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

PHYSICAL, CHEMICAL AND OTHER PHENOMENA, AS THE BASES OF SENSORS

PACS: 34.50RK, 31.70HQ, 95.55SH ; УДК 535.42.,539.184.

NUCLEAR QUANTUM OPTICS: ENERGY APPROACH TO MULTI-PHOTON RESONANCES IN NUCLEI

A. V. Glushkov[1,2] and A. A. Svinarenko[2]

[1]Odessa National Polytechnic University, Odessa, Ukraine
[2]Odessa State Environmental University, Odessa, Ukraine

NUCLEAR QUANTUM OPTICS: ENERGY APPROACH TO MULTI-PHOTON RESONANCES IN NUCLEI

A. V. Glushkov, A. A. Svinarenko

Abstract. Modeling nuclear ensembles in a super strong laser field provides opening new field of nuclear quantum optics and nuclear sensorics. In paper a consistent energy approach to multiphoton resonances in nuclei is presented.

Keywords: nuclear quantum optics, multiphoton resonances, energy approach

ЯДЕРНА КВАНТОВА ОПТИКА: ЕНЕРГЕТИЧНИЙ ПІДХІД ДО ОПИСУ БАГАТОФОТОННИХ РЕЗОНАНСІВ В ЯДРАХ

А. В. Глушков, А. А. Свинаренко

Анотація. Моделювання динамики ядер у понадсильному полі лазерного випромінювання відкриває горизонти нового напрямку фізичних досліджень — ядерної квантової оптики і ядерної сенсоріки. У роботі викладено новий послідовний енергетичний підхід до опису багато фотонних резонансів в ядрах.

Ключові слова: ядерна квантова оптика, багато фотонні резонанси, енергетичний підхід

ЯДЕРНАЯ КВАНТОВАЯ ОПТИКА: ЭНЕРГЕТИЧЕСКИЙ ПОДХОД К ОПИСАНИЮ МНОГОФОТОННЫХ РЕЗОНАНСОВ В ЯДРАХ

А. В. Глушков, А. А. Свинаренко

Аннотация. Моделирование динамики ядер в сверхсильном поле лазерного излучения открывает горизонты нового направления — ядерной квантовой оптики и ядерной сенсорики. В работе изложен новый последовательный энергетический подход к описанию много фотонных резонансов в ядрах.

Ключевые слова: ядерная квантовая оптика, многофотонные резонансы, энергетический подход

1. The interaction of the quantum systems with the external alternating fields, in particular, laser fields has been the subject of intensive experimental and theoretical investigations (look, for example, [1-41]). The appearance of the powerful laser sources allowing to obtain the radiation field amplitude of the order of atomic field in the wide range of wavelengths results to the systematic investigations of the nonlinear interaction of radiation with atoms and molecules (traditional quantum optics). So, it is known that the field of laser–matter interactions usually deals with the atomic or molecular response to an external light wave. However, due to the enormous technological progress in recent years (look [19-23]), it is possible today to produce kilo electronvolt photons, mega electronvolt ions, and giga electronvolt electrons by laser radiation, which lies far beyond the typical atomic energy scale. The question arises of whether direct interactions with super intense laser fields could also be employed in nuclear physics, besides atomic and molecular physics. Naturally a great number of papers were devoted to studying the coupling of electric and nuclear transitions (including spectroscopy of laser-alpha,beta-gamma-nuclear phenomena) [4-11,16-30,41]. In some phenomena electrons or plasmas are encountered by a laser pulse and then, directly or by creating radiation, react with the nucleus. The most typical examples are the production of MeV X-rays in a plasma that is generated by femtosecond laser pulses, the study of gamma-induced nuclear reactions in plasma radiated by a super-intense laser, or neutron production in laser plasma, the control of Mцssbauer spectra or even the inversionless amplification. In the last years an especial interest attracts optically induced nuclear fission and fusion, nuclear reactions, isomer excitations, or nuclear collisions [18-20,25-30,36,37]. In this context, the known Mцssbauer, Szilard-Chalmers and other cooperative effects should be mentioned [4-9]. The consistent quantum electrodynamics (QED) theory of cooperative electron γ-nuclear processes in atoms and molecules is developed in Refs. [29,30]. In fact, it is possibly a reverse bridging between nuclear structure theory and quantum chemistry (atomic and molecular physics). In ref. [41] the cooperative electron-β-nuclear processes in atomic systems (e-β-nuclear spectroscopy), including the processes of excitation, ionization, and electronic rearrangement induced by nuclear reactions and β-decay, are discussed and studied on the example of a number of allowed (super allowed) transitions (^{33}P-^{33}S, ^{241}Pu-^{241}Am etc). There are a few factors that have to be taken into account: changing the integration limits in the Fermi function integral, energy corrections for different chemical substances, and the possibility of the bound β-decay or other decay channels. The interesting example of the electronic rearrangement induced by nuclear transmutation in the β-decay ${}^{4}_{2}He_4 \rightarrow ({}^{6}_{3}Li^{+}_{3})^{*} + e^{-} + {}^{-}_{e}$ is considered. The half-life periods for β-transition in the tritium atom (molecule) are estimated by taking into account the bound β-decay channel correction and some other accompanying effects. It has been given a detailed analysis how the data on β-decay parameters can be used for studying the chemical bond nature, treating the spatial structure of molecular orbitals, identifying the electron states in some tritium-containing systems and diagnostics of the compounds by means of exchange of the hydrogen atoms by tritium ("tritium probe").

Further it is important to note that at the same time a direct laser-nucleus interactions traditionally have been dismissed because of the well known effect of small interaction matrix elements [5,7,9,20]. Some exceptions have been discovered before [5]. Speech is about the interaction of x-ray laser fields with nuclei in relation to alpha, beta-decay and x-ray-driven gamma emission of nuclei. With the advent of new coherent x-ray laser sources in the near future, however, these conclusions have to be reconsidered. From the design report (look table 1) for SASE 1 at TESLA XFEL and parameters for current and future ion beam sources [21,22], the signal rate due to spontaneous emission after real excitations of the nuclei can be estimated. For nuclei accelerated with an energy resolution of 0.1% such that 12.4 keV photons produced by SASE 1 become resonant with the *E*1 transition in a whole number of nuclei (for example, ^{153}Sm, ^{181}Ta, ^{223}Ra, ^{225}Ac , ^{227}Th etc), i.e. the resonance condition (ω~Δε, where Δε is a typical level spacing, ω is a laser frequency) is fulfilled. More over, according to estimate [23] from the peak photon brilliance, a xux of approximately 4:1 10^{18}photons=second resonant within the transition width of the excited state. The coherence of the laser light expected from new sources (TESLA XFEL) may allow to access the extended coherence or interference phenomena. In particular, in conjunction with moderate acceleration of the target nuclei it allows principally to get photon and transition frequencies and to achieve the nuclear Rabi oscillations, photon echoes or more advanced quantum optical schemes in nuclei [9,19]. In refs.

[19,20,23], it has been shown that a direct laser-nucleus interactions may indeed become of relevance in future experiments employing x-ray lasers. In result one could say about opening the field of nuclear quantum optics. It is well known that an efficient direct coupling of the particles to the radiation field is guaranteed if the condition: $\Delta\varepsilon \sim eE\Delta r$ is satisfied. Here, e is the electric charge of the particles and Δr is the characteristic length of the system. For atoms (or muonic atoms), $\Delta r \sim a_B \sim 10^{-8}$ cm (10^{-10} cm), a_B is the Bohr radius; for nuclei, $\Delta r \sim R_n \sim 10^{-12}$ cm is the nuclear size; and for the QED vacuum, $\Delta r \sim \lambda_C \sim 10^{-10}$ cm is the Compton wavelength of the electron. It is worth to present here the known estimates of the respective transition energies such as $\Delta\varepsilon \sim$ 1 eV (1 keV), 100 keV and 1 MeV. Therefore [23], an efficient direct coupling of the electromagnetic wave to (muonic) atoms requires intensities on the order of $I \sim 10^{16}$ W/cm^2 (10^{24}W/cm^2), while for direct interactions with nuclei or the QED vacuum, $I \sim 10^{29}$W/cm^2 is required.

Table 1

The parameters of the most powerful laser systems (XRL, XFEL, TESLA): w_{max} is maximal photon energy; I_s is an intensity of the laser radiation [21]

Current X- ray laser design	w_{max} [eV]	I, [W/cm^2]
X-1 XFEL at DESY*	56	$8\cdot10^{20}$
X-2 XRL at GSI**	90	$3\cdot10^{21}$
T TESLA at DESY*	12400	$2\cdot10^{17}$–$2\cdot10^{21}$

In ref. [15] it has been firstly presented an experimental evidence for nuclear multiphoton transitions in ^{57}Fe based on radio-frequency sidebands to the forbidden hyperfine components of the 14.4-keV transition. In principle theory of the multiphoton effects in nuclei should be in the known degree similar to the corresponding atomic one, nevertheless it should be remembered that nuclei throughout the nuclear chart exhibit various kinds of excitations. The most prominent and simple ones in terms of theoretical understanding are probably (quadrupole-type) vibrations in even-even spherical systems and rotations in even-even deformed nuclei [42]. The above mentioned nuclei (especially many actinide nuclei) possess rather low (collective) $E1$ excitations [19]. Naturally these $E1$ transitions can be found, e.g., in alternating parity rotating bands. In fact they can be related to the collective potential of these nuclei and the interplay between quadrupole and octupole degrees of freedom in this area of the nuclear chart. In refs. [5,6,19,20,23-30] there are presented the simple physical models for AC one-photon Stark effect, the laser radiation effect on nuclear decay processes (internal conversion, beta-decay), but the corresponding theory for multiphoton resonances in nuclei is in fact absent. Naturally, one could propose analogs of the atomic multiphoton models [10,31].

In this paper we will firstly present a comprehensive theory (an energy approach) to to multiphoton resonances in nuclei, based on the energy approach (S-matrix formalism). Earlier this approach has been successfully developed and applied to solve different classes of problems [3,8-11,14,24,29-40] in atomic, mesoatomic, nuclear physics, including nuclear laser physics, for example, creation of new possible principal scheme of γ -laser on quickly decayed nuclear isomers with laser autoionization or electric field ionization sorting excited atoms. Naturally, though the basic formalism is used further, some purely nuclear aspects are required to be reconsidered.

2. In the theory of the relativistic atom it has been developed a convenient field procedure for calculating the energy shifts ΔE of degenerate states. This procedure is connected with the secular matrix M diagonalization [33-35]. In constructing M, the Gell-Mann and Low adiabatic formula for ΔE is used [31]. In relativistic theory the secular matrix elements are already complex in the second perturbation theory (PT) order. Their imaginary parts are connected with radiation decay possibility. The total energy shift is usually presented in the form:

$$\Delta E = \mathrm{Re}\Delta E + \mathrm{i}\ \mathrm{Im}\Delta E$$
$$\mathrm{Im}\ \Delta E = -\Gamma/2 \qquad (2)$$

where Γ is the level width (decay possibility $P = \Gamma$). The whole calculation of the energies and decay probabilities of a non-degenerate excited state is reduced to calculation and diagonalization of the complex matrix M and matrix of the coefficients with eigen state vectors $B^{IK}_{ie,iv}$ [32-35]. To calculate all matrix elements one must use the basis's of the 1QP relativistic functions (look below).

Further we will study the radiation emission and absorption lines. If we consider, for example, an ^{57}Fe nucleus under a magnetic (electromagnetic) field in principle, eight transitions are possible between the four hyperfine substates of the 14.4 keV excited level e and the two substates of the ground state g. The main our purpose is to define the corresponding emission and absorption lines moments μ_n , which are naturally to be dependent upon the laser pulse quality: intensity and mode constitution. This question is never even discussed.

Let us describe the interaction "atom — an external alternating field" by the following potential:

$$V(r,t)= V(r) \int d\omega f(\omega - \omega_0)\times$$
$$\times \sum_{n=-\infty}^{\infty} \cos [\omega_0 t+ \omega_0 n\tau]. \quad (3)$$

Here ω_0 is the central radiation frequency, n is the whole number. The potential V represents the infinite duration of laser pulses with known frequency τ. The function $f(\omega)$ is a Fourier component of the laser pulse. The condition $\int d\omega f^2(\omega)=1$ normalizes potential $V(rt)$ on the definite energy in the pulse. Further we will consider an interaction with a single pulse.

In concrete multiphoton nuclear experiments the radio-frequency magnetic field should be applied [15]. If the static magnetic hyperfine splitting of the ground and excited states are respectively $\omega_g>0$ and $\omega_e>0$, the transition frequencies corresponding to forbidden gamma-ray transitions are $(E_e-E_g)/h\pm3\omega_g/2\pm\omega_g/2$, where E_e, E_g are respectively the energies of the 14.4-keV and ground states of the ^{57}Fe nucleus in an absence of any applied magnetic field. This picture is experimentally observed in the Mцssbauer spectra of ^{57}Fe nuclei in Permalloy by Tittonen et al, 1992 (look [15]). An application of the radio-frequency electromagnetic field ($\sim\cos\omega_0 t$) results in an appearance of new lines in spectrum, shifted with respect to their patient lines by $\pm\omega_0$.

Further we consider a general case of the Gaussian electromagnetic pulse: $f(\omega) = N\exp[\ln2(\omega^2/\Delta^2)]$. The further program results in the calculating an imaginary part of energy shift Im $E_\alpha(\omega_0)$ for any atomic level as the function of ω_0. An according function has the shape of the resonance, which is connected with the transition α-p (α, p-discrete levels) with absorption (or emission) of the "k" number of photons. For the resonance we calculate the following values:

$$\delta\omega(p\alpha|k) = \int' d\omega \,\mathrm{Im}\, E_\alpha(\omega)\,(\omega - \omega_{p\alpha}/k)/N, \quad (4)$$

$$\mu_m = \int' d\omega \,\mathrm{Im}\, E_\alpha(\omega)\,(\omega - \omega_{p\alpha}/k)^m/N,$$

where $\int' d\omega \mathrm{Im} E_\alpha$ is the normalizing multiplier; $\omega_{p\alpha}$ is position of the non-shifted line for transition α-p, $\delta\omega(p\alpha|k)$ is the line shift under k-photon absorption; $\omega_{p\alpha}=\omega_{p\alpha}+ k\cdot\delta\omega(p\alpha|k)$. The first moments μ_1, μ_2 and μ_3 determine the nuclear line centre shift, its dispersion and the asymmetry.

To find μ_m, we need to get an expansion of E_α to PT series: $E_\alpha = \sum E_\alpha^{(2k)}(\omega_0)$. One may use here the Gell-Mann and Low adiabatic formula for δE_α [31]. The representation of the S- matrix in the form of PT series induces the expansion for δE_α:

$$\delta E_\alpha(\omega_0) = \lim_{\gamma\to0} \gamma \sum_{k_1k_2\ldots k_n} a(k_1, k_2,\ldots,k_n), \quad (5)$$

$$I_\gamma(k_1, k_2,\ldots,k_n) = \prod_{j=1} S_\gamma^{(kj)}, \quad (6)$$

$$S_\gamma^{(m)} = (-1)^m \int_{-\infty}^{0} d t_1 \ldots \int_{-\infty}^{t_m-1} d t_m \times$$
$$\times \langle\Phi_\alpha | V_1 V_2 \ldots V_m | \Phi_\alpha\rangle, \quad (7)$$

$$V_j = \exp(iH_0 t_j)\, V(rt_j) \exp(-iH_0 t_j) \exp(\gamma t_j). \quad (8)$$

Here H is the nuclear hamiltonian, $a(k_1, k_2,\ldots,k_n)$ are the numerical coefficients. The structure of matrix elements $S_\gamma^{(m)}$ is similar to atomic case and in details described in [10,40]. After some transformations one can get the expressions for the nuclear multiphoton resonant transition line shift and corresponding moments:

$$\delta\omega(p\alpha | k) = \{\pi\Delta / (k + 1)k\} \times$$
$$\times [E(p, \omega_{p\alpha}/k) - E(\alpha, \omega_{p\alpha}/k)], \quad (9)$$
$$\mu_2 = \Delta^2/k$$
$$\mu_3 = \{4\pi\Delta^3 / [k(k + 1)]\} \times$$
$$\times [E(p, \omega_{p\alpha}/k) - E(\alpha, \omega_{p\alpha}/k)],$$

where

$$E(j, \omega_{p\alpha}/k) = 0{,}5 \sum_{p_i} V_{jpi} V_{pij} \times$$
$$\times \left[\frac{1}{\omega_{jp_i} + \omega_{p\alpha}/k} + \frac{1}{\omega_{jp_i} - \omega_{p\alpha}/k}\right]. \quad (10)$$

Naturally, the summation in (10) is over all nuclear states.

3. So, the presented expressions for $\delta\omega(p\alpha|k)$ and μ_n describe the main characteristics of the nuclear line of the multi-photon absorption (emission) near resonant frequency $\omega_{p\alpha}/k$. It is important to underline that all unusual features of the multiphoton resonances in a nuclear case are remained, including unstandard quantness measure effect and other ones. Naturally, under superposition of resonances the shape of the line is significantly complicated. It is principally important to underline that the nuclear Multiphoton characteristics are defined not only the frequency of external field, but and by the quantness measure. For example, the shift will be proportional to $1/(\kappa+1)$ (not only to not to $1/\kappa$). Under

k=1 there is an additional non-standard term. The asymmetry of the multiphoton nuclear line is firstly predicted here and explained as follows. The central resonant part of a line has the maximal shift; at the same time, the wings of a line will be deformed more weakly. The especial features of the nuclear multiphoton case are significantly connected with estimating the corresponding matrix elements by using the basis of nuclear wave functions. In the modern theory of a nucleus there is sufficiently great number of the different models for generating the proton and neutron wave functions basis's. At present time it is accepted that quite adequate description of the nuclear density is provided by the relativistic mean-field (RMF) model of the nucleus. In many papers it has stated that though there is no guaranty that these wave-functions yield a close approximation to nature, the known success of the RMF approach supports their choice [42]. From the other side, these wave functions do not suffer from known deficiencies of other approaches, e.g., the wrong asymptotics of wave functions obtained in a harmonic oscillator potential. As a Kohn-Sham density functional scheme, the RMF model can incorporate certain ground-state correlations and yields a ground-state description beyond the literal mean-field picture. Alternative approach can be based on the effective Dirac-Wood-Saxon type model [24]. In any case this topic is of a great importance for correct predicting the multiphoton resonances parameters in nuclei and requires the separated consideration.

In conclusion the authors would like to thank Professors L.Ivanov, V.Letokhov, W.Kohn, E.Brandas, I.Kaplan, V.Rusov, A. Theophilou for useful discussions and the referees for useful comments.

References:

1. Letokhov V. S. Nonlinear Selective Photo-processes in atoms and molecules. — M.,1983. — 408c.
2. Scully M. O., Zubairy M. S., Qantum Optics. — Cambridge University Press, Cambridge. — 1997. — 380P.
3. Glushkov A. V., Relativistic quantum theory. Quabtum mechanicvs of atomic systems. — Odessa: Astroprint, 2008. — 900P.
4. Mцssbauer R., Gammastrahlung in Ir^{191}//Zeitschrift fьr Physik A. Hadrons and Nuclei. — 1958. — Vol.151. — P.124–143.
5. Goldansky V. I., Letokhov V. S. Effect of laser radiation on nuclear decay processes// Sov. Phys. JETP. — 1974. — Vol.67. — P.513-516.
6. Baldwin G. G., Salem J. C., Goldansky V. I., Approaches to the development of gamma ray lasers // Rev.Mod.Phys. — 1981. — Vol.53,N4. — P.687-742.
7. Letokhov V. S., Using lasers in Atomic, nuclear and molecular physics// In: Apllication of Lasers in Atomic, Nuclear and Molecular Physics. Ed. Prokhorov A. M., Letokhov V. S.. — Moscow:Nauka,1979. — P.405-414.
8. Ivanov L. N., Letokhov V. S. Spectroscopy of autoionization resonances in heavy elements atoms// Com. Mod.Phys.D.:At.Mol.Phys. — 1985. — Vol.4. — P.169-184.
9. Glushkov A. V., Ivanov L. N., Letokhov V. S., Nuclear quantum optics// Preprint of Institute for Spectroscopy of the USSR Acad. Sci.(ISAN), AS N4, 1992. — 16P
10. Glushkov A. V., Ivanov L. N.,Shift and deformation of the radiation emission and absorption atomic lines in laser field. Multi-photon Processes// Proc. Int. Sem. On Atomic Spectroscopy. — Moscow-Chernogolovka, 1992. — P.II-4; Preprint of Institute for Spectroscopy of the USSR Acad. Sci.(ISAN), AS N3, 1992. — 13P.
11. Glushkov A. V.,Ivanov L. N. DC Strong-Field Stark-Effect: consistent quantum-mechanical approach// J.Phys.B: At. Mol. Opt. Phys. — 1993. — Vol.26,N16. — P.L379-L386.
12. Matter in super-intense laser fields. Eds. D. Batani and C. J. Joachain. — AIP Serie. — 2006;
13. Superintense Laser Atoms Physics.Eds. C.A Ullrich., S Erhard., E. K. Gross. — N-Y: Kluwer,2005.
14. Glushkov A. V., Atom in an electromagnetic field. — Kiev: KNT, 2005. — 450P.
15. Olariu S., Sinor T. W., Collins C. B., Evidence for nuclear multiphoton transitions in ^{57}Fe based on radio-frequency sidebands to the forbidden hyperfine components of the 14.4-keV transition// Phys. Rev.B-1994. — Vol.50. — P.616-618.
16. Wauters L., Vaeck N., Study of the electron rearrangement induced by nuclear transmutation: A B-spline approach applied to the beta decay of ^{6}He// Phys. Rev. C. — 1996. — Vol.53,N1. — P.497-500.
17. Kaplan I., Endpoint energy in the molecular beta spectrum, atomic mass defect and the negative $m^2_{\nu_e}$ puzzle// J.Phys.G.: Nucl.Part.Phys. — 1997. — Vol.23. — P.683-692.
18. Zagrebaev V. I., Oganessian Yu.Ts., Itkis M. G., Greiner W., Superheavy nuclei and quasi-atoms produced in collisions of transuranium ions// Phys. Rev.C. — 2006. — Vol.73. — P.031602 (6p).
19. Burvenich T. J., Evers J., Keitel C. H., Nuclear quantum optics with X-ray laser pulses// Phys.Rev.Lett. — 2006. — Vol.96. — P.142501.
20. Burvenich T. J., Evers J., Keitel C. H., Dynamic nuclear Stark shift in superintense laser fields// Phys. Rev.C. — 2006. — Vol.74. — P.044601.
21. The European X-Ray Laser project homepage,

http://www.xfel.net; TESLA Technical Design Report Supplement, DESY Document No. 2002-167.
22. Lozhkarev V. V., Garanin S. G., Gerke R. R. etal, 100-TW Femtosecond Laser Based on Parametric Amplification // JETP Lett. — 2005. — Vol.82,N4. — P.178-180.
23. Mьller C., Di Piazza A., Shahbaz A., Bьrvenich T. J., Evers J., Hatsagortsyan H. Z., Keitel C. H., High-Energy, Nuclear, and QED Processes in Strong Laser Fields // Laser Physics. — 2008. — Vol. 18,N3. — P.175-184.
24. Glushkov A. V., Malinovskaya S., Dubrovskaya Yu., Vitavetskaya L., Quantum theory of co-operative muon-nuclear processes: Discharge of metastable nuclei during muon capture// Recent Adv. in Theory of Phys. and Chem. Systems (Berlin, Springer). — 2006. — Vol.15. — P.301-308.
25. Tkalya E. V., Theory of the nuclear excitation by electron transition process near the K edge//Phys. Rev.A. — 2007. — Vol.75. — P.022509.
26. Romanovsky M.Yu., Nuclear excitation and decay at the superstrong laser field// Laser Physics. — 1998. — Vol.1,N1. — P.17-24.
27. Ahmad I., Dunfird R. W., Esbensen H., Gemmell D. S., Kanter E. P., Run U., Siuthwirth S. H., Nuclear excitation by electron transition in ^{189}Os// Phys.Rev.C. — 2000. — Vol.61. — P.051304.
28. Kishimoto S., Yoda Y., Kobayashi Y., Kitao S., Haruki R., Masuda R., Seto M., Nuclear excitation by electron transition on ^{197}Au by photoionization around the K-absorption edge// Phys.Rev.C. — 2006. — Vol.74. — P.031301.
29. Glushkov A. V., Khetselius O.Yu., Malinovskaya S. V., Optics and spectroscopy of cooperative laser-electron nuclear processes in atomic and molecular systems — New trend in quantum optics// Europ.Phys.Journ. ST. — 2008. — Vol.160,N1. — P.195-204
30. Glushkov A. V., Khetselius O.Yu., Malinovskaya S. V., New laser-electron nuclear effects in the nuclear γ transition spectra in atomic and molecular systems// Frontiers in Quantum Systems in Chemistry and Physics (Berlin, Springer). — 2008. — Vol.18. — P.523-540.
31. Glushkov A. V., Ivanov L. N. Radiation Decay of Atomic States: atomic residue and gauge non-invariant contributions // Phys. Lett.A. — 1992. — Vol.170,N1. — P.33-37.
32. Ivanov L. N., Ivanova E. P., Knight L. Energy Approach to consistent QED theory for calculation of electron-collision strengths//Phys.Rev.A. — 1993. — Vol.48,N6. — P.4365-4374.
33. Ivanov L. N., Tolmachev V. V., The perturbation theory formalism for degenerate atomic states//Sov. Phys. — 1969. — Vol.2.
34. Ivanova E. P., Ivanov L. N., Aglitsky E. V., Modern Trends in Spectroscopy of Multicharged Ions// Physics Rep. — 1991. — Vol.166,N6. — P.315-390.
35. Ivanova E. P., Ivanov L. N., Glushkov A. V., Kramida A. E. High order corrections in the relativistic perturbation theory with the model zeroth approximation, Mg-like and Ne-like ions //Phys.Scripta —1985. — Vol.32. — P.512-524.
36. Glushkov A., Energy approach to resonance states of compound super-heavy nucleus and EPPP in heavy nucleus collisions//Low Energy Antiproton Phys. (AIP)-2005. — Vol.796-P.206-210
37. Glushkov A. V., Rusov V. D., Ambrosov S. V., Loboda A. V., Resonance states of compound super-heavy nucleus and EPPP in heavy nucleus collisions // In: New projects and new lines of research in nuclear physics. Eds. G.Fazio, F.Hanappe, Singapore : World Sci. — 2003. — P.126-142.
38. Glushkov A. V., QED theory of radiation emission and absorption lines for atoms and ions in a strong laser field// Spectral Line Shapes (AIP). — 2008. — Vol. 15. — P.134-136.
39. Glushkov A. V., Loboda A. V., Gurnitskaya E. P., Svinarenko A. A., QED theory of radiation emission and absorption lines for atoms and atomic ensembles in a strong laser field//Physica Scripta. — 2009. — Vol.T.135. — P. 014022.
40. Glushkov A. V., Khetselius O.Yu., Loboda A. V., Svinarenko A. A., QED approach to atoms in a laser field: Multi-photon resonances and above threshold ionization//Frontiers in Quantum Systems in Chemistry and Physics (Berlin, Springer). — 2008. — Vol.18. — P.541-558.
41. Glushkov A. V., Khetselius O.Yu., Lovett L., Electron-β-Nuclear Spectroscopy of Atoms and Molecules and Chemical Environment Effect on the β-Decay parameters// Advances in the Theory of Atomic and Molecular Systems Dynamics, Spectroscopy, Clusters, and Nanostructures. Series: Progress in Theoretical Chemistry and Physics, Eds. Piecuch P., Maruani J., Delgado-Barrio G., Wilson S. (Berlin, Springer). — 2009. — Vol. 20. — P.125-184.
42. Serot B. D., Walecka J. D. , Advances in Nuclear Physics Vol. 16: The Relativistic Nuclear Many Body Problem. Plenum Press, New York, 1986.
43. Glushkov A. V., Lovett L., Khetselius O.Yu., Loboda A. V., Gurnitskaya E. P., Dubrovskaya Yu.V., Generalized multiconfiguration model of decay of multipole giant resonances applied to analysis of reaction (μ-n) on the nucleus ^{40}Ca//Intern. Journal of Modern Physics A. Particles, Fields, Nucl.Phys. — 2009. — Vol. 24. — P.611-615.