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PARTIAL TRANSITIONS IN RADIATIVE PION CAPTURE ON LIGHT ATOMIC NUCLEI

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Парциальные переходы при радиационном захвате пи-мезонов легкими атомными ядрами

В рамках модели оболочек с промежуточной связью исследованы парциальные переходы при радиационном захвате π-мезонов легкими ядрами. Рассчитаны вероятности захвата из s- и p-состояний мезоатома и суммарный выход γ-квантов. Полученные результаты сравниваются с экспериментальными данными.

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Partial Transitions in Radiative Pion Capture on Light Atomic Nuclei

The partial transitions at the radiative pion capture on light nuclei are studied within the shell model with intermediate coupling.

There are calculated the probabilities of capture from s - and p-states of a mesoatom and the total yield of γ-quanta. The obtained results are compared with experimental data.

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

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I. Introduction

Presently the process of the radiative pion capture on atomic nuclei

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

is more completely studied experimentally for 1p-shell nuclei ($^6Li - ^{16}O$). The interest in this process is due to two factors. First, investigating the transitions to definite discrete nuclear states, one can obtain information about the structure of the transition amplitude and thus verify the main hypothesis used for its construction. Second, a common feature of the process (π,γ) is the appearance of a wide maximum in the measured spectrum of hard γ-quanta located in the range of collective state excitation of the nuclear system. The study of the structure of giant resonance in the radiative pion capture allows the investigation of specific features of the collective states of atomic nuclei.

To discuss the problem of the radiative pion capture we should rather begin with the consideration of partial transitions to the low-lying states of daughter nuclei. Such transitions are rather fully investigated experimantally, and this enables us to compare the experimental values with those calculated within various representations both of the nuclear structure and of the process amplitude. In this way one can verify the validity of the approaches used and the reliability of the obtained results. The clarification of these problems will permit one to pass to the description of excitations in the region of the giant resonance more reliably.

II. Basic Ideas of the Theory of Radiative Pion Capture

The radiative pion capture by atomic nuclei is usually considered within the impulse approximation. The process amplitude on proton taking account of the terms of the order $\vec{q}/m_\pi$ has the form /1/

$$f=\frac{\tau^-}{\sqrt{2}}\, i\{A(\vec{\sigma}\cdot\vec{\epsilon}_\lambda)+B(\vec{\sigma}\cdot\vec{\epsilon}_\lambda)(\vec{k}\cdot\vec{q})+C(\vec{\sigma}\cdot\vec{k})(\vec{\epsilon}_\lambda\cdot\vec{q})+iD\vec{\epsilon}_\lambda\cdot(\vec{q}\times\vec{k})\}, \quad (2)$$

where $\tau^- = \frac{\tau_x - i\tau_y}{\sqrt{2}}$, , $\vec{\epsilon}_\lambda$ and $\vec{k}$ are the polarization vector and the momentum of the outgoing γ-quantum, respectively; $A = -33.2\cdot 10^{-3}\ m_\pi^{-1}$, $B = 4.8\cdot 10^{-3}\ m_\pi^{-3}$; $C = -32.9\cdot 10^{-3}\ m_\pi^{-3}$ and $D = 11.7\cdot 10^{-3}\ m_\pi^{-3}$.

The probability of the radiative pion capture by an atomic nucleus with the excitation of level with spin J_f is the following /1/

$$\lambda_{n\ell} = \frac{(1+m_\pi/M_N)^2}{(1+k/M_N)}\left(\frac{k}{m_\pi}\right)\cdot\frac{1}{(2J_i+1)(2\ell+1)}\int\Sigma|\langle J_f M_f|\mathfrak{M}|J_i M_i\rangle|^2 d\Omega_{\vec{k}}, \quad (3)$$

where

$$\mathfrak{M} = \sum_{j=1}^{A} i^{-1} f e^{-i\vec{k}\vec{r}}\,\phi_{n\ell m}(\vec{r})\cdot\delta(\vec{r}-\vec{r}_j) \quad (4)$$

$\phi_{n\ell m}(\vec{r})$ is the pion wave function with the principal quantum number n, orbital momentum ℓ and its projection m; m_π and M_N are the masses of a pion and a nucleon, respectively.

The pion wave function has been obtained by solving the Klein-Gordon equation

$$\{\nabla^2 + [(E-V_c)^2 - \mu^2]\}\phi_{n\ell}(\vec{r}) = 2\mu V(\vec{r})\phi_{n\ell}(\vec{r}) \quad (5)$$

with the Kisslinger-Ericson nonlocal optical potential

$$2\mu V(\vec{r}) = q(\vec{q}) - \vec{\nabla}\frac{\alpha_0(\vec{r})}{1-\frac{1}{3}\xi\alpha_0(\vec{r})}\vec{\nabla} + O\left(\frac{1}{A}\right),$$

$$q(\vec{r}) = -4\pi\{p_1 b_0\rho(\vec{r}) + p_1 b_1[\rho_n(\vec{r})-\rho_p(\vec{r})] + p_2 B_0\rho^2(\vec{r})\}, \quad (6)$$

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

where

$$\rho(\vec{r}) = \rho_n(\vec{r}) + \rho_p(\vec{r}); \; p = 1 + \frac{m_\pi}{M_N}; \; p = 1 + \frac{m_\pi}{2M_N};$$

ξ - specifies the polarization of the nuclear matter: in the calculations this value was taken to be equal to unity.

The density distribution of nucleons in a nucleus was described using the symmetrized Fermi-distribution [2]. The proton $\rho_p(\vec{r})$ and neutron $\rho_n(\vec{r})$ distributions were assumed to be the same.

In the lightest nuclei ^6Li, ^7Li and ^9Be the shifts and widths of 1s-levels calculated with empirically found parameters of the optical potential [3]

$$b_0 = -0.03\, m_\pi^{-1}, \; b_1 = -0.08\, m_\pi^{-1}, \; \mathrm{Im}\, B_0 = 0.04\, m_\pi^{-4}, \; \mathrm{Re}\, B_0 = 0,$$
$$c_0 = 0.22\, m_\pi^{-3}, \; c_1 = 0.18\, m_\pi^{-3}, \; \mathrm{Im}\, C_0 = 0.08\, m_\pi^{-4}, \; \mathrm{Re}\, C_0 = 0, \qquad (7)$$

considerably disagree with the experimental ones [4]. One fails to remove the discrepancy between theory and experiment by varying the diffuseness parameters T and mean-square nuclear radius of the nucleus $\langle r^2 \rangle^{1/2}$.

The shifts and widths of s-levels of a mesoatom are mainly connected with the values b_0, b_1, $\mathrm{Im}\, B_0$ and $\mathrm{Re}\, B_0$, the shifts and widths of p-, d- and other levels with the values c_0, c_1, $\mathrm{Im}\, C_0$ and $\mathrm{Re}\, C_0$. The optical potential suppresses the wave functions of s-states in the nuclear region and, on the contrary, it increases the wave functions of p-, d- and other states. The amount of suppression and increase depends on the shifts ΔE. The degree of conformity between ΔE_{theor} and ΔE_{exp} allows one to judge how well the mesoatomic state is described and how well the behaviour of the pion wave function in the inner nuclear region is reproduced.

In the present paper when calculating the wave functions of π-mesons in 1s-states, the shifts and widths of levels are fixed and taken to be equal to experimental ones: $\Delta E = \Delta E_{exp}$, $\Gamma = \Gamma_{exp}$. The parameters $\mathrm{Re}\, B_0$ and b_1 have been taken to be equal to $\mathrm{Re}\, B_0 = 0$ and $b_1 = -0.08\, m_\pi^{-1}$ according to (7), and the parameters b_0 and $\mathrm{Im}\, B_0$ have been chosen individually for each nucleus. (The effects of finite size of nuclei and of vacuum polarization on the value ΔE are taken into account). The so-obtained values of the parameters b_0 and $\mathrm{Im}\, B_0$ and the corresponding values of the quantities* $\Delta E_{1s} = E_{exp}(2p \to 1s) - E_{K-G}(2p \to 1s)$ and $\Gamma_{exp}(1s)$ are represented in table 1.

The necessity of renormalization of the constant b_0 is due to two reasons:

a) the value of b_0 depends on the Fermi nucleon momentum in the nucleus P_F. For the lightest nuclei P_F noticeably changes from nucleus to nucleus. For instance, according to experimental data [5], for the nucleus ^6Li $P_F = (169 \pm 5)$ MeV/c and for ^{12}C $P_F = (221 \pm 5)$ MeV/c;

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* $E_{exp}(2p \to 1s)$ is the experimental $(2p \to 1s)$ transition energy in the mesic atoms, $E_{K-G}(2p \to 1s)$ is the corresponding one calculated with the point Coulomb potential.

<u>Table 1</u>

Optical potential parameters

Nucleus	$-\Delta E_{1s}$ [KeV]	Γ_{1s} [KeV]	b_0 [m_π^{-1}]	$Im B_0$ [m_π^{-3}]	T [fm]	$\langle r^2\rangle^{1/2}$ [fm]
^6Li	0,302	0,195	-0,0220	0,0534	2,21	2,536
^7Li	0,524	0,195	-0,0233	0,0473	2,41	2,44
^9Be	1,613	0,591	-0,0253	0,0427	2,34	2,42
^{10}B	3,117	1,59	-0,0278	0,0515	2,12	2,45
^{11}B	3,879	1,79	-0,0288	0,0556	2,10	2,42
^{12}C	6,144	3,14	-0,0288	0,0509	2,06	2,496
^{14}N	11,735	4,34	-0,0292	0,0381	1,85	2,48
^{16}O	18,21	7,64	-0,0275	0,0461	2,14	2,71

b) in the optical potential there are no terms of the order 1/A.

Taking into account these effects results in ~~that the~~ parameter ReB_0 in the optical potential differs from zero. More thoroughly these questions were investigated in paper /6/. The solution of equation (5) with two different sets of parameters of the optical potential (in one of which $ReB_0 = 0$ and in the other $ReB_0 \neq 0$) using the same fixed values of the shift ΔE_{1s} and width Γ_{1s} differ only slightly. In the present paper for calculating the pion wave functions of 1s -state we have used the set of parameters in which $ReB_0 = 0$. Here $b = -0.08\ m_\pi^{-1}$, and the individually chosen values of the quantities b_0 and ImB_0 are presented in <u>table 1</u>.

For nuclei of the 1p-shell, except ^{16}O there are no experimental data on the shifts of 2p-levels. In ^{16}O the shift and width of the 2p-level which are specified only by the strong interaction of the pion with the nucleus are equal to /7/ $\Delta E_{2p} = (4.1 \pm 2.3)$ eV and $\Gamma_{2p} = (11 \pm 6)$ eV. According to other experimental data $\Gamma_{2p} = (12 \pm 4)$ eV /8/ and $\Gamma_{2p} = (4.7 \pm 0.8)$ eV /9/. The calculation with the standard set of parameters of the optical potential (7) results in the following values of the quantities ΔE_{2p} and $\Delta\Gamma_{2p}$: $\Delta E_{2p}(opt) = 10.3$ eV and $\Gamma_{2p}(opt) = 4.2$ eV. From empirically found dependence ΔE_{2p} and Γ_{2p} on the nuclear charge /10/ follows that $\Delta E_{2p}(emp) = 6.5$ eV and $\Gamma_{2p}(emp) = 5.2$ eV.

<u>Table 2</u> presents the values of the widths of 2p -levels obtained from experimental data and by calculation. The quantities $\Gamma_{2p}(emp)$ are obtained by the empirical formula from paper /10/ ; $\Gamma_{2p}(opt)_1$ are calculated with the parameters b_0 and ImB_0 given in <u>table 1</u> ; the parameters c_0, c_1, ImC_0 and ReC_0 have been chosen from the set (7). The quantity $\Gamma_{2p}(opt)_2$ was calculated with the numerical values of the parameters c_0, ReC_0 and ImC_0 obtained from theory /11/ taking account of their dependence on P_F.

The theoretical values of the widths of 2p -levels, obtained using the last set of parameters, better agree with the experimental data. This set of parameters results in a somewhat smaller value of the shift of 2p-levels than the others (for ^{16}O it appeared to be equal to $\Delta E_{2p}(opt)_2 = 8.5$ eV). In the present paper the probabilities of the radiative capture from 2p-state have been calculated with the pion wave functions

Table 2

Experimental and theoretical values of the quantities Γ_{2p}

Nucleus	$\Gamma_{2p}(exp)$ [eV]	$\Gamma_{2p}(opt)_1$ [eV]	$\Gamma_{2p}(opt)_2$ [eV]	$\Gamma_{2p}(emp)$ [eV]
^6Li	0,015±0,004 /8/	0,007	0,010	0,019
^7Li	0,016±0,007 /8/	0,010	0,013	0,020
^9Be	0,053±0,013 /8/ 0,16 ± 0,03 /9/	0,070	0,079	0,103
^{10}B	0,32 ± 0,06 /9/	0,256	0,289	0,359
^{11}B	0,27 ± 0,04 /9/	0,289	0,363	0,383
^{12}C	1,02 ± 0,29 /9/ 1,25/8/ 2,6 ± 0,9 /8/	0,881	0,895	1,02
^{14}N	2,2 ± 0,3 /9/	2,28	2,33	2,46
^{16}O	4,7 ± 0,8 /9/ 12 ± 4 /8/ 11 ± 6 /10/	5,5	5,11	5,26

obtained using the last set of parameters of the optical potential.

In the 1p-shell nuclei the pions are captured from s- and p-orbits. Therefore the calculated yield R of hard γ-quanta is the sum of two terms: $R = R_s + R_p$, where

$$R_s = \frac{\lambda_{1s}}{\Lambda_{1s}}\omega_s; \quad R_p = \frac{\lambda_{2p}}{\Lambda_{2p}}\omega_p;$$

Λ_{1s} and Λ_{2p} are the total probabilities of absorption of pions from 1s and 2p-orbits,

respectively, and ω_s and ω_p are the relative probabilities of absorption of pions from s - and p -orbits ($\omega_s + \omega_p = 1$). These values are rather poorly known, and not for all nuclei. In the last case we have extrapolated them from the known values in the neighbouring nuclei. The values of $\Lambda_{n\ell}$ and ω_ℓ adopted in the calculation * are given in the tables together with the calculated quantities $\lambda_{n\ell}$ and R . The values R obtained by other authors are given according to the mesoatomic characteristics which are presented in the tables. The absence of reliable data on the quantities $\Lambda_{n\ell}$ and ω_ℓ makes it difficult to a great extent to interprete the experimental yield of hard γ -quanta.

III. Transitions to Low-Lying Nuclear States

In order to describe the initial and final states of nuclei, we have used the shell model with intermediate coupling. The ground state and levels of normal parity (of the same parity as the ground state of the initial nucleus) have been described by the wave functions calculated with the Cohen-Kurath parameters /12/ in the version (8-16)2BME. For the nucleus ^6Li the Barker functions were used /13/. To describe the states of anomalous parity (opposite to parity of the ground state), the wave func-

* The values of $\Lambda_{n\ell}$ and ω_ℓ used in the present paper are almost the same as those found in experiments /3-9/.

tions were obtained on the basis of the approach presented in paper [14]. Spurious states caused by the motion of the c.m.s. are completely extracted.

In the inner region of a nucleus the gradient of the wave function of the pion in the s-state is negligible. Therefore, in absorption from this state the main contribution to the matrix element is given by the first term of the amplitude (2). It follows that in the case of radiative pion capture from s-orbit with excitation of states of normal parity the transition operator will be analogous to the spin part of the operator of M1-transition or to the operator of the allowed transition in the processes of μ-capture and β-decay. Thus, in the radiative pion capture from s-orbits the states of the magnetic dipole resonance [15-17] in the nuclear system will be excited more intensively. For the capture from p-orbits the operator $\vec{\sigma}$ plays the basic role too. Therefore, before discussing the partial transitions in (π,γ)-process, let us analyze the results of electromagnetic M1 and β-transitions [12,18] and the transitions in the muon-capture by 1p-shell nuclei [19]. The corresponding results are given in tables 3 and 4.

It should be noted that in odd-A nuclei the main component of the wave function of the nuclear ground state (to which there corresponds the maximal space symmetry) does not contribute to the transitions caused by the operator $r\vec{\sigma}$ due to the selection rule according to the Young scheme. Therefore the transitions in odd-A nuclei which are connected with this operator will

Table 3

The probabilities of M1 - and β-transitions in the nuclei of 1p-shell. The energies, given in brackets, are calculated ones

Nucleus	J_f^π	$J_0^{\pi_0}; T_0$	ΔE [MeV]	$B(M1;\downarrow)$	$\Gamma(M1;\downarrow)$ [eV] theory	$\Gamma(M1;\downarrow)$ [eV] experiment [18]	$\log ft$ theory [12]	$\log ft$ experiment [18]
^7Li	$3/2^-$ $5/2^-$ $1/2^-$	$3/2^-$, 1/2	11,2 (14,6) (12,5)	0,2I4 0,069 0,050	3,48 3,50 I,I3	1,3 ± 0,4		
^9Be	$3/2^-$ $1/2^-$ $5/2^-$	$3/2^-$, 1/2	14,4 17,0 (18,0)	0,30I 0,04I 0,003	I0,4I 2,33 0,I9	6,9 ± 0,5	4,75	5,12 ± 0,02
^{10}B	2^+ 2^+ 2^+ 3^+ 4^+	3^+, 0	5,2 7,5 8,9 (10,5) (12,0)	0,285 4,93 0,504 I,I4 0,077	0,464 23,85 4,II I5,26 I,54	0,145±0,05 11,0 ± 2,2		
^{11}B	$1/2^-$ $3/2^-$ $5/2^-$	$3/2^-$, 1/2	12,9 14,3 (17,1)	0,874 0,485 0,055	2I,78 I6,48 3,I8	29±9; 36±7 14,5 ± 4,3		
^{12}C	1^+	0^+, 0	15,1	0,835	33,34	35,74±0,86	4,08	4,072 ± 0,002
^{13}C	$3/2^-$	$1/2^-$, 1/2	15,1	0,7I3	28,5I	22,7 ± 2,6	3,89	4,02 ± 0,02
^{14}N	0^+ 2^+ 2^+	1^+; 0	2,3 9,2 10,4	0,032 {2,97	$4,64\cdot10^{-3}$ I3,0 20,0	$(8,1\pm1,4)\cdot10^{-3}$ 7,7 ± 0,9 12,1±1,5		

Table 4

Capture rates of muons by nuclei of 1p-shell following data from paper /19/ in units sec^{-1}

Process	J_f^π	k=-1,2;	Experiment	k =-1,4
$^9Be(\mu^-,\nu)^9Li$	$(3/2^-)1$	74		54
	$(3/2^-)2$	60		50
	$(1/2^-)1$	63		57
	$(5/2^-)1$	47		33
$^{10}B(\mu^-,\nu)^{10}Be$	$(2^+)1$	$1,86\cdot10^3$		$2,23\cdot10^3$
	$(2^+)2$	$6,55\cdot10^3$		$6,80\cdot10^3$
$^{12}C(\mu^-,\nu)^{12}B$	$(1^+)1$	$7,5\cdot10^3$	$(6,3\pm0,3)\cdot10^3$ /20/	$6\cdot10^3$
$^{13}C(\mu^-,\nu)^{13}B$	$(1/2^-)1$	133		158
	$(3/2^-)1$	$6,81\cdot10^3$		$5,30\cdot10^3$
$^{14}N(\mu^-,\nu)^{14}C$	$(2^+)1$	$2,22\cdot10^4$	$(10\pm3)\cdot10^3$	$2,16\cdot10^4$
	$(2^+)2$			
$^{11}B(\mu^-,\nu)^{11}Be$	$(1/2^-)1$	$1,07\cdot10^3$	$(1,00\pm0,10)\cdot10^3$ /21/	$1,02\cdot10^3$

be suppressed to some extent. Most strongly suppressed are the transitions in the nucleus ^{9}Be which is clearly seen from the calculation of the μ-capture rates. Really, the main components of the wave function of the ground state of nuclei ^{7}Li, ^{9}Be, ^{11}B and ^{13}C are $0.99|p^3[3]^{22}P>$; $0.90|p^5[41]^{22}P>+0.40|p^5[41]^{22}D>$; $0.64|p^7[43]^{22}P>+0.57|p^7[43]^{22}D>$ and $0.89|p^9[441]^{22}P>$, respectively /22/. There are no components with the mentioned Young schemes in the daughter nuclei. An analogous situation appears for the nucleus ^{12}C. In this case the role of small components of the nuclear wave function and of correction terms in the

process amplitude increases. Small components and, consequently, the transition characteristics determined by them usually depend rather strongly on the model parameters. Table 4 presents the rates of μ-capture calculated at the optimal value of the intermediate coupling patameter /22/ which is equal to k = -1.2, and at somewhat large value (k = -1.4). In the nucleus ^{9}Be, such a change of the parameter may change the capture rate by 30%. As it is impossible to fix strictly the model parameters, some uncertainty remains in the characteristics of such transitions. An analogous situation may occur for the process (π,γ) and one should take into account this fact when interpreting experimental data.

It follows from the experimental data and calculation results presented in tables 3 and 4 that on the whole the theory describes the transitions with $\Delta T=1$ in 1p-shell nuclei. Therefore the use of the same wave functions for describing the radiative pion capture is quite natural.

The transitions to the levels of anomalous parity are mainly connected with the operator of the type $[\sigma \times Y_1]_{k=0,1,2}$. This operator is also responsible for the axial-vector excitation branch in the case of μ-capture.

Transitions in Even Nuclei

The calculated probabilities of the radiative pion capture and yields of hard γ-quanta are presented in tables 5-8.

Table 5

The probabilities of the partial transitions λ_{1s} and λ_{2p} and the yield R of hard γ-quanta in the process $^6Li(\pi^-,\gamma)\,^6He$. Γ_{1s} = 195 eV; ω_s = 0.40; Γ_{2p} = 0.015 eV; ω_p = 0.60

J^{π}; T=1	$E^*(^6He)$ [MeV]	E_γ [MeV]		r_0 [fm]	λ_{1s} [$10^{15}sec^{-1}$]	λ_{2p} [$10^{11}sec^{-1}$]	R_s, %	R_p, %	R, %	R_{exp}, % /23/
0^+	0	134,0	/24/	1,89	1,46	0,412	0,198	0,108	0,306	0,306±0,035
			/1/	2,05	1,51	0,526	0,204	0,138	0,342	
			/25/		1,57	0,375	0,212	0,098	0,310	
			/26/	1,95	1,64	0,586	0,221	0,154	0,375	
			/27/	1,95	1,69	0,435	0,227	0,114	0,341	
2^+	1,8	132,2	/26/	1,95					0,147*)	0,148±0,025
			/27/	1,95	0,550	0,311	0,074	0,082	0,156	

* This value is obtained at Γ_{1s} = 150 eV.

Table 6

The probabilities of the partial transitions λ_{1s} and λ_{2p} and the yield R of hard γ-quanta in the process $^{12}C(\pi^-,\gamma)\,^{12}B$. Γ_{1s}=3.140 KeV, ω_s = 0.15; Γ_{2p} = 1.02 eV, ω_p = 0.85

J^{π}; T=1	$E^*(^{12}B)$ [MeV]	E_γ [MeV]		r_0 [fm]	λ_{1s} [$10^{15}sec^{-1}$]	λ_{2p} [$10^{11}sec^{-1}$]	R_s [10^{-4}]	R_p [10^{-4}]	R [10^{-4}]	R_{exp} /28/ [10^{-4}]
1^+	0	125,0	/25/		12,2	42,4	3,84	23,3	27,07	8,4±0,6
			/1/	1,90	9,3	11,5	2,9	6,3	9,23	
			/29/	1,64	13,3	10,3	4,2	5,7	9,83	
				1,67	11,6	8,2	3,65	4,5	8,15	
2^+	0,95	124,1	/25/		1,84	6,24	0.6	3,4	4,0	2,2±0,3
			/1/	1,90	1,0	5,7	0,3	3,1	3,4	
			/29/	1,64	1,9	7,7	0,6	4,2	4,8	
				1,67	1,0	5,8	0,3	3,2	3,5	
2^-	1,7	123,3	/1/	1,90	0,9	4,0	0,3	2,2	2,5	0,3±0,2
1^-	2,6	122,4	/1/	1,90	2,7	1,3	0,8	0,7	1,5	1,9±0,3
3^+	(5,6)	119,4		1,67	0,55	3,6	0,2	2,0	2,17	

Table 7

The probabilities of the partial transitions λ_{1s} and λ_{2p} and the yield R of hard γ-quanta in the process $^{10}B(\pi^-,\gamma)^{10}Be$. Γ_{1s}=1.680 KeV, ω_s=0.2; Γ_{2p}=0.32 eV, ω_p=0.8

J^π; T=1	$E^*(^{10}Be)$ [MeV]	E_γ [MeV]		λ_{1s} [10^{15} sec^{-1}]	λ_{2p} [10^{11} sec^{-1}]	R_s [10^{-4}]	R_p [10^{-4}]	R [10^{-4}]	R_{exp} /15/ [10^{-4}]
0^+	0	137,6	/25/	0,31	0,70	0,25	1,23	1,48	2,5±0,4
				0,332	1,06	0,26	1,75	2,01	
			/15/	0,355	2,0	0,28	3,28	3,56	
2^+	3,37	134,3	/25/	0,82	1,68	0,68	2,77	3,45	4,4±0,7
				1,68	2,27	1,32	3,74	5,06	
			/15/	1,00	4,69	0,78	7,71	8,48	
2^+	5,95	131,7		9,15	5,29	7,16	8,71	15,87	10,5±1,3
			/15/	7,48	6,62	5,86	10,99	16,85	
0^+	6,17	131,5		0,05	0,19	0,04	0,31	0,35	
2^+	7,54	129,8		0,30	0,37	0,24	0,61	0,85	
			/15/	2,20	2,87	1,73	4,72	6,45	
2^+	9,4	128,3		0,24	0,69	0,19	1,13	1,32	10.6±1.6
(3^+)	(10,7)	126,9		3,77	1,89	2,95	3,11	6,06	
	(7,0)		/15/	0,58	0,60	0,45	0,99	1,44	
4^+	(11,4)	126,3		1,08	1,28	0,85	2,11	2,96	
	(8,6)		/15/	0,87	1,23	0,62	2,03	2,65	
4^+	(16,0)	121,9		0,03	0,12	0,03	0,20	0,23	
	(14,1)		/15/	1,46	1,69	1,14	3,21	4,35	

Table 8

The probabilities of the partial transitions λ_{1s} and λ_{2p} and the yield R of hard γ-quanta in the process $^{14}N(\pi^-,\gamma)^{14}C$. Γ_{1s}=4.480 KeV; ω_s=0.1; Γ_{2p}= 2.1 eV, ω_p= 0.9

J^π; T=1	$E^*(^{14}C)$ [MeV]	E_γ [MeV]		λ_{1s} [10^{15} sec^{-1}]	λ_{2p} [10^{11} sec^{-1}]	R_s [10^{-4}]	R_p [10^{-4}]	R [10^{-4}]	R_{exp} /15/ [10^{-4}]
0^+	0	138,2	/25/	0.050	8.815	0.01	3,47	3.48	0.3±0.2
				0.280	2.567	0.04	0.72	0.76	
			/15/	1.982	2.598	0.29	0.73	1.02	
1^-	6.09	132.1		0.974	1.075	0.14	0.30	0.44	
0^+	6.58	131.6		0.345	1.296	0.05	0.37	0.42	
			/15/	0.811	2.625	0.12	0.74	0.86	
3^-	6.72	131.4		8.494	31.090	1.25	8.77	10.02	
0^-	6.90	131.3		0.490	0.621	0.07	0.18	0.25	
2^+	7.01	131.2		15.610	24.015	2.30	6.77	9.07	7.7±0.9
			/15/	18.910	33.260	2.78	9.35	12.16	
2^-	7.34	130.9		1.923	7.697	0.28	2.17	2.45	
2^+	8.31	130.0		15.610	24.015	2.30	6.77	9.07	4.0±0.6
			/15/	18.910	32.260	2.78	9.35	12.16	
1^+	(9.5)	128.8		3.410	11.670	0.50	3.29	3.79	
	(7.0)		/15/	4.141	15.100	0.61	4.25	4.86	
1^-	(9.8)	128.4		0.253	0.422	0.04	0.12	0.16	5.1±0.7
2^-	(10.1)	128.2		1.158	1.953	0.17	0.55	0.72	
2^+	(15.2)	123.1		0.267	2.167	0.04	0.61	0.65	
	(12.7)		/15/	0.906	3.725	0.13	1.05	1.18	

a) $^{6}Li(\pi^-,\gamma)^{6}He$. The transition probabilities to the ground state of the nucleus ^{6}He and to the level J^π; $E = 2^+$; 1.8 MeV were calculated in many papers. The results of calculations of yields R performed by various groups agree on the whole with each other and with experimental data. There is some discrepancy between the calculated values of λ_{1s} and especially of λ_{2p}. Partly this is due to the fact that the wave function of the ground state of the nucleus ^{6}Li somewhat differs in different papers.

b) $^{12}C(\pi^-,\gamma)^{12}B$. The theory on the whole correctly explains the relation between the transition intensities to individual low-lying states and the absolute values of the quantities R. However, as for the nucleus ^{6}Li there is some discrepancy between theoretical values presented by different authors.

c) $^{10}B(\pi^-,\gamma)^{10}Be$. Using the Cohen-Kurath type wave functions one fails to describe in detail the experimentally observed distribution of M1-intensities. The excitation spectrum in low-lying states of the nucleus ^{10}Be is dominated by the transitions to the states $J^\pi = 2^+$. The total excitation intensity of these states depends weakly on its distribution over the levels. Without considering the excitations of negative parity levels, the yield of hard γ-quanta up to the excitation energy of the ^{10}Be, nucleus, $E^* =$ = 9MeV, appears to be equal to R_{theor} = = 0.241%. The experimental value of the quantity R with excitation of levels ^{10}B up to 9 MeV including the levels of negative parity is R_{exp} ($E^* \leq 9$ MeV) = 0.223%.

d) $^{14}N(\pi^-,\gamma)^{14}C$. In the nucleus ^{14}C there are seven bound states. The levels $J^\pi = 2^+$, and J^π ; $E = 3^-$; 6.72 MeV are excited most intensively. The shell model state $|1p^{-2}\, 2^+;1\rangle$ is distributed over two levels J^π ; $E = 2^+$; 7.01 MeV and 2^+ ; 8.31 MeV with almost the same weight. This distribution is due to a large contribution of excitations of the type two particle - two holes (2p - 2h). The wave function of the ^{14}N ground state contains a very small admixture of such excitations and, consequantly, (2p - 2h) -components do not contribute to the transition. Therefore, the value of R calculated within the configuration $1p^{-2}$ is almost equally distributed between these two levels $J^\pi = 2^+$. Among the bound states of the nucleus ^{14}C there is one level of negative parity $J^\pi = 3^-$. The main components of the wave function of this level have the form $|1p_{1/2}, 1d_{5/2}\rangle$. Due to the fact that the single-particle matrix element of the transition $1p \to 1d_{5/2}$ is very large, the state J^π; $E = 3^-$; 6.72 MeV should be excited very strongly. The calculated value of the yield of hard γ-quanta to the bound states is twice higher than that observed experimentally. A reason of the excess may be connected with the level $J^\pi = 3^-$ which may also split as the neighbouring level $J^\pi = 2^+$, and its intensity is distributed over several states. On the other hand it may be due to a poor knowledge of mesoatomic characteristics $\Lambda_{n\ell}$ and ω_ℓ. Thus, at present this problem is unsolved. The level J^π; $E = 3^-$; 6.72 MeV should be noticeably excited in the case of muon capture by the nucleus ^{14}N. Its excitation probability is 8 times less than the total excitation probability of two levels $J^\pi = 2^+$ with energy 7.02 MeV and 8.32 MeV. In the (π,γ) process this ratio is somewhat less: if the capture proceeds from s-orbit then the ratio of probabilities is equal to four, and from p-orbit it is equal to about 1.5.

Transitions in Odd-A Nuclei

The values of level energies of odd-A nuclei presented in table 9 are theoretical and therefore they are given in brackets. They may somewhat differ from the experimental values. The calculated values of capture rates are presented in table 9.

a) $^7Li(\pi^-,\gamma)^7He$. The system ^7He has no bound states. The resonances in this system are analogs of states of the nucleus ^7Li with isospin T=3/2. It follows from the calculation that the resonances with quantum numbers J^π ; $E = 3/2^-$; 0 and J^π ; $E = 1/2^-$; 1.24 MeV should be excited more intensively.

b) $^9Be(\pi\ ,\gamma)^9Li$. In the nucleus ^9Li a group of states both of positive and negative parity should be excited with almost the same intensity. Note that the theory predicts the appearance of levels of anomalous (positive) parity beginning from 5 MeV and they are in the region of M1-resonance.

c) $^{11}B(\pi^-,\gamma)^{11}Be$. The ground state of the nucleus ^{11}Be is the level of anomalous parity. In the nucleus ^{11}Be the levels of this nature, as it follows from the calculations, are located rather densely, and they have almost the same excitation intensity as the

Table 9

The probabilities of the partial transitions λ_{1s} and λ_{2p} and the yield R of hard γ-quanta in the process $A(\pi^-,\gamma)B$. . ^7Li : $\Gamma_{1s} = 0.195$ KeV, $\omega_1 = 0.4$; $\Gamma_{2p} = 0.016$ eV, $\omega_p = 0.6$; ^9Be : $\Gamma_{1s} = 0.591$ KeV, $\omega_s = 0.3$; $\Gamma_{2p} = 0.16$ eV, $\omega_{2p} = 0.7$; ^{11}B : $\Gamma_{1s} = 1.680$ KeV, $\omega_s = 0.2$; $\Gamma_{2p} = 0.32$ eV, $\omega_{2p} = 0.8$; ^{13}C : $\Gamma_{1s} = 3.140$ KeV, $\omega_s = 0.15$; $\Gamma_{2p} = 1.02$ eV, $\omega_p = 0.85$

A J^π; T=1/2	B J^π_f; T=3/2	$E^*(B)$ [MeV]	E_γ [MeV]	λ_{1s} [10^{15} sec^{-1}]	λ_{2p} [10^{14} sec^{-1}]	R_s [10^{-4}]	R_p [10^{-4}]	R [10^{-4}]
^7Li ($3/2^-$)	^7He $3/2^-$	0	126,6	0,096	0,108	1,30	2,67	3,98
	$1/2^-$	(1,2)	125,4	0,179	0,068	2,42	1,68	4,10
	$3/2^-$	(3,3)	123,4	0,012	0,014	0,16	0,34	0,50
	$5/2^-$	(3,4)	123,5	0,032	0,020	0,43	0,50	0,93
^9Be ($3/2^-$)	^9Li $3/2^-$	0	123,9	0,371	0,308	1,24	0,89	2,12
	$1/2^-$	2,7	120,4	0,018	0,047	0,06	0,14	0,20
	$5/2^-$	(3,7)	120,3	0,291	0,200	0,97	0,57	1,55
	$3/2^+$	(4,6)	119,4	0,295	0,281	0,99	0,81	1,79
	$3/2^-$	(4,9)	119,1	0,374	0,102	1,25	0,29	1,54
	$1/2^+$	(5,3)	118,7	0,396	0,213	1,32	0,61	1,94
^{11}B($3/2^-$)	^{11}Be $1/2^+$	0	I26,7	0,3I9	0,2I9	0,25	0,36	0,6I
	$1/2^-$	0,3	I26,4	I,609	I,I85	I,26	I,95	3,2I
	$5/2^+$	(0,4)	I26,3	I,238	2,438	0,97	4,0I	4,98
	$3/2^-$	(2,1)	I24,5	2,II9	I,556	I,66	2,56	4,22
	$3/2^+$	(3,4)	I23,3	0,332	0,298	0,26	0,49	0,75
	$7/2^+$	(4,1)	I22,6	I,468	3,009	I,I5	4,95	6,10
	$5/2^-$	(4,2)	I22,5	0,536	I,27I	0,42	2,09	2,5I
	$5/2^+$	(4,3)	I22,4	I,277	2,085	I,00	3,43	4,43
	$1/2^+$	(5,3)	I2I,4	0,677	I,368	0,53	2,25	2,78
^{13}C ($1/2^-$)	^{13}B $3/2^-$	0	125,0	10,56	14,54	3,32	7,97	11,29
	$5/2^+$	(3,6)	121,5	1,54	4,60	0,48	2,52	3,01
	$3/2^+$	(5,5)	119,6	5,27	16,1	1,66	8,85	10,5

levels of normal parity forming the M1-resonance.

d) $^{13}C(\pi,\gamma)\,^{13}B$. In the nucleus ^{13}B two levels, the ground state and J^{π}; $E=3/2^{+}$; 5.5 MeV are expected to be excited with the same intensity.

Presently the analysis of experimental data on transitions in odd-A nuclei is almost finished[28] and this will enable us to compare them with the calculated results.

IV. Conclusion

From the comparison of the calculated yields of γ-quanta with excitation of individual states of the final nucleus with those observed experimentally it is seen that the theory describes rather well this characteristics. Presently it is difficult to obtain better agreement since a number of quantities ($\Gamma_{n\ell}$ and ω_{ℓ}) on which the yield depends is not uniquely determined. Thus, one should first determine these mesoatomic data with more accuracy.

To obtain reliable information on the partial transitions in the process (π,γ), it is important to investigate the electron scattering process and to analyze the magnetic form factors at momentum transfer which is realized in the process (π,γ). All available information will enable us to solve the problem of partial transitions in the process (π,γ) in order to get information both on the structure of the transition amplitude and on the structure of those states which are excited more intensively in these processes. Presently we can only state that there is no sharp discrepancy between theory and experiment in describing the yield of hard γ-quanta with the excitation of low-lying states of daughter nuclei.

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