amplitude of the radiative decay of the nucleus in the long-wave approximation [26] can be represented as

$$\langle\gamma'(k',\lambda'), A_f|T_\gamma(RJ)\,|A^*\rangle^* = 2\pi\delta(i)^J\left(\frac{2J+1}{k_0'}\right)^{1/2}\frac{(k_0')^J}{(2J+1)!!}\,\frac{e}{2m_p}\sum_m D^J_{m\lambda'}(\varphi_{\gamma'}\theta_{\gamma'}0)$$
$$\times\langle J_fM_f, JM|J^*M^*\rangle\,\langle\psi(\varepsilon)\|\mathcal{M}(RJ)\,\|\psi(0)\rangle\,(2J^*+1)^{-1/2}. \tag{4.3}$$

Here for the magnetic type of radiation ($R = M$) $\delta = 1$, and for the electric type ($R = E$) $\delta = -i\lambda'$ where λ' is the polarization index of the decay photon, J and m are the photon angu ar momentum and projection, $D^J_{m\lambda'}(\varphi_{\gamma'}\theta_{\gamma'}0)$ are the generalized spherical functions and $\langle\psi(\varepsilon)\|\mathcal{M}(RJ)\|\psi(0)\rangle$ is the reduced nuclear matrix element related to the radiation width Γ_γ by the relation

$$\Gamma_\gamma = \frac{8\pi\varepsilon^{2J+1}}{[(2J+1)!!]^2}\,\frac{1}{2J^*+1}\left(\frac{e}{2m_p}\right)^2\times|\langle\psi(\varepsilon)\|\mathcal{M}(RJ)\,\|\psi(0)\rangle|^2. \tag{4.4}$$

TABLE II

The radiation widths of the ^{6}Li levels

Excitation energy ε [MeV]	Type of radiation	Nuclear wave function	$\Gamma_\gamma^{\text{theor.}}$ [eV]	$\Gamma_\gamma^{\text{exp.}}$ [eV]
2.18	E2	Donnelly et al. [17]	4.58×10^{-4}	$(4.40\pm0.34)\times10^{-4}$ [28]
3.56	M1	Donnelly et al. [17]	7.95	8.16 ± 0.19 [18]
3.56	M1	Bergstrom et al. [18]	8.12	8.16 ± 0.19 [18]
5.37	M1	Neuhausen et al. [16]	0.238	0.19 ± 0.04 [16]

The radiation widths of the ^{6}Li excited states, calculated using the wave functions given in Table I, are consistent with the experimental values (see Table II).

Substituting into Eq. (4.2) the amplitude of the partial pion photoproduction reaction (2.6) and the radiative decay amplitude (4.3), we obtain the following expression in the laboratory system for unpolarized initial particles

$$\frac{d^2\sigma}{d\Omega_\pi d\Omega_{\gamma'}} \simeq \frac{|\boldsymbol{q}|^2 q_0 Q_{0f}}{64\pi^3(|\boldsymbol{q}|(q_0+Q_{0f})-k_0 q_0\cos\theta)} \times \frac{(A-4)^2}{2J_i+1}\sum_{t,t'}\langle T_i M_{T_i}, t\mu|T^* M_{T^*}\rangle$$

$$\times\langle T_i M_{T_i}, t'\mu|T^* M_{T^*}\rangle\frac{\Gamma_\gamma}{\Gamma}\frac{2J+1}{(1-\beta_{A^*}\cos\alpha)^{2J-1}}\times\Pi. \tag{4.5}$$

Here

$$\Pi = \sum_{\kappa,\xi,L,L^*,j}\ \sum_{\kappa',\xi',L'\tilde{L}^*,j'} B^{\kappa\xi t}_{LL^*j}(J_i T_i, J^*T^*) B^{\kappa'\xi' t'}_{L'\tilde{L}^*j'}(J_i T_i, J^*T^*)\tfrac{1}{12}\alpha_{LL^*}\alpha_{L'\tilde{L}^*}$$

$$\langle 1P\|\mathscr{M}^{\kappa\xi t}\|1P\rangle\langle 1P\|\mathscr{M}^{\kappa'\xi' t'}\|1P\rangle\times Z(\kappa,\kappa',\xi,\xi',j,j';J); \tag{4.6}$$

$$Z(\kappa,\kappa',\xi,\xi',j,j';J) = [4\pi(2\kappa+1)(2\kappa'+1)]^{1/2}\sum_{L=|\kappa-\kappa'|}^{\kappa+\kappa'}\frac{\langle\kappa 0,\kappa' 0|L0\rangle}{\sqrt{2L+1}}$$

$$\times\sum_{\lambda,\lambda',M_i,M_f}\ \sum_{\nu,\nu',M^*,\bar{M}^*}(-1)^{m+\nu}\langle\kappa-m,\kappa' m'|LM_L\rangle Y^L_{M_L}(\hat{p})[H^{\xi t}_{-\nu\mu}(\lambda)]^* H^{\xi' t'}_{\nu'\mu}(\lambda)$$

$$\langle J_i M_i, \xi'\nu'|j' m_{j'}\rangle\langle j' m_{j'}, \kappa' m'|J^*\bar{M}^*\rangle\langle J_i M_i, \xi\nu|j m_j\rangle\langle j m_j, \kappa m|J^* M^*\rangle$$

$$[D^J_{m\gamma\lambda'}(\varphi_{\gamma'}\theta_{\gamma'}0)]^* D^J_{m_{\gamma'}\lambda'}(\varphi_{\gamma'}\theta_{\gamma'}0)\langle J_f M_f, Jm'_\gamma|J^*\bar{M}^*\rangle\langle J_f M_f, Jm_\gamma|J^*M^*\rangle. \tag{4.7}$$

In expression (4.5) $\beta_{A^*} = |\boldsymbol{Q}^*|/Q^*_0$ is the velocity of the recoil nucleus A^* and $\cos\alpha = (\hat{\boldsymbol{k}}'\cdot\hat{\boldsymbol{Q}}^*)$. In deriving Eq. (4.5), the quantities proportional to k'_0/k_0 were neglected and the resonance factor in Eq. (4.2) was approximately replaced by the δ-function.

As can be seen from Eqs. (4.5)-(4.7), the angular distribution of secondary photons is a function of the polarization characteristics of the recoil nucleus in the $\gamma A \to \pi A^*$ reaction.

Since the spin of the excited state of the nucleus in the reaction

$$\gamma(k,\lambda)+{}^6\text{Li}(Q_i)\to\pi^0(q)+{}^6\text{Li}^*(\varepsilon = 3.56, J^* = 0, T^* = 1)$$
$$\hookrightarrow \gamma'(k',\lambda')+{}^6\text{Li}(Q_f) \tag{4.8}$$

is zero, there is a simple relation between the cross sections for the reactions (4.8) and (3.2)

$$\frac{d^2\sigma}{d\Omega_\pi d\Omega_{\gamma'}} \simeq (1-\beta_{A_*}\cos\alpha)^{-1}\frac{1}{4\pi}\frac{d\sigma}{d\Omega}[\gamma\ {}^6\text{Li}\to\pi^0\ {}^6\text{Li}^*(3.56)]. \tag{4.9}$$

The general expression for the cross section of the reaction

$$\gamma(k,\lambda)+{}^6\text{Li}\,(Q_i) \rightarrow \pi^0(q)+{}^6\text{Li}^*\,(\varepsilon = 5.37,\ J^* = 2,\ T^* = 1)$$
$$\hookrightarrow \gamma'(k',\lambda')+{}^6\text{Li}\,(Q_f) \tag{4.10}$$

is rather cumbersome. In calculations, however, we can take into account only two transitions $|{}^{31}S_1\rangle \rightarrow |{}^{13}D_2\rangle$, $|{}^{11}P_1\rangle \rightarrow |{}^{33}P_2\rangle$ in the reaction (3.4): calculations show that other transitions provide a small contribution to the cross section in the covered energy region of incident gamma quanta. In this case the double differential cross section for the reaction (4.10) can be approximately written as

$$\frac{d^2\sigma}{d\Omega_\pi d\Omega_{\gamma'}} \simeq \frac{\Gamma_\gamma}{\Gamma}\,\frac{W(\theta_{\gamma'},\varphi_{\gamma'})}{4\pi}\,(1-\beta_{A*}\cos\alpha)^{-1}\,\frac{d\sigma}{d\Omega}\,[\gamma\ {}^6\text{Li} \rightarrow \pi^0\ {}^6\text{Li}^*\,(5.37)], \tag{4.11}$$

where

$$W(\theta_{\gamma'},\varphi_{\gamma'}) = 1+\tfrac{3}{8}\,[(3\cos^2\theta_R-1)\,\tfrac{1}{3}\,(1-3\cos^2\theta_{\gamma'})+\tfrac{1}{2}\sin(2\theta_R)\sin(2\theta_{\gamma'})\cos\varphi_{\gamma'}$$
$$-\sin^2\theta_R\sin^2\theta_{\gamma'}\cos(2\varphi_{\gamma'})], \tag{4.12}$$

θ_R is the emission angle of the recoil nucleus in the $\gamma{}^6\text{Li} \rightarrow \pi^0\ {}^6\text{Li}^*$ (5.37) reaction, and $\theta_{\gamma'}$ and $\varphi_{\gamma'}$ are the emission angles of the secondary photon in the reaction (4.10), the azimuthal angle $\varphi_{\gamma'}$ being counted off from the reaction plane determined by momenta

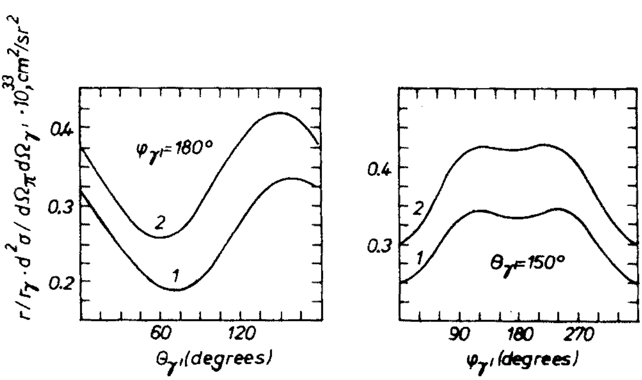

Fig. 4. The angular distribution of secondary photons in the $\gamma\,{}^6\text{Li} \rightarrow \pi^0\,{}^6\text{Li}^*\,(5.37) \rightarrow \pi^0\gamma'\,{}^6\text{Li}$ reaction in the laboratory system for different emission angles of π^0 mesons: *1*, $\theta = 28.5°$; *2*, $\theta = 57°$ at the incident gamma-quantum energy $k_0^{\text{lab}} = 300$ MeV

k and ***q***. In deriving Eq. (4.11), we neglected the small admixture of the electric quadrupole radiation to the magnetic dipole radiation [27] in the radiative decay of the excited state of the nucleus. The calculated cross sections (4.11) are presented in Figs. 4 and 5 as functions of the emission angles of secondary photons. For the incident gamma-quantum energy $k_0 = 300$ MeV the shape of the angular distribution of decay photon of ^{6}Li (5.37) in the reaction (4.10) is weakly dependent on the emission angle θ of π^0 mesons (see curves *1* and *2* in Fig. 4). Fig. 5 illustrates the dependence of the cross section $d^2\sigma/d\Omega_\pi d\Omega_{\gamma'}$, calculated for the incident gamma-quantum energy 650 MeV, on the polar $\theta_{\gamma'}$ and azimuthal $\varphi_{\gamma'}$ angle.

Consideration of the reactions (4.8) and (4.10) shows that the two-step processes (4.1) can be used to obtain additional data on the partial photoproduction reactions.

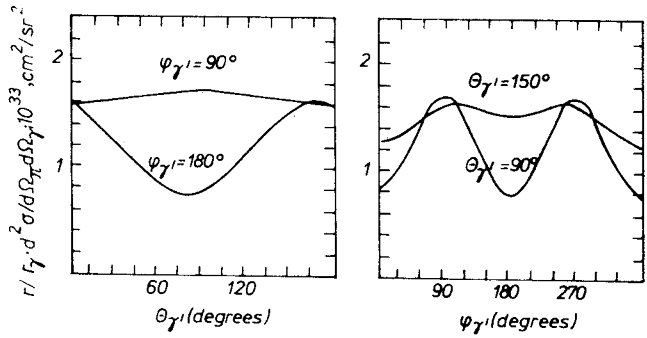

Fig. 5. The dependence of the differential cross sections for the $\gamma\,^6Li \to \pi^0\,^6Li^*$ (5.37) $\to \pi^0\gamma'\,^6Li$ reaction on the polar $\theta_{\gamma'}$ and azimuthal $\varphi_{\gamma'}$ emission angles of secondary photons at the incident gamma-quantum energy $k_0^{lab} = 650$ MeV for the angle $\theta = 27°$

It should be noted, however, that the differential cross sections for the reaction (4.10) are strongly suppressed because of the smallness of the ratio $\frac{\Gamma_\gamma}{\Gamma}$ since the excited state of $^6Li^*$ (5.37) decays predominantly through strong interactions.

5. *Conclusion*

In the present paper we have used the plane wave impulse approximation in order to consider the main qualitative features of partial reactions for the π^0-meson photoproduction on ^6Li. The analysis made suggests that the differential cross sections for the $\gamma^6Li \to \pi^0\,^6Li^*$ reactions contain information on the single-nucleon amplitudes of meson photoproduction and on the structure of the ^6Li nucleus.

Meson–nuclear interaction in the final state, estimated in the eikonal approximation with the local optical potential, leads to suppression of cross sections but without essential disturbing of ratios between cross sections of different channels of the reaction. On the other hand charge exchange rescattering corrections may play significant part for the reactions involving small cross sections [10, 11] and further investigations of such processes are of interest for locking into the mechanism of meson photcproduction on nuclei.

As was demonstrated in Ref. [12], reactions with the formation of a final nucleus in a definite excited state can be separated out by the coincidence detection of a meson and secondary photon. Measurements of the meson momentum and secondary photon energy for different emission angles of particles will make it possible not only to obtain angular distributions but also to determine the incident photon energy. This aspect of the method is important when working with bremsstrahlung beams.

The theoretical treatment of two-step reactions carried out in the present paper, using the $\gamma^6Li \to \pi^{0\,6}Li^* \to \pi^0\gamma'^6Li$ reactions, and in Refs. [12, 14], using the $\gamma^4He \to K^+\,{}^4_\Lambda H^* \to K^+\gamma'\,{}^4_\Lambda H$, $\gamma^6Li^* \to \eta^6Li^* \to \eta\gamma'^6Li$ processes, indicates that in the case of the nonzero spin of an excited nucleus the angular distribution of secondary photons is determined by other combinations of the single-nucleon amplitudes, which differ from those determining the angular distribution of mesons. Thus, the measurement of the angular distribution of secondary photons is also of interest for obtaining additional data on the single-nucleon amplitudes.

When choosing nuclear transitions for measuring the characteristics of two-step reactions, one should remember that the factor $\frac{\Gamma_\gamma}{\Gamma}$ occurs in the expressions for the cross section. For the high-lying levels decaying through many channels $\Gamma_\gamma/\Gamma \ll 1$, which leads to small reaction yields. However, for the low-lying levels of nuclei the ratio $\frac{\Gamma_\gamma}{\Gamma}$ is equal to unity in many cases. In addition to the ^6Li nucleus, ^{10}B, ^{12}C, ^{14}N and other nuclei can be recommended as targets for investigating the processes of the meson photoproduction on nuclei with the subsequent emission of secondary gamma quanta.

REFERENCES

[1] A. K. Rej, T. Engeland, *Phys. Lett.* **45B**, 77 (1973).
[2] C. Lazard, Z. Maric, *Nuovo Cimento* **16A**, 605 (1973).
[3] V. Devanathan, G. E. S. Prasad, *Proc. Nucl. Phys. and Solid State Phys. Symp. Calcutta* **18B**, 93 (1975).
[4] R. Händel, W. Weise, *Lett. Nuovo Cimento* **14**, 592 (1975).
[5] J. B. Cammarata, T. W. Donnelly, *Nucl. Phys.* **A267**, 365 (1976).
[6] A. Nagl, H. Überall, *Phys. Lett.* **63B**, 291 (1976).
[7] I. Blomqvist et al., *Phys. Rev.* **C15**, 988 (1977).
[8] G. Ramachandran, N. D. Prabhakar, A, K. Rej, *Nucl. Phys.* **B20**, 369 (1970).
[9] A. K. Rej, N. D. Prabhakar, G. Ramachandran, *Nucl. Phys.* **B15**, 56 (1970).
[10] J. D. Vergados, R. M. Woloshyn, *Phys. Rev.* **C16**, 292 (1977).
[11] J. H. Koch, R. M. Woloshyn, *Phys. Lett.* **60B**, 221 (1976).
[12] V. N. Fetisov, M. I. Kozlov, *Gamma spectroscopy of hypernuclei in processes of K^+-meson photoproduction* (in Russian), Preprint of P. N. Lebedev Physical Institute 1974, No. 25.
[13] G. A. Sokol, V. N. Fetisov, *Study of partial transitions in the π-meson photoproduction on nuclei* (in Russian), Preprint of P. N. Lebedev Physical Institute 1975, No. 144.
[14] A. I. Lebedev, V. A. Tryasuchev, V. N. Fetisov, *Yad. Fiz.* **27**, 1584 (1978).
[15] A. S. Belousov et al., *Partial cross sections for photoproduction of neutral mesons on ^6Li in resonance energy region* (in Russian), Preprint of P. N. Lebedev Physical Institute 1978, No. 93.
[16] R. Neuhausen, R. M. Hutcheon, *Nucl. Phys.* **A164**, 497 (1971).
[17] T. W. Donnelly, J. D. Walecka, *Phys. Lett.* **44B**, 330 (1973).
[18] J. C. Bergstrom, I. P. Auer, R. S. Hicks, *Nucl. Phys.* **A251**, 401 (1975).
[19] G. Ya. Korenman, V. P. Popov, *Yad. Fiz.* **26**, 84 (1977).
[20] V. A. Tryasuchev, *Yad. Fiz.* **27**, 316 (1978).
[21] A. N. Boyarkina, M. A. Zhusopuv, V. V. Karapetyan, *Structure of light nuclei* (in Russian), Moscow State University, Moscow 1968.

[22] V. G. Neudatchin, Yu. F. Smirnov, *Nucleon clusters in light nuclei* (in Russian), Nauka, Moscow 1969.
[23] G. Ramachandran, V. Devanathan, *Nucl. Phys.* **66**, 595 (1965).
[24] F. Ajezenberg-Selove, T. Lauritsen, *Nucl. Phys.* **A227**, 1 (1974).
[25] R. G. Moorhouse, H. Oberlack, A. H. Rosenfeld, *Phys. Rev.* **D9**, 1 (1974).
[26] J. M. Eisenberg, W. Greiner, *Nuclear Theory*. Vol. 2. *Excitation Mechanisms of the Nucleus Electromagnetic and Weak Interactions*, North-Holland Pub. Comp., Amsterdam-London 1970.
[27] E. V. Lan'ko, G. S. Dombrovsky, Yu. K. Shubnyi, *Probabilities for electromagnetic transitions of atomic nuclei* ($Z = 1$–30) (in Russian), Nauka, Leningrad 1972.
[28] F. Eingenbrod, *Z. Phys.* **226**, 337 (1969).