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RADIATIVE PION CAPTURE BY ^{32}S

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Радиационный захват π^--мезонов ядром ^{32}S

В рамках модели оболочек рассмотрен процесс радиационного захвата π-мезона ядром ^{32}S. Рассчитаны вероятности переходов и выходы γ-квантов с возбуждением состояний со спинами $J^{\pi} = 0^-, 1^-, 2^-$ и 3^-. Учёт только $1\hbar\omega$ переходов не исчерпывает всей экспериментальной силы. Выход γ-квантов с возбуждением этих состояний составляет 30% от полного. Хорошее согласие с экспериментом может быть достигнуто при учёте переходов квадрупольного типа. Наличие у мезона орбитального момента и специфики мультипольного разложения амплитуды приводят к тому, что в ядре с заметной вероятностью возбуждаются состояния со спином $J = 3,4$.

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Radiative Pion Capture by ^{32}S

The radiative pion capture by ^{32}S nucleus was considered in the framework of shell model. The transition rates and the yield of hard γ-quanta with the excitation of $J^{\pi}=0^-, 1^-, 2^-$ and 3^- states were calculated. It is shown that the $1\hbar\omega$ basis cannot give adequate description of the experimental data. The calculated yield of γ-quanta due to $1\hbar\omega$ excitations is 30% of the total one. It is pointed out that the agreement with available experimental results can be obtained if quadrupole type transitions are taken into account.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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1. INTRODUCTION

The radiative pion capture by atomic nuclei

$$\pi^- + (A,Z) \to \gamma + (A, Z-1) \qquad (1)$$

belongs to process of the resonance type. The observed spectrum of γ-quanta has a broad maximum smoothly damping with growing of excitation energy of nucleus and, hence with decreasing energy of γ-quantum /1/. The very hard part of γ-spectrum clearly possesses individual peaks. In light nuclei (except for magic ones) these mean the isobar analogs of M1-resonance in the target nucleus. The energy region of excitation of the nuclear system that corresponds to a broad maximum of the spectrum coincides with the region of localization of states of the isovector giant resonance.

A consistent theoretical study of the radiative pion capture by atomic nuclei has been performed only for 1p-shell nuclei /2-4/. In these papers, main regularities of the process have been established at the basis of the idea of the dominant role of resonance excitation mechanism.

In this paper, we investigated the radiative pion capture by nucleus ^{32}S, typical for the (2s-1d) shell nuclei. The reason for that choice is that earlier some other processes have been considered (photoabsorption, electroexcitation and μ^--capture) /5-8/ which give rise to excitation of different kinds of spin-isospin giant resonances. Good agreement with experiment has been achieved there.

In spite of analogy between μ-capture and radiative pion capture, a number of specific properties of the latter produces new regularities. These peculiarities are due to the fact that the radiative pion capture proceeds mainly from the high-lying orbits of a mesoatom. Because of the existence of orbital momentum for pion and large momentum transferred to nucleus, different types of resonances are generated in the nuclear system. These resonances are distributed over large energy interval and the corresponding hard γ-quantum spectrum possesses a different structure than corresponding neutrino spectrum (nuclear excitation spectrum) in μ-capture.

The aim of the present paper is to establish specific properties of radiative pion capture for nuclei of the $(2s-1d)$ shell through concrete calculations.

II. CALCULATION PROCEDURE

1. Radiative Pion Capture

The impulse approximation for the effective Hamiltonian of radiative pion capture by atomic nuclei is written in the form /9/

$$H_{eff} = \sum_{j}^{A} \tau_{-}(j)\, e^{-i\vec{k}\vec{r}_j} f(j)\cdot \Phi_{n\ell m}(\vec{r}_j). \qquad (2)$$

Here $\tau_{-}|p\rangle = |n\rangle$, $\vec{k}$ is the momentum of γ-quantum and $\Phi_{n\ell m}(\vec{r})$ is the pion wave function. The amplitude $f(j)$ describes the process on an isolated proton. This amplitude up to the terms linear in pion momentum, $\vec{q}$, is of the form

$$f(j) = i\{A\cdot(\vec{\sigma}_j\cdot\vec{\epsilon}_\lambda) + B(\vec{\sigma}_j\cdot\vec{\epsilon}_\lambda)(\vec{k}\cdot\vec{q}) + C\cdot(\vec{\sigma}_j\cdot\vec{k})(\vec{\epsilon}_\lambda\cdot\vec{q}) + \qquad (3)$$

$$+\, iD\cdot\vec{\epsilon}_\lambda\cdot(\vec{q}\times\vec{k})\},$$

where $\vec{\epsilon}_\lambda$ is the polarization vector of γ- quantum. We used the following values of form factors /9/

$$A = -0.0332 m_\pi^{-1};\ B = 0.0048 m_\pi^{-3};\ C = -0.0329 m_\pi^{-3};\ D = -0.0117 m_\pi^{-3}.$$

The probability of radiative pion capture from $(n\ell)$ orbit with transition of a nucleus from state $|i\rangle$ to state $|f\rangle$

is given by the following expression (M_N is the nucleon mass, M_A is the mass of nucleus, m_π is the pion mass)

$$\lambda(n\ell) = \frac{(1+m_\pi/M_N)^2}{(1+k/M_A)}\left(\frac{k}{m_\pi}\right)\frac{1}{(2J_i+1)(2\ell+1)} \times$$

$$\times \int d\Omega_{\vec{k}} \, \Sigma \, |\langle J_f M_f | H_{eff} | J_i M_i \rangle|^2 . \qquad (4)$$

Summation runs over all projection (m, λ, M_i, M_f).

As a rule, the experiment measures the yield of γ-quanta

$$R = \sum_{n\ell} \frac{\lambda(n\ell)}{\Lambda_{abs}(n\ell)} \cdot \omega_{n\ell} , \qquad (5)$$

where $\Lambda_{abs}(n\ell)$ is the total probability of pion absorption from $(n\ell)$ orbit, and $\omega_{n\ell}$ is the contribution of the corresponding mesoatomic orbit to the total yield.

Assuming, as usual, that the ratio $\lambda(n\ell)/\Lambda_{abs}(n\ell)$ does not depend on n and denoting $\omega_\ell = \sum_n \omega_{n\ell}$, we rewrite expression (5) for the radiative pion capture by nucleus ^{32}S in the following form

$$R = \frac{\lambda(2p)}{\Lambda_{abs}(2p)} \cdot \omega_p + \frac{\lambda(3d)}{\Lambda_{abs}(3d)} \cdot \omega_d \qquad (6)$$

with

$$\omega_p + \omega_d = 1 .$$

Mesoatomic parameters $\Gamma_{n\ell} = \hbar \cdot \Lambda_{abs}(n\ell)$ and ω_ℓ in (6) are taken to equal

$\Gamma_{2p} = 0{,}79$ keV /10/, $\omega_p = 0{,}9$ /11/,

$\Gamma_{3d} = 0.25$ eV /10/, $\omega_d = 0.1$ /11/.

Further conventional step is the multipole expansion of the Hamiltonian (2) [2]. The most general form of the transition multipole operator Q_{kq} can be expressed by two terms

$$Q_{kq} = \sum_{k_2} [\sigma_1 \cdot Y_{k_2}]_{kq} \cdot F_1(r;k,k_2) + Y_{kq} \cdot F_2(r;k). \tag{7}$$

The functions $F_1(r;k,k_2)$ and $F_2(r;k)$ include the coefficients of recoupling of moments, pion radial wave function and components originating from the multipole expansion of the plane wave of outgoing γ-qunatum. As a rule, the second term of (7) is smaller than the first. Therefore, in a qualitative analysis it can be neglected. Then from exp. (7) it follows that to $k_2 = 0$ there corresponds the operator σ_1 which coincides with the spin part of the isovector operator of electromagnetic M1 transition, to $k_2 = 1$ spin-isospin operator of the dipole type with respect to angular component, and to $k_2 = 2$ that of the quadrupole type.

The angular part $Y_{k_2 q_2}(n_\gamma)$ of the operator Q_{kq} is formed of the angular part of the plane wave expansion of the outgoing γ-quantum and of the angular part of the wave function of pion on the orbit. If the pion capture proceeds from orbits with $\ell \neq 0$ the rank of the Bessel spherical function (from the plane wave expansion of outgoing γ-quantums) does not coincide with k_2 value. Therefore, in (π^-,γ) process with the same rank of the Bessel function in the radial part (because of the pion orbital momentum) there appear operators of a higher multipolarity in the angular part as compared to analogous operators in the multipole expansion for the μ-capture, photoabsorption and electron scattering. As a result, in the process (π^-,γ) the states with higher spin will be excited with large intensity. A rather noticeable effect can be expected in heavy nuclei in which pion is captured from high ($\ell = 3,4$) orbits. In these nuclei, the states with spin J=6,7 and higher can be excited with large probability. Even in light nuclei of 1p-shell this effect manifests itself in pion capture from p-orbits.

2. Nuclear Model

The wave functions of negative parity states of the ^{32}P corresponding to excitation of the nucleus in the interval $1\hbar\omega$ have been calculated by assuming that the shells 1s, 1p, $1d_{5/2}$ are closed. We considered the states $J^{\pi} = 0^-$, 1^-, 2^- and 3^-. The shell model basis for these states has been constructed allowing for the effect of phonon states, i.e., low-lying states of ^{32}S. The levels with $J^{\pi} = 3^-$ were calculated in the approximation of doorway states neglecting the effect of phonon excitations. In the considered approximation there are three types of basis states only

$$
\begin{aligned}
&|1d^{-1}_{5/2}, (2s-1d_{3/2})^4\, J_0 T_0, j_2 : J^-, T=1\rangle,\\
&|j^{-1}_1, (2s-1d_{3/2})^5\, J_1 T_1, J^-, T=1\rangle, \qquad (8)\\
&|(2s_{1/2}-1d_{3/2})^3\, J_2 T_2, j_2 : J^-, T=1\rangle,
\end{aligned}
$$

where $j_1 = 1p_{1/2}, 1p_{3/2}$; $j_2 = 1f_{7/2}, 1f_{5/2}, 2p_{3/2}, 2p_{1/2}$.

The wave functions have been found by diagonalizing the Hamiltonian of residual interaction of nucleons in a nucleus which is taken in the form of the Serber potential with the Gaussian radial dependence. As the single particle potential, we used the harmonic oscillator with parameter

$r_0 = \sqrt{\frac{h}{m\omega}} = 1.96$ *Fm*. A detailed scheme for construction of the basis, zero-order approximation and resulting wave functions can be found in paper /5/.

The wave function of the ^{32}S ground state was taken, according to ref. /12/, in the form (only main components are presented)

$$\Psi(0^+\,0) = -\sqrt{0.496}\,|2s^4_{1/2}\rangle + \sqrt{0.391}\,|2s^2_{1/2}\,01, 1d^2_{3/2}01\rangle. \quad (9)$$

The wave functions describing $0\hbar\omega$, $2\hbar\omega$, $3\hbar\omega$ excitations in A = 32 system, were constructed in the pure particle-hole approximation. Of cause, this approximation is very rough. But it allows a qualitative estimation of the role of such excitations.

3. *Pion Wave Function*

The pion wave function was obtained by numerical solving the Klein-Gordon equation

$$[\Delta^2 + [(E - V_c)^2 - \mu^2]]\Phi_{n\ell}(\vec{r}) = 2\mu \cdot V(\vec{r}) \cdot \Phi_{n\ell}(\vec{r}) \tag{10}$$

with the Kisslinger-Ericson nonlocal optical potential [13]

$$2\mu \cdot V(r) = q(\vec{r}) - \vec{\nabla} \frac{\alpha_0(\vec{r})}{1 - \frac{1}{3}\alpha_0(\vec{r})} \vec{\nabla} \quad , \tag{11}$$

where

$$q(r) = -4\pi[p_1 \cdot b_0 \rho(r) + p_1 \cdot b_1 [\rho_n(r) - \rho_p(r)] + p_2 \cdot B_0 \cdot \rho^2(r)],$$

$$\alpha_0(r) = -4\pi[p_1^{-1} c_0 \cdot \rho(r) + p_1^{-1} \cdot c_1 [\rho_n(r) - \rho_p(r)] + p_2^{-1} C_0 \rho^2(r)],$$

$$\rho(r) = \rho_n(r) + \rho_p(r); \; p_1 = 1 + m_\pi/M_N; \; p_2 = 1 + m_\pi/(2 \cdot M_N) . \tag{12}$$

The density distribution for nucleons in the nucleus was described by a symmetrized Fermi distribution [14], assuming the same for neutrons and protons, i.e., $\rho_p(r) = \rho_n(r)$.

The shifts and widths of $2p$ and $3d$ levels of mesoatom ^{32}S calculated with the standard set of parameters of the optical potential [10] are in poor agreement with experiment:

ΔE_{2p} (theor) = 0.45 keV, Γ_{2p} (theor) = 0.36 keV,

ΔE_{2p} (exp) = (0.50 ± 0.10) keV, Γ_{2p} (exp) = (0.79 ± 0.15) keV [10],

Γ_{3d} (theor) = 0.10 eV, Γ_{3d} (exp) = (0.25 ± 0.15) eV [10].

ΔE_{2p} represents the level shift due to the strong interaction of pion with nucleus.

The shifts and widths of 2p and 3d levels are mainly defined by parameters c_0 and C_0 of the optical potential. When the wave function was calculated for the 2p state, the shifts and widths of 2p levels were fixed from experimental data, and the parameters c_0 and $\mathrm{Im}\,C_0$ were fitted (the influence on ΔE of nucleus finite dimensions and vacuum polarization was taken into account). The parameters c_0 and $\mathrm{Im}\,C_0$ were found to equal

$$c_0 = 0.252\ m_\pi^{-3}, \qquad \mathrm{Im}\,C_0 = 0.269\ m_\pi^{-6}.$$

The other parameters of the potential were taken the same as in ref. /15/:

$$b_0 = -0.027\ m_\pi^{-1}, \quad \mathrm{Re}\,B_0 = 0.053\ m_\pi^{-4}, \quad \mathrm{Im}\,B_0 = 0.051\ m_\pi^{-4},$$
$$\mathrm{Re}\,C_0 = -0.14\ m_\pi^{-6}.$$

This set of parameters provides for the width of 3d level the value is in good agreement with experiment $\Gamma_{3d} = 0.247$ *eV*.

III. RESULTS OF CALCULATION AND DISCUSSION

1. Excitation of $1\hbar\omega$ States of Negative Parity

The capture rates calculated by formulae (4) and (6) and γ-quantum yields for transitions to states $J^\pi = 0^-, 1^-, 2^-, 3^-$ are given in *Table 1*. The Table presents also the main components of the wave function for each state, the contribution from states with spin $J^\pi = 4^-$ was estimated in the particle-hole approximation.

The radiative pion capture by valence nucleons produces the resonances in the low-energy region of nucleus

Table 1

The calculated transition rates $\lambda(n\ell)$ and yield of γ-quanta in the radiative pion capture on ^{32}S nucleus with the excitation of $J^{\pi}=0^-,1^-,2^-$ and 3^- states ($1\hbar\omega$ transitions). Only those states are given where $R > 2\cdot10^{-5}$

J^{π}	Main configurations	$\lambda(2p)$ $[10^{13}sec^{-1}]$	$\lambda(3d)$ $[10^{10}sec^{-1}]$	I_n $[10^{-6}]$			$E^*(^{32}P)$ $[MeV]$	E_{γ} $[MeV]$
				R_p	R_d	R		
	$1d^{-1}5/2, j^4(0^+)_1, 1f\,5/2$	2,08	2,55	15,5	6,8	22,3	18,1	119,0
0^-	$1p^{-1}3/2, j^5(3/2)_1$	4,84	3,42	36,3	9,0	45,3	26,7	110,3
	$1p^{-1}3/2, j^5(3/2)_2$	8,24	5,55	61,7	14,7	76,4	28,4	106,7
	$j^3(1/2)_1, 2p\,3/2$	3,35	1,11	25,1	3,0	28,1	3,6	133,4
	$j^3(1/2)_1, 2p\,1/2$	4,42	1,29	33,1	3,4	36,5	6,2	130,9
	$1d^{-1}5/2, j^4(0^+)_1, 2p\,3/2$	12,32	1,37	92,4	3,6	96,0	11,0	126,1
	$1d^{-1}5/2, j^4(2^+), 1f\,7/2$	2,36	0,70	17,8	1,9	19,7	12,0	125,1
	$j^3(5/2)_1, 1f\,5/2$	7,76	2,30	58,2	6,1	64,3	12,5	124,6
1^-	$1d^{-1}5/2, j^4(0^+)_1, 1f\,7/2$	16,98	4,96	127,2	13,1	140,3	12,6	124,5
	$1d^{-1}5/2, j^4(2^+)_1, 1f\,7/2$	2,91	0,78	21,6	2,1	23,9	12,9	124,2
	$1d^{-1}5/2, j^4(0^+)_1, 1f\,7/2$	31,08	11,99	233,1	31,5	264,6	17,5	119,5
	$1d^{-1}5/2, j^4(2^+), 1f\,5/2$	3,69	1,67	27,6	4,3	31,9	23,5	113,6
	$1p^{-1}3/2, j^5(1/2)_1$	3,15	0,67	23,6	1,8	25,4	25,3	111,9
	$1p^{-1}3/2, j^5(3/2)_1$	33,97	14,54	254,7	38,3	293,0	26,6	110,5
	$1p^{-1}3/2, j^5(3/2)_2$	2,94	1,52	22,1	4,0	26,1	27,5	109,6
	$j^3(1/2)_1, 2p\,3/2$	17,54	4,68	131,5	12,3	143,8	3,9	133,2
	$j^3(3/2)_1, 1f\,7/2$	29,53	4,67	221,4	12,3	233,7	4,1	132,9
	$j^3(1/2)_1, 1f\,5/2$	7,73	0,51	57,9	1,3	59,2	9,3	127,7
	$1d^{-1}5/2, j^4(0^+)_1, 2p\,3/2$	7,18	0,81	53,6	2,1	55,9	10,0	127,0
	$j^3(3/2)_1, 1f\,5/2$	7,84	1,03	58,7	2,7	61,4	10,5	126,5
2^-	$1d^{-1}5/2, j^4(0^+)_1, 1f\,7/2$	54,72	16,32	410,4	42,9	453,3	10,9	125,1
	$1d^{-1}5/2, j^4(0^+)_1, 2p\,1/2$	21,75	11,77	163,2	31,0	194,2	13,0	124,0
	$1d^{-1}5/2, j^4(0^+)_1, 1f\,5/2$	18,20	2,46	136,8	6,4	143,2	16,3	120,8
	$1d^{-1}5/2, j^4(0^+)_1, 1f\,5/2$	35,41	4,53	265,5	11,9	277,4	16,4	120,7
	$1p^{-1}3/2, j^5(3/2)_1$	31,64	2,14	236,8	5,7	242,5	24,3	112,8

Table 1 (continue)

	$j^3(1/2)_1, 1f\,7/2$	7,67	3,81	57,5	10,0	67,5	3,0	134,1
	$j^3(3/2)_1, 1f\,7/2$	9,12	3,96	69,4	10,4	78,8	5,1	132,0
	$j^3(1/2)_1, 2p\,3/2$	10,19	4,31	76,4	11,3	87,7	6,1	131,0
3^-	$j^3(1/2)_1, 1f\,5/2$	15,54	4,12	116,1	10,9	127,0	9,4	127,0
	$1d^{-1}5/2, j^4(0^+)_1, 2p\,1/2$	12,21	3,06	91,8	8,1	99,9	13,2	123,9
	$1d^{-1}5/2, j^4(0^+)_2, 1f\,5/2$	39,41	13,43	295,5	35,4	330,9	16,5	120,6
	$1p^{-1}3/2, j^5(3/2)_1$	20,98	9,22	156,9	24,3	181,2	24,5	112,6

excitation. Main maxima in γ-spectrum are due to the excitation of nucleons from inner $1d_{5/2}$ and $1p$-shells. Because of a large energy distance between $(2s - 1d_{3/2})$, $1d_{5/2}$ and $1p$ shells there arise three groups of transitions. This effect is known as the configurational splitting of the giant resonance /16/.

Due to a structure of the operator of the external field, the transition $1p_{3/2} \to 1d_{3/2}$ with spin flip appears to be very strong. This high-energy branch is excited weakly in reactions of photoabsorption, and the effect of configurational splitting is not as clear as in the radiative pion capture. A similar intensification of the transition $1p_{3/2} \to 1d_{3/2}$ occurs also in the μ-capture /7/.

The spin-isospin component of the external field (7) produces a strong excitation of the states with spin $J^{\pi} = 2^-, 3^-$, these states being spreaded over the wide energy interval. Due to this fact and configurational splitting of giant resonance the γ-quantum spectrum appears to be distributed in a rather wide energy region.

The total yield of γ-quanta with excitation of the above states appears to equal 0.55%. The calculated yield is very small as compared to the measured value /17/: $R_{exp} = (1.8 \pm 0.1)\%$. It means that the consideration only for $1\hbar\omega$ transitions is insufficient for the description of the radiative pion capture by nuclei of $(2s-1d)$ shell.

2. *Excitation of* $0\hbar\omega$, $2\hbar\omega$, $3\hbar\omega$ *States*

The contribution of transitions corresponding to excitations of nucleus in the energy range $0\hbar\omega$, $2\hbar\omega$, $3\hbar\omega$

has been estimated in the particle-hole approximation. The wave function of the ground state of ^{32}S was taken as $|(2s_{1/2})^4:00\rangle$. The mean excitation energy of relevant states was assumed to be 5, 30 and 40 *MeV*. In this approach, we have estimated also the contribution from states corresponding to $1\hbar\omega$ excitation, already considered in the framework of a many particle shell model. This comparison of both approaches shows that quantitatively results are not deviated from each other very much. Therefore, the one-particle approach used allows a qualitative estimation of the excitations above listed.

As follows from the results of calculation given in *Tables 2* and *3* there is a large contribution from excitations of the magnetic dipole M1 and spin-quadrupole type. The latter are connected with the operator $|\sigma_1 \times Y_2|_k$ and with transitions mainly through the shell ($2\hbar\omega$ excitation). A large contribution of the quadrupole branch of excitation gives rise to a further broadening and

Table 2a

The single particle estimation of the $\lambda(nl)$ due to the $0\hbar\omega$ ($E^* \sim 5$ *MeV*) transitions.

$\lambda(nl)$	$\|n_i l_i j_i\rangle \to \|n_f l_f j_f\rangle$	J^π: 1^+	2^+	3^+	4^+	$\sum_{J_f^\pi} \lambda(J_f^\pi)$
$\lambda(2p)$ $[10^{13}sec^{-1}]$	1d 5/2 → 1d 3/2	138,1	62,6	42,7	11,7	255,1
	2s → 1d 3/2	4,9	28,7	-	-	33,6
	Total rate	143,0	91,3	42,7	11,7	288,7
$\lambda(3d)$ $[10^{10}sec^{-1}]$	1d 5/2 → 1d 3/2	21,0	5,7	8,6	8,3	43,6
	2s → 1 3/2	1,6	3,3	-	-	4,9
	Total rate	22,6	9,0	8,6	8,3	48,5

Table 2b

The single particle estimations of the $\lambda(nl)$ due to the $2\hbar\omega$ ($E^* \approx 30$ *MeV*) transitions.

$\lambda(nl)$	$\lvert n_i l_i j_i\rangle \to \lvert n_f l_f j_f\rangle$	J_f^π					$\sum_{J_f^\pi} \lambda(J_f^\pi)$
		1^+	2^+	3^+	4^+	5^+	
$\lambda(2p)$ $[10^{13}\,sec^{-1}]$	$1d\,5/2 \to 1g, 2d, 3s$	55,8	169,9	59,8	3,9	7,9	332,3
	$1p; 1s \to 1f, 2p; 1d\,3/2$	59,0	143,1	136,1	5,2	3,1	346,5
	$2s \to 1g, 2d, 3s$	13,8	23,0	31,3	10,4	6,4	84,9
	Total rate	128,6	336,0	257,2	24,5	17,4	763,7
$\lambda(3d)$ $[10^{10}\,sec^{-1}]$	$1d\,5/2 \quad 1g, 2d, 3s$	12,9	26,8	25,2	10,3	12,8	80,0
	$1p; 1s \quad 1f, 2p; 1d\,3/2$	8,3	18,3	37,2	6,9	5,5	76,2
	$2s \to 1g, 2d, 3s$	4,3	3,8	9,3	12,8	10,5	40,7
	Total rate	25,5	40,9	71	30,0	28,8	204,9

smoothing of the giant resonance. The analogous situation appears even in the nucleus ^{16}O where the contribution of $2\hbar\omega$ transitions amounts to about a half of the total yeild of γ-quanta [18]. Because of a large number of peaks with equal intensity in the excitation spectrum distributed over a large energy interval, the giant resonance is observed as broad maximum without structure.

As follows from the results listed in Table 3, in the absorption of pions from 2p orbit in ^{32}S the contribution of states with spins $J^\pi = 3^-, 4^-$ becomes noticeable. The excitation of these states is due to the operators $[\sigma_1 \times Y_3]_{k=3,4}$. In the pion capture from 3d orbit there are observed the states with spins $J^\pi = 4^+, 5^+$ whose excitation is due to the operator $[\sigma_1 \times Y_4]_{k=4,5}$.

The capture from d orbit of mesoatom equals 10%. The role of capture from d orbit increases with increasing spin of the finite state.

Table 2c

The single particle estimation of the $\lambda(n\ell)$ due to the $3\hbar\omega$ ($E^* ..$ 40 *MeV*) transitions.

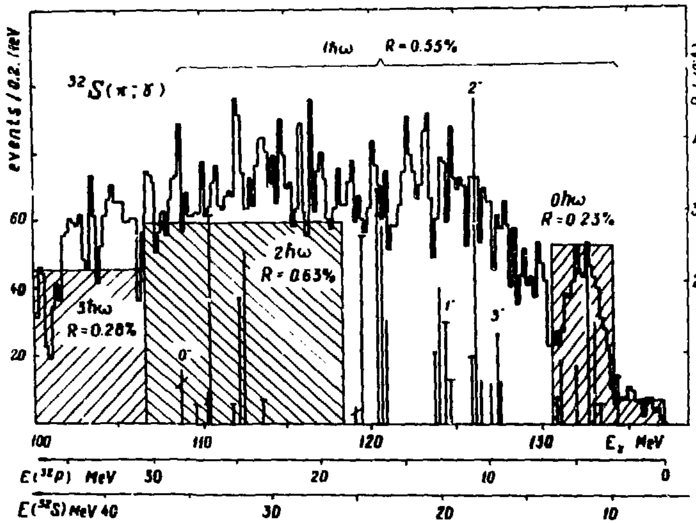
$\lambda(n\ell)$	$\|n_i \ell_i j_i\rangle \to \|n_f \ell_f j_f\rangle$	J_f^π				$\sum_{J_f^\pi} \lambda(J_f^\pi)$
		1^-	2^-	3^-	4^-	
$\lambda(2p)$ $[10^{13} sec^{-1}]$	$1s \to 1f, 2p$	5,5	9,5	6,5	4,8	26,4
	$1p \to 1g, 2d, 3s$	22,9	42,0	29,4	21,3	115,5
	$1d\,5/2 \to 1h, 2f, 3p$	30,5	50,7	48,9	16,6	146,7
	$2s \to 1h, 2f, 3p$	10,2	17,7	6,2	5,3	39,3
	Total rate	69,2	119,8	91,0	47,9	327,9
$\lambda(3d)$ $[10^{10} sec^{-1}]$	$1s \to 1f, 2p$	0,5	2,3	4,8	5,1	12,6
	$1p \to 1g, 2d, 3s$	1,7	8,1	19,2	21,2	50,2
	$1d\,5/2 \to 1h, 2f, 3p$	2,4	11,2	32,4	15,3	61,3
	$2s \to 1h, 2f, 3p$	0,7	2,0	2,8	4,3	9,9
	Total rate	5,4	23,6	59,1	45,8	133,9

Consider now excitations which correspond to the transitions of nucleons within the same valent shell ($0\hbar\omega$ excitations). They should be concentrated in the low-energy range of the excitation spectrum of ^{32}P. As in the case of 1p-shell nuclei, they correspond to the M1 resonances in ^{32}S and resonances with spins $J^\pi = 2^+, 3^+$. The excitation region of resonances corresponds to an energy of γ-quanta of about 135 *MeV*. Thus, in this region one can expect the resonance structure to be observed in the γ-spectrum. A large probability of excitation of states with $J^\pi = 2^+$ and 3^+ is due to a considerable contribution of radial integrals from the second-rank Bessel spherical functions and by specific

Table 3

The transitions rates $\lambda(nl)$ and corresponding yield of hard γ-quanta summed over different final states with definite spin.

$N\hbar\omega$	J_f^π	$\lambda(2p)$ $[10^{13}\,sec^{-1}]$	$\lambda(3d)$ $[10^{10}\,sec^{-1}]$	I_n $[10^{-4}]$		
				R_p	R_d	R
$0\hbar\omega$	1^+	143,0	22,6	10,73	0,59	11,32
	2^+	91,3	9,0	6,83	0,23	7,06
	3^+	42,7	8,6	3,24	0,23	3,47
	4^+	11,7	8,3	0,91	0,20	1,11
$1\hbar\omega$	0^-	16,7	13,3	1,24	0,36	1,60
	1^-	155,4	55,5	11,66	1,47	13,13
	2^-	295,3	64,4	22,09	1,70	23,79
	3^-	115,4	42,2	8,66	1,11	9,77
	4^-	71,0	52,2	5,33	1,38	6,71
$2\hbar\omega$	1^+	128,6	25,5	9,66	0,68	10,34
	2^+	336,0	48,9	25,20	1,29	26,49
	3^+	257,2	71,7	19,31	1,90	21,21
	4^+	24,5	30,0	1,83	0,79	2,62
	5^+	17,4	28,8	1,33	0,75	2,08
$3\hbar\omega$	1^-	69,2	5,4	5,19	0,14	5,33
	2^-	119,8	23,6	8,98	0,62	9,60
	3^-	91,0	55,1	6,82	1,56	8,38
	4^-	47,9	45,8	3,59	1,21	4,80
$0\hbar\omega$	$\sum J_f^\pi$	288,7	48,5	21,71	1,25	22,96
$1\hbar\omega$	$\sum J_f^\pi$	653,6	227,6	48,98	6,02	55,00
$2\hbar\omega$	$\sum J_f^\pi$	763,7	204,9	57,33	5,41	62,74
$3\hbar\omega$	$\sum J_f^\pi$	327,9	135,9	24,59	3,53	28,12
Total		2034,1	614,9	152,61	16,21	168,8



Yield of γ-quanta in the process $^{32}S(\pi^-, \gamma)^{32}P^*$. The histogram is the experimental γ-spectrum, shaded area and vertical lines represent the calculation.

properties of the multipole expansion of the Hamiltonian (2) /19/ .

The calculated yield of γ-quanta and experimental data /20/ are shown in the *Figure*. Vertical lines represent the contribution of states with spin $J^\pi = 0^-, 1^-, 2^-, 3^-$ ($1\hbar\omega$ - excitations), shaded areas, the contribution of states due to $0\hbar\omega$, $2\hbar\omega$, $3\hbar\omega$ excitations. As a whole, the theory admits the interpretation of the spectrum observed experimentally. The calculated total yield of γ-quanta turns out to be equal to about 1.69%.

IV. CONCLUSION

In the present paper we have considered the radiative capture of π^- -meson by nucleus ^{32}S in the framework of the shell model. The results of calculation indicate that in this process the configurational splitting of resonance $1\hbar\omega$ is far more pronounced than in the photoabsorption, electroexcitation and μ-capture. At the same time, the effect of states $2\hbar\omega$ becomes more considerable than in 1p-shell nuclei.

From the superposition of these two effects it is clear that the resonance structure of the spectrum is smeared and the excitation spectrum looks like a very broad maximum with an undistinguished structure.

A considerable contribution to the yeild of γ-quanta comes from the states with $J^{\pi}=3^+,3^-,4^-$. Thus, in the radiative pion capture, unlike all other processes mentioned above, there are excited the states with higher spins. One of the reasons for these specific features of the process is that the capture proceeds from the orbits with $l \neq 0$.

The analysis we have carried out for the radiative pion capture on the typical nucleus of $(2s-1d)$ shell allows a deeper understanding of the properties of the process in that range of nuclei.

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