ФІЗИЧНІ, ХІМІЧНІ ТА ІНШІ ЯВИЩА, НА ОСНОВІ ЯКИХ МОЖУТЬ БУТИ СТВОРЕНІ СЕНСОРИ

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SENSING NEW γ- QUANTUM-MUON-NUCLEAR INTERACTION EFFECTS: DISCHARGE OF METASTABLE NUCLEI DURING MUON CAPTURE

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Abstract

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Consistent theoretical scheme developed and used for sensing new γ quantum-muon-nuclear interaction effects, which can be used for creation of the new type sensors in tasks of nuclear technologies. Estimates of probabilities for discharge of a nucleus with emission of γ quantum and further muon or electron conversion are presented.

Key words: nuclear sensors, sensing new g-quantum-muon-nuclear interaction effects, decay probabilities, quantum theory.

Резюме

ДЕТЕКТУВАННЯ НОВИХ ЕФЕКТІВ ВЗАЄМОДІЇ γ-КВАНТІВ, МЮОНІВ І ЯДЕР: РОЗРЯДКА МЕТАСТАБІЛЬНИХ ЯДЕР В ПРОЦЕСІ ЗАХОПЛЕННЯ МЮОНА

С. В. Малиновська

Послідовна теоретична схема розвинута та використана у задачі детектування нових ефектів взаємодії γ-квантів, мюонів і ядер, які можуть бути використані при побудові нових типів сенсорів для задач ядерних технологій. Виконані оцінки імовірностей розрядки метастабільного ядра з випромінюванням γ-кванта та подальшою мюонною і електронною конверсією.

Ключові слова: ядерні сенсори, детектування нових ефектів взаємодії g-квантів, мюонів і ядер, імовірністі розпаду, квантова теорія.

Резюме

ДЕТЕКТИРОВАНИЕ НОВЫХ ЭФФЕКТОВ ВЗАИМОДЕЙСТВИЯ γ-КВАНТОВ, МЮОНОВ И ЯДЕР: РАЗРЯДКА МЕТАСТАБИЛЬНЫХ ЯДЕР В ПРОЦЕССЕ ЗАХВАТА МЮОНА

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Последовательная теоретическая схема развита и использована в задаче детектирования новых эффектов взаимодействия γ-квантов, мюонов и ядер, которые могут быть использованы при создании новых типов сенсоров для задач ядерных технологий. Выполнены оценки вероятностей разрядки метастабильного ядра с излучением γ-кванта и дальнейшей мюонной и электронной конверсией.

Ключевые слова: ядерные сенсоры, детектирование новых эффектов взаимодействия g-квантов, мюонов и ядер, вероятности распада, квантовая теория.

This paper goes on our studies [1,2] on carrying out theoretical schemes for sensing new γ quantum-muon-nuclear interaction effects , which can be used for creation of the new type sensors in tasks of nuclear technologies. Let us note at beginning that in last years with appearance of the intensive neutron pensils, powerful laser sources new interest attracts a class of problems, connected with the γ quantum-muon-nuclear interactions (c.f.[1-5]). In fact, speech is about processes of elementary particle-nuclear interactions, which were studied ealier (c.f.[6-10]), but for significantly other energy and geometry scales. It is well known that a negative muon μ captures by a metastable nucleus may accelerate the discharge of the latter by many orders of magnitude (c.f.[7,8]). Principal possibility of storage of significant quantities f the metastable nuclei in processes of the nuclear technology and their concentrating by chemical and laser methods leads to question regarding methods of governing velocity of their decay. It had been studied a possibility of action on processes of decay of the nuclei with participating the electrons of atomic shells (K-capture and internal conversion)by means their ionization (c.f.[1,2,7]). It had been considered a possibility of accelerating discharge of a metastable nucleus by means of the angle momentum part to electron shell of atom [2,6]. A comprehensive QED theory of cooperative laser-electron-nuclear processes is developed in refs. [1,2,10-15]. An effect of electron shell is quite small as the parameter r_n/r_a is small (r_n is a radius of nucleus and r_a is a radius of atom). A meso-atomic system differs advantageously of usual atom, as a relation r_n/r_a can vary in the wide limits in dependence upon the nuclear charge. For a certain relation between the energy range of the nuclear and muonic levels the discharge of metastable nucleus may be followed by the ejection of a muon, which may then participate in the discharge of other nuclei. Below we will present the estimates regarding probabilities for discharge of a nucleus with emission of γ quantum and further muon or electron conversion, using a consistent energy approach [1,2]in the QED theory. Traditional processes of the muon capture are considered in the fundamental papers (c.f.[7,8]) and here are not studied. Within energy approach (c.f.[1,2,10-17]), a decay probability is presented as an imaginary part of the energy shift (an energy of excited state of the system). In our situation the probability of the corresponding process (decay) is linked with an imaginary part of the “nucleus core + proton + muon or electron” system. For radiative decays it is manifested as effect of the retarding in interaction and self-action.

We consider a simple one-particle system of nucleus (c.f.[2,7,8]). It is supposed that the system consists off a twice-magic core. A single proton and single muon moves in the core field. The proton and muon interact through the Coulomb potential. This interaction will be accounted for in the first order of the atomic perturbation theory (PT) or second order of the QED PT (c.f.[15-17]). Surely a majority of known excited nuclear states have the multi-particle character and it is hardly possible to describe their structure within one-particle model. Nevertheless, the studied effects of muon-proton interaction are not connected with one-particle character of the model. In principle it is possible to consider also a dynamical interaction of two particles through the core. It accounts for a finiteness of mass of the core. However this interaction may decrease a multipolity of nuclear transition only on unit. Indeed, an interest attract strongly forbidden transitions of high multipolity. We will calculate probabilities of decay to different channels of the system, which consists of the proton (in an excited state $\Phi_{N_1J_1}$) and muon (in the ground state $\Psi\mu_{1s}$). Three channels should be taken into account: i). a radiative purely nuclear 2^j-poled transition (probability P_1); ii). non-radiative decay, when proton transits to the ground state and muon leaves a nucleus with energy: $E = \Delta E^p_{N_1J_1} - E^i_\mu$; $\Delta E^p_{N_1J_1}$ is the energy of nuclear transition; E^i_μ is a bond energy of muon in the *1s* state (P_2); iii). transition of a proton to the ground state with excitation of muon and emission of ε-quantum with energy $h\omega = \Delta E^p_{N_1J_1} - \Delta E^\mu_{nl}$ (P_3). The Feynman diagrams, corresponding to different channels of decay of the muon-nuclear system, are presented in figure 1.

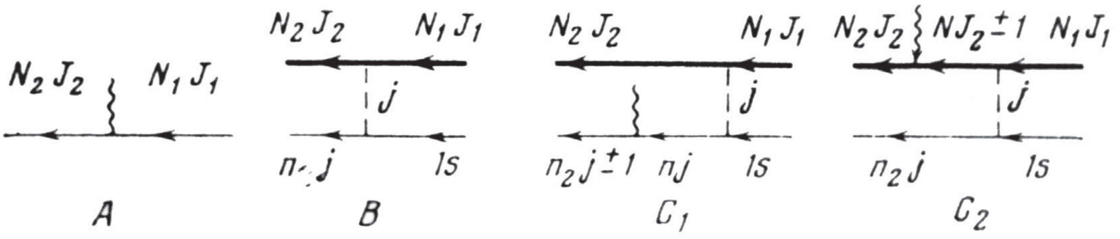

Figure 1. Feynman diagrams corresponding to different channels of decay of the mesosystem

The diagram A (fig.1) is corresponding to the first channel, diagram B- to the second channel and diagrams $C_1$and C_2 — to third channel. The thin line on the diagrams is corresponding to the muon state, the bold line — to the proton state. The indexes on the lines are corresponding to initial and final states of proton and muon. The dashed line with index j means the Coulomb interaction between muon and proton with exchange of 2^j-pole quanta. The waved line is corresponding to operator of the radiative dipole transition. This effect is due to the muon-proton interaction. The diagram A (fig.1) has a zeroth order on the muon-proton interaction; other diagrams (fig.1) — the first order. A probability of the purely radiative nuclear 2^j — pole transition is defined by standard way as follows (r_n=$5\cdot10^{-13}$cm) [8]:

$$P_1 = 2\cdot10^{20}\cdot\frac{j+1}{j[(2j+1)!!]^2}\left(\frac{3}{j+3}\right)^2\left(\frac{\Delta E[MeV]}{40}\right)^{2j+1} \qquad (1)$$

The diagrams $C_1$and C_2 account for an effect of interaction of the particles on the initial state. Surely there are other versions of these diagrams, but their contribution to probabilities of studied processes is significantly less than contribution of the diagrams $C_1$and C_2 (c.f.[3]).

Within the QED PT a full probability is divided into the sum of the partial contributions, connected with decay to definite final states of system. These contributions are equal to the corresponding transitions probabilities (P_i). For example, under condition $\Delta E^p_{N_1J_1} > E^i_\mu$ a probability definition reduces to QED calculation of probability of the autoionization decay of the two-particle system. An imaginary part of the energy of excited state of the system in the lowest QED PT order can be written in a standard form (c.f.[14-18]):

$$\begin{aligned}\operatorname{Im}E = e^2\operatorname{Im}i\lim\iint d^4x_1 d^4x_2 e^{\gamma(t_1+t_2)}\bullet\{&D(r_{c1t1},r_{c2t2})\cdot\\ &<\Phi_I|(j_{cv}(x_1)j_{cv}(x_2))|\Phi_I>+\\ &+D(r_{p1t1},r_{p2t2})<\Phi_I|(j_{pv}(x_1)j_{pv}(x_2))|\Phi_I>\\ &+D(r_{\mu1t1},r_{\mu2t2})<\Phi_I|(j_{\mu v}(x_1)j_{\mu v}(x_2))|\Phi_I>\}\end{aligned} \qquad (2)$$

Here $D(r_1t_1,r_2t_2)$ is the photon propagator; j_{cv}, j_{pv}, $j\mu_v$ are the four-dimensional components for operator of current for particles: core, proton, muon; $x = (r_c, r_p, r\mu, t)$ includes the space co-ordinates of three particles and time (equal for all particles); γ - adiabatic parameter. For the photon propagator it is possible to use the exact electrodynamical expression. Below we are limited by the lowest order of the QED PT, i.e. the next QED corrections to *Im E* will not be considered. After trivial transformations one can get the following expression for imaginary part of the excited state energy of the system as a sum of the corresponding contributions:

$$\begin{gathered}\operatorname{Im}E = \operatorname{Im}Ec + \operatorname{Im}Ep + \operatorname{Im}E\mu,\\ \operatorname{Im}Ea = -Z_a^2/4\pi\sum_F\iint dr_{c1}dr_{c2}\iint dr_{p1}dr_{p2}\iint dr_{+1\mu1}dr_{\mu2}\cdot\\ \cdot\Phi_I^*(1)\Phi_F^*(2)\cdot\cdot T_a(1,2)\Phi_F(1)\Phi_I(2),\\ T_a(1,2) = \exp(w_{IF}r_{a12})/r_{a12}\{1-\alpha_1\alpha_2\},\end{gathered} \qquad (3)$$

Here $r_{a12} = |r_{a1} - r_{aa2}|$; Φ_c, Φ_p, Φ_e are the secondly quantified operators of field of core particles, the fields of proton and muon. Sum on *F* means a summation on the final states of a system..

Let us consider a case, when energy of excitation of a nucleus ΔE^p is more than energy of ionization of the meso-atomic system E^i_μ. It is obvious that value $P_3 << P_2$, as P_3 has an additional small parameter on interaction with electromagnetic field [3]. Calculation of the probability P_2 can be led to calculation of probability of autoionization decay of the state for two-particle system, i.e. $P_2 = 2ImE/\hbar$, where ImE is defined by eq. (3). In table 1 we present the values for probabilities of the electron (P^e_2) and muon ($P\mu_2$) conversion and 2^j-pole (P_1) nuclear transition (nucleus of Ca; Z=20).

Table 1.

Probabilities (s^{-1}) of radiative 2^j-pole nuclear transition P_1, muon conversion $P\mu_2$ and electron conversion P^e_2 for $\Delta E^p \approx \Delta E\mu_i$ (unit of energy 1 *Мэв,* Z=20)

J	P_1	$P^{?}_{2}$	P^e_2
1	$4{,}7\cdot10^{14} E^3$	$1{,}3\cdot10^{16}$	$1{,}7\cdot10^{10} E^{-0,5}$
2	$5{,}2\cdot10^{9} E^5$	$1{,}7\cdot10^{16}$	$5{,}8\cdot10^{5} E^{0,5}$
3	$3{,}9\cdot10^{4} E^7$	$3{,}3\cdot10^{15}$	$9{,}2\cdot10^{0} E^{1,5}$
4	$2{,}6\cdot10^{-1} E^9$	$4{,}9\cdot10^{14}$	$8{,}4\cdot10^{-5} E^{2,5}$
5	$4{,}2\cdot10^{-7} E^{11}$	$5{,}7\cdot10^{13}$	$5{,}4\cdot10^{-10} E^{3,5}$
6	$2{,}9\cdot10^{-12} E^{13}$	$5{,}6\cdot10^{12}$	$2{,}3\cdot10^{-15} E^{4,5}$

Nuclear matrix elements are calculated as in ref.[1]. As wave functions of muon (and electron) the relativistic Dirac functions have been used. One can see that it's true the following relationship between corresponding probabilities: $P\mu_2 >> P_1 >> P^e_2$. Besides, the relations $P\mu_2/P_1$ >and $P\mu_2/P^e_2$ increase very quickly with growth transition multipolity. Indeed, the same situation has a place in the non-relativistic approximation [8]. For example, for J=1 calculation of Letokohv-Ivanov gives the following values: $P_1 = 4{,}0\cdot10^{14} E^3$, $P\mu_2 = \cdot10^{16}$, $P^e_2 = 1{,}3\cdot10^{10} E^{-0,5}$. So, when $\Delta E^p > E^i_\mu$, a reaction of the periodic capture of muon by metastable nucleus occurs with further muon conversion. An opposite case $\Delta E^p < E^i_\mu$ is corresponding to situation, when muon is captured to the lowest *1s* state (resonant effect and nucleus is a trap for muons), and considered in details in ref.[2]. Experimantal possibilities for search an effect of discharge of the metastable nuclei have been considered in ref.[8,2] and require a choise of the special type nuclei. A probability of muon capture by excited nucleus must be comparable or more than a probability of capture by other (non-excited or admixtured) nuclei of a target, radiated by muons. As result, a target must be prepared as the excited nuclei concentrate with minimal size of order or more a length *l* of free passing for muon in relation to capture by nucleus. The Ivanov-Letokhov condition for minimal number of excited nuclei in a targer is $N_{min} > l^3 n_0$, where n_0 is density of the target atoms.For preliminary slowing of muons to energies 0,1-0,3 MeV, their free passing length is ~0,1 cm. So, for $n_0 = 10^{22}cm^{-3}$ necessary number of metastable nuclei is $N_{min} > 10^{19}$. Radioactivity of such target of excited nuclei will be $R = N_{min}/T$, where T is a decay time. For example, for T=100 days, $R \sim 10^3$ curre.

So, it is obvious that a direct experimental observation of the manifestating γ quantum-muon-nuclear interaction effects is of a great importance from theoretical point of view as well as different applications, including a construction of new type sensors for tasks of nuclear physics and nuclear technologies.

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