RELATIVISTIC MODELS IN DYNAMICS OF INTERACTION BETWEEN ELECTRON SHELLS OF ATOMS AND NUCLEONS: NEW EFFECTS

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A consistent quantum electrodynamical (QED) perturbation theory approach is developed for the calculation of the electron-nuclear γ transition spectra in atoms and ions. The intensities of the satellites are determined in the relativistic version of the energy approach (S-matrix formalism). As an example, the nuclear transition in $^{57}_{26}Fe$ isotope (energy 14.41 keV) is considered. The results of relativistic calculation for the electron-nuclear γ-transition spectra (a set of electron satellites) of the nucleus in multicharged FeXIX ion are presented and compared with the corresponding non-relativistic estimates.

1. The paper is devoted to the studies of cooperative dynamical phenomena due to interaction between electron shells of atoms and nucleons of nuclei. In this new direction the following problems are considered: i) The studies of the mixed optical quantum transitions; ii). Spectroscopy of resonances and creation of additional satellites and narrow resonances inside the Doppler contour of the radiation line; iii). control of the intensity of the complicated transitions due to change of the atomic and molecular excited states population in a laser field; iv). the relativistic quantum calculation of the complex "laser-electron-nuclei" systems [1-12].

The nuclear emission or absorption spectrum of the atom possesses a set of electron satellites due to the alteration of the state of electron shell [1, 2, 5–7]. The mechanism of satellite formation in neutral atoms and highly charged ion is different. In the first case (loose electron shell) a shaking of the shell resulting from the interaction between the nucleus and the γ-quantum is predominant. In the second case (rigid electron shell) the mechanism involves a direct interaction between the γ-quantum and electrons. The second mechanism is important in the case of dipole nuclear transitions and predominates at the γ-quantum energies $\leq 4z$ keV (z is effective nuclear charge). The traditional selection rules and known intensity hierarchy with respect to electron transition multiplicity do not pertain to the second mechanism. Consequently, the satellite spectrum is much enriched and transitions between the fine and hyperfine structure components, 0-0 transitions and transitions which do not involve a change in the electron configuration can be considered.

There is a great number of different channels for the electron-nuclear processes in atoms, ions and molecules. The possibility of their interference makes the analysis more complicated. The analysis of some processes must be, as a rule, based on the comprehensive relativistic approach. In the theory of radiative and non-radiative decay of the quasi-stationary states of a multielectron atom an energy approach, based on the adiabatic Gell-Mann and Low formula [5-8,13] for the energy shift δE with electrodynamics scattering matrices, is well known. This approach represents the decay probability as an imaginary part of the energy shift. The method is consistently electrodynamical, allowing for the uniform consideration of a variety of induced and spontaneous processes. Their contributions and interference effects are represented by successive corrections of the QED perturbation theory. The energy approach had been applied previously in the study of purely electronic, electron-nuclear processes in atoms and meso-atomic systems [5–7]. We use this consistent approach in the calculation of the electron-nuclear γ transition spectra of a nucleus in atom. The intensities of the satellites are determined in the relativistic version of the energy approach (S-matrix formalism) [7, 10]. Decay and excitation probabilities are connected with the imaginary part of the "nucleons-electron shells -field" system. For the radiative decay it is manifested as the effect of retarding in interaction and self-action. The calculation results of the electron-nuclear γ-transition spectra (a set of electron satellites) of the nucleus in a multicharged FeXIX ion are presented. To calculate the spectra of the multicharged FeXIX ion, the relativistic perturbation theory with model zeroth approximation has been used (version in [11, 12]).

2. We consider the following model of the atomic system: a rigid nuclear core (c), a proton above the core (p) and an electron (e). We will calculate the imaginary part of the excited state of the system. Even for a two-particle system the exact electrodynamical solution is unknown. Following the quasi-potential method [14], we introduce the bare interaction as follows:

$$V(r_c, r_p, r_c) = v(r_{pc}) - Ze^2 / r_{ec} - e^2 / r_{pe} \quad (1)$$

where all interactions are obvious. The imaginary part of the excited state energy for the three-quasi-particle system in the lowest perturbation theory order is as follows:

$$\begin{aligned} \operatorname{Im} E = e^2 \operatorname{Im} i \lim \iint d^4x_1 d^4x_2 e^{\gamma(t1+t2)} \bullet \{ D(r_{c1t1}, r_{c2t2}) < \Phi_I \mid (j_{cv}(x_1) j_{cv}(x_2)) \mid \Phi_I > + \\ + D(r_{p1t1}, r_{p2t2}) < \Phi_I \mid (j_{pv}(x_1) j_{pv}(x_2)) \mid \Phi_I > + D(r_{e1t1}, r_{e2t2}) < \Phi_I \mid (j_{ev}(x_1) j_{ev}(x_2)) \mid \Phi_I > \} \end{aligned} \quad (2)$$

Here D is the photon propagator; **j** – the four-dimensional operator of current of the core, protons, electrons; $x=\{rc\ , rp\ , re\ , t\}$; For the photon propagator it is possible to use the exact electrodynamical expression:

$$D(12) = -\frac{i}{8\pi^2} \frac{1}{r_{12}} \int_{-\infty}^{\infty} d\omega e^{i\omega t12 + i|\omega| r12} \quad (3)$$

We use the relativistic solutions of the Dirac equation as functions of the state of the system. Substituting all expressions into (2), one can obtain the following general expression for the imaginary part of the excited state energy for the three-quasi-particle system:

$$\begin{aligned} &\operatorname{Im} E = \operatorname{Im} Ec + \operatorname{Im} Ep + \operatorname{Im} Ee, \\ &\operatorname{Im} Ea = -Z_a^2 / 4\pi \sum_F \iint dr_{c1}\ dr_{c2} \iint dr_{p1} dr_{p2} \iint dr_{+1e1} dr_{e2} \Phi_I^*(1) \Phi_F^*(2) T_a(1,2) \Phi_F(1) \Phi_I(2), \quad (4) \\ &T_a(1,2) = \sin(w_{IF} r_{a12}) / r_{a12} \{1 / M\mu_a (\nabla_{ra1}, \nabla_{ra2}) + 1\}, \end{aligned}$$

where $\mathrm{r}\, r_{a12} = | r_{a1} - r_{aa2} |$. In the QED perturbation theory second order the full width of the level is divided into the sum of the partial contributions, related to the radiative decay into definite final states of the system. These contributions are proportional to the probabilities of the corresponding transitions. The intensity of the satellite P(pe) is related to the imaginary part of energy as follows: P=2ImE/h.. The system of red (blue) satellites corresponds to the transitions with excitation (de-excitation) of the electron shell.

Note that the form of the operator in (4) is determined by the calibration of the propagator. In [7, 10] the corresponding expressions are derived for different calibrations of the photon propagator.

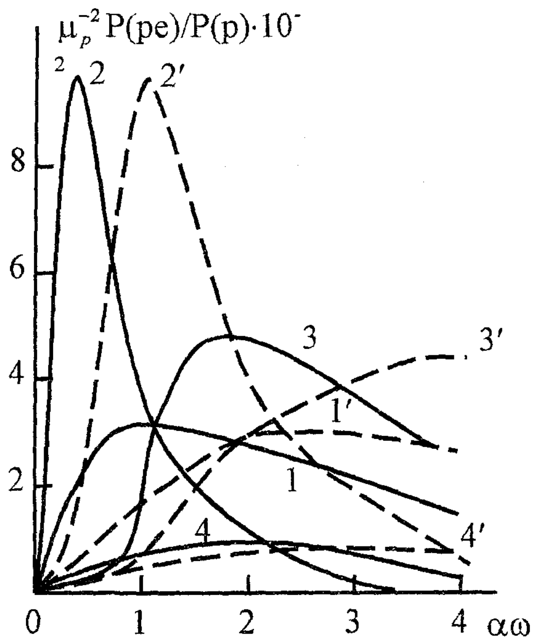

Fig. 1. The contribution of Im E to the relative intensity of the satellite; P(pe) – the satellite intensity; P(p) – the intensity of the nuclear transition; 1- $1s-2p_{3/2}$ transition; 2 – $2s-2p_{3/2}$ transition; 3 – $2p_{1/2}-2p_{3/2}$ transition; 4- 1s-2s transition; ----- = relativistic calculation; ——— = non-relativistic calculation; energy of the quantum $E_\gamma[keV] \approx 4Z(\alpha\omega)$.

As an example, we consider the nuclear transition in the isotope ${}^{57}_{26}Fe$ with energy 14.41 keV (half-life period $T_{1/2} = 9{,}77 \cdot 10^{-8}\, s$, energy of recoil: $1{,}96 \cdot 10^{-6} keV$; $\alpha\omega = 0{,}27$;)[15]. The results of calculation are shown in Fig. 1. We also present the corresponding non-relativistic data. The account of the relativistic effects resulted in the shift of the curves to the region of higher energies. As seen from the figure, the intense satellites correspond to the 2s-2p transitions.

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РЕЛЯТИВІСТСЬКІ МОДЕЛІ В ДИНАМІЦІ ВЗАЄМОДІЇ ЕЛЕКТРОННИХ ОБОЛОНОК АТОМІВ ТА НУКЛОНІВ ЯДЕР: НОВІ ЕФЕКТИ

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У розрахунку спектру електронно-ядерних γ переходів ядра в атомі та іоні використано послідовний квантово-електродинамічний підхід. Інтенсивності сателітів визначено у релятивістській версії енергетичного підходу (S-матричний формалізм). Імовірності розпаду і збудження пов'язані з уявною частиною енергії системи "нуклони – електроні оболонки – поле". Як приклад, розглянуто ядерний перехід в ізотопі $^{57}_{26}Fe$ з енергією 14,41 keV. Представлені результати релятивістського розрахунку спектру електронно-ядерних γ-переходів (спектр електронних сателітів) ядра в багатозарядному іоні FeXIX порівнюються з нерелятивістськими оцінками.