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DISCHARGE OF METASTABLE NUCLEI DURING NEGATIVE MUON CAPTURE: ENERGY APPROACH

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Abstract

It is presented a consistent energy approach to the quantum electrodynamics (QED) theory of discharge of a nucleus with emission of γ quantum and further muon conversion, which initiates this discharge. Numerical calculation is carried out for nucleus of $^{49}_{21}Sc_{28}$.

1 Introduction

A negative muon μ captures by a metastable nucleus may accelerate the discharge of the latter by many orders of magnitude (c.f.[1-3]). 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 considered a possibility of accelerating discharge of a metastable nucleus by means of the angle momentum part to electron shell of atom [3]. A comprehensive QED theory of cooperative laser-electron-nuclear processes is developed in refs. [4-6]. 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_acan 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 may be followed by the ejection of a muon, which may then participate in the discharge of other nuclei. Here we present a consistent

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energy approach in the QED theory of discharge of a nucleus with emission of γ quantum and further muon conversion, which initiates this discharge. Traditional processes of the muon capture are considered in the fundamental papers [7-9] (c.f.[10-13]) and here are not studied. Within energy QED approach (c.f.[4-6, 14-19]), a decay probability is presented as an imaginary part of the energy shift (an energy of excited state of the system).

2 Model and channels of decay for meso-atomic system: Energy approach

We consider a simple one-particle system of nucleus. 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. 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. 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 Ψ^{μ}_{1s}).Three channels should be taken into account [3]: 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: $\mathrm{E} = \Delta\mathrm{E}^p_{N_1J_1} - \mathrm{E}^i_{\mu}$;$\Delta\mathrm{E}^p_{N_1J_1}$is the energy of nuclear transition; $\mathrm{E}^i_{\mu}$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 γ-quantum with energy $h\omega = \Delta\mathrm{E}^p_{N_1J_1} - \Delta\mathrm{E}^{\mu}_{nl}$ (P_3).

A probability of purely radiative nuclear 2^{j} pole transition is defined as follows ($r_n = 5{\cdot}10^{-13}$cm):

$$P_1 = 2\cdot 10^{20}\cdot \frac{j+1}{j[(2j+1)!!]^2}(\frac{3}{j+3})^2(\frac{\Delta E[MeV]}{40})^{2j+1} \tag{1}$$

Within the QED PT [5-7], 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 $\Delta\mathrm{E}^p_{N_1J_1}$¿$\mathrm{E}^i_{\mu}$ 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]):

$$ImE = e^2 Imi \lim \iint d^4x_1 d^4x_2 e^{\gamma(t_1+t_2)} \bullet \{D(r_{c1t1}, r_{c2t2}) \cdot \\ <?_I|(j_{cv}(x_1) j_{cv}(x_2))|?_I> + D(r_{p1t1}, r_{p2t2}) <?_I|(j_{pv}(x_1) j_{pv}(x_2))|?_I> \\ + D(r_{\mu 1t1}, r_{\mu 2t2}) <?_I|(j_{\mu v}(x_1) j_{\mu v}(x_2))|?_I>\} \quad (2)$$

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; $? = (r_?, r_?, r_\mu, t)$ includes the space co-ordinates of three particles and time (equal for all particles); γ adiabatic parameter. 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:

$$ImE = ImEc + ImEp + ImE\mu, \\ ImEa = -Z_a^2/4\pi \sum_F \iint dr_{c1} dr_{c2} \iint dr_{p1} dr_{p2} \iint dr_{+1\mu 1} dr_{\mu 2} ?_I^*(1) ?_F^*(\mathbf{??}) \cdot \\ \cdot T_a(1,2) ?_F(1) ?_I(2), \\ T_a(1,2) = \exp(w_{IF} r_{a12})/r_{a12}\{1 - \alpha_1\alpha_2\}, \quad (2)$$

Here $r_{a12} = |r_{a1} - r_{aa2}|$; $\hat{O}_c,\ \hat{O}_p,\ \hat{O}_e$ are the secondly quantified operators of field of the core particles, the fields of proton and muon. The sum on F designs the summation on the final states of system. 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/ž*, where *ImE* is defined by eq. (2).

3 Calculation for the nucleus $^{49}_{21}\boldsymbol{Sc}_{28}$.

The nucleus of $^{49}_{21}Sc_{28}$ contains one proton above twice magic core $^{49}_{20}Ca_{28}$. The life-time for isolated nucleus in the excited states is of order 10^{-11}. Follow to papers [3,20], let us suppose that a proton moves in an effective field of the core:

$$V - 25 \cdot f(l,j) \cdot V'/r \quad (3)$$

For the self nuclear part of interaction V we accepted the expression from [3,4]. To calculate the corresponding integrals in expression (2), we use the effective Ivanov-Ivanova technique (c.f.[16-19]). The probabilities of the meso- atomic decay (in s^{-1}) for different nuclear transitions are as follows: $P_2(p_{1/2} - p_{3/2})$ =3,93·10^{15}, $P_2(p_{1/2} - f_{7/2})$=3,15·10^{12}, $P_2(p_{3/2} - -f_{7/2})$=

8,83·10^{14}. Let us note that these values are significantly higher that the corresponding non-relativistic estimates [3]. For example, according to [3]: $P_2(p_{1/2}-p_{3/2})$ =3,30·10^{15}. For above indicated transitions the nucleus must give the momentum ΔJ no less than 2,4 and 2 according to the momentum and parity rules. If a meso-atomic system is in the initial state $p_{1/2}$, than the cascade discharge occurs with ejection of the muon on the first stage and the γ quantum emission on the second stage. To consider a case when the second channel is closed and the third one is opened, let us suppose that$E^p(p_{1/2})-E^p(p_{3/2})$=0.92 MeV (fig 2). The energy of the nuclear transition is not sufficient for transition of the muon to the continuum state. However, it is sufficient for excitation to the $2p$ state. It is important note here that this energy is not lying in the resonant range. The diagram C_1 (fig.1.) describes the proton transition $p_{1/2}-p_{3/2}$ with a virtual excitation of muon to states of series nd and with γ quantum emission of energy:

$$hw{=}E^p(p_{1/2})+E^\mu(1s)-E^p(p_{3/2})-E^\mu(2p).$$

Further the dipole transition $2p-1s$ can occur. The calculated value for probability of this transition is P_3=*1.9*·10^{13} s^{-1}. This value is significantly more than the corresponding non-relativistic one [3]. It is important also to underline that the value P_3 is more than the probability of the radiation transition $p_{1/2}-p_{3/2}$and probability of un-radiative transition $p_{1/2}--f_{7/2}$. The next transition $p_{3/2}--f_{7/2}$ occurs without radiation during the time 10^{-15}s with ejection of the muon.

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4 References

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