CONSISTENT QUANTUM-MECHANICAL THEORY CALCULATION OF ELECTRON-POSITRON PAIR PRODUCTION IN HEAVY ATOMIC NUCLEUS COLLISIONS. ATOMIC PARITY NONCONSERVATION EFFECT

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A consistent unified quantum-mechanical and quantum-electrodynamical (QED) approach (operator perturbation theory (PT) method and QED perturbation theory) is used for studying electron-positron pair production (EPPP) process and atomic parity non-conservation effect. We have analyzed the possibility of treating the positron spectrum narrow peaks as resonances states of a compound superheavy nucleus. Resonance phenomena in the nuclear subsystem lead to the structurization of the positron spectrum produced. To calculate the electron-positron pair production cross-section in both cases we use the modified versions of the relativistic energy approach, based on the S-matrix Gell-Mann and Low formalism. The calculation is carried out for the case of the U-U collision. We developed a consistent QED perturbation theory method for studying the characteristics (the energy levels, E1- and M1-transitions amplitudes etc.) of heavy and superheavy atomic systems and applied it to the calculation of the parity non-conservation E1 amplitude for 6s-7s transition in Cs.

1. In modern atomic physics the processes in the inner shells of heavy atoms are under extensive theoretical and experimental study [1-8]. The energy and time scales of these processes are comparable with those of the low-energy nuclear processes. In view of this fact, new possibilities for systematic study of the cooperative electron-nuclear processes have appeared. We mean the situation where the interaction of the nuclear and electron subsystems opens new reaction channels or leads to appreciable corrections to observable characteristics. The correct approach to the solution of the related problems must be based on the consistent quantum-mechanical theory of the complicated electron-nuclear system taking into account the quantum-electrodynamical properties of the electron subsystem. The quality of the modelling for nuclear potential may have a decisive importance. A striking example of such kind presents the electron-positron pair production (EPPP) in the nuclei collision and in a strong electromagnetic field. The variation of parameters of the inter-nuclear potential within the reasonable limits leads to the qualitative and quantitative changes in positron spectra. The nuclear subsystem (NS) and electron subsystem (ES) have been considered as two parts of the complicated system, interacting with each other through the model potential. The NS dynamics has been treated within the Schrödinger (Dirac) equation with the model potential. The solution of the total electron-nuclear system quantum-mechanical equation is based on the formally exact PT with the zeroth order Hamiltonian H of the total system. This Hamiltonian is determined by its energy spectrum [1–3]. The subsequent PT corrections can be expressed in terms of the matrix elements of total Hamiltonian. All the spontaneous decay or the new particle (particles) production processes are excluded in the zeroth order. The approach treats the widely known distorted waves approximation as the

zeroth-order approximation in the formally exact quantum mechanical PT allowing for successive refinement of the calculations.

Upon collisions of atomic ions or nuclei with energy E> 1 MeV the EPPP is allowed. The cross-section $\sigma(\varepsilon, E)$ of this process depends on the collision energy E and the positron energy ε. The energy range close to the Coulomb barrier (it corresponds to the energy of several MeV per nucleon) is of great importance. Presently such collisions are under extensive theoretical and experimental study [1]. The narrow peaks in the differential cross-section $d\sigma(\varepsilon,E)/d\varepsilon$ attract special interest. The reasonable interpretation.of these peaks is now absent. In principle, the positron spectrum structure can be related to the resonances phenomena of different nature (resonances in the residual electron shell of colliding ions or resonances of a compound nucleus which is created by the colliding nuclei or resonances of new non-identified particles [6, 7] etc.). Here we use a consistent unified quantum-mechanical and quantum-electrodynamical approach (operator perturbation theory method and QED perturbation theory) [1–4] for studying the EPPP process and treat the positron spectrum narrow peaks as resonance states of the compound superheavy nucleus [1]). Resonance phenomena in the nuclear subsystem lead to the structurization of the positron spectrum produced. To calculate the EPPP cross-section in both cases, we use modified versions of the relativistic energy approach, based on the S-matrix Gell-Mann and Low formalism [1–5]. The calculation is carried out for the case of the U-U collision, total nuclear system charge being Z=184. As usually, we calculate the imaginary part of the energy of system. In the lowest perturbation theory order the second-order diagram describing the polarization of the electron-positron vacuum is calculated [1]:

$$\mathrm{Im}E = -\Gamma/2 = \mathrm{Im}\sum (M_{1s,1,F,\varepsilon s})^2/(E_F+\varepsilon(ns)-E_1-\varepsilon s)$$

and differential cross-section is determined as follows:

$$d\sigma(\varepsilon,E)/d\varepsilon. = \pi\ (M_{1s,1,F,\varepsilon s})^2(dP_F/dE_F)$$

where P and E are the momentum and energy of the nuclear system final state. The calculation results for log(dσ/dε) (plotted against e(1s)-es; in B/MeV) at the NS collision energy 352.2 keV (fifth upper s-resonance) are presented in Fig. 1.

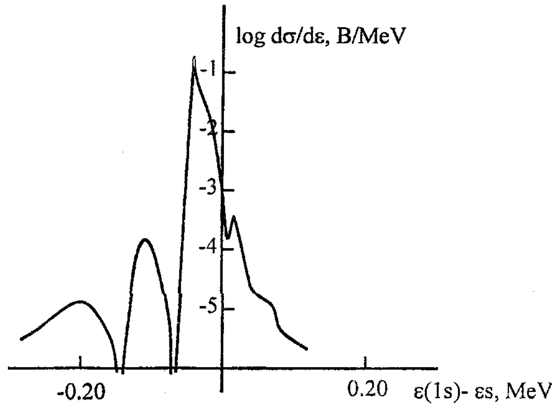

Fig. 1. The differential cross-section (plotted against e(1s)-es) for nuclear system collision energy 352.2 keV (fifth upper s-resonance).

The details of the calculation procedure were described in [1, 2, 8]. Note that in our calculation we have used the two-pocket nuclear potential. The calculation leads to principally the same physical picture as a calculation with one-pocket potential besides the appearance of a pronounced peak.

2. At present the atomic parity non-conservation effect attracts great attention. This effect was experimentally measured for four atoms: Cs,. Tl, Pb, Bi. The theoretical calculation reached quite high level of accuracy. Nevertheless, an elaboration of the method of calculation with accuracy within ~1% or less remains an important problem fo the theory. We have developed a consistent theoretical approach, based on the QED perturbation theory [2–5]. The main purpose is the study of the spectroscopic characteristics for heavy and superheavy atomic systems, including the atomic parity non-conservation effect. The zeroth approximation is generated by the effective *ab initio* model functional, constructed on the basis of the gauge invariance principle [2]. The PT zeroth-order potential includes the core *ab initio* potential, the electric and polarization potentials of the spherically symmetric nucleus (Gaussian form of charge distribution

in the nucleus and the uniformly charged sphere are considered). We have taken into account all correlation corrections of the PT second order. The PT higher-order corrections (particle-hole interaction, mass operator iterations) are effectively accounted. The magnetic inter-electron interaction is taken into account in the PT lowest (α^2 parameter) order, the Lamb shift polarization part in the Ueling-Serber approximation. The self-energy part of the Lamb shift is accounted effectively with the use of the 'exact' calculation for H-like ions with point nucleus. We have applied the developed approach to the calculations of the energy levels, hyperfine structure intervals, E1-,M1-transitions amplitudes in heavy and superheavy atoms and also the parity nonconservation E1 amplitude for the 6s-7s transition in Cs. Calculation gave the following result:

$$\langle 6s|Dz|7s\rangle = -0.92 \times i10^{-11} i|e|a_0(-Qw/N)$$

(all notations are standard). Note that this result is in a reasonable agreement with other theoretical data [6, 7].

References

1. L.N. Ivanov, T.V.Zueva, *Phys.Scr.* **43**, 374 (1991).
2. A.V.Glushkov,L.N.Ivanov, *Phys.Lett.A* **170**, 36 (1992); *J.Phys.B:* **26**, L379 (1993);
3. A.V.Glushkov, S.V.Ambrosov, S.V.Malinovskaya, *J.Tech.Phys.* **38**, 213 (1997).
4. L.N.Ivanov, E.P.Ivanova, L.V.Knight, *Phys.Rev.A* **48**, 4365 (1993).
5. A.V.Glushkov, S.V.Ambrosov, S.V.Malinovskaya, *J.Techn.Phys.* **38**, 211 (1997)
6. V.A.Dzuba, V.V.Flambaum, P.Silvestrov, O.Sushkov, *Phys. Rev. A* **44**, 2828 (1991).
7. W.R.Johnson, J.Sapirstein, S.A.Blundell, *Phys.Scr.* **46**, 184 (1993)
8. A.V.Glushkov, S.V.Malinovskaya, S.V.Filatov, Proc. Europ.Workshop "Quantum systems .in Chem. & Phys.", Uppsala, (2000) p.31; Proc.5th Int. Conf. on Atomic Physics, Firenze, (2000) p.331.

РОЗРАХУНОК ЕФЕКТІВ НАРОДЖЕННЯ ЕЛЕКТРОННО-ПОЗИТРОННИХ ПАР У ЗІТКНЕННЯХ ВАЖКИХ АТОМНИХ ЯДЕР НА ОСНОВІ ПОСЛІДОВНОЇ КВАНТОВОМЕХАНІЧНОЇ ТЕОРІЇ. ЕФЕКТ НЕЗБЕРЕЖЕННЯ АТОМНОЇ ПАРНОСТІ

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У дослідженні характеристик процесу народження електронно-позитронних пар (НЕПП) та ефекту незбереження атомної парності використано послідовний квантовомеханічний та квантовоелектродинамічний (КЕД) підхід (операторна теорія збурень та КЕД теорія збурень). Проаналізовано можливість інтерпретації вузьких піків позитронного спектру як резонансних станів складного надважкого ядра. Резонансні явища в ядерній підсистемі ведуть до структуризації позитронного спектру. Для розрахунку перетину НЕПП використано модифіковану версію релятивістського енергетичного підходу, який ґрунтується на S-матричному формалізмі Гелл-Мана та Лоу. Розрахунок виконано для випадку зіткнення ядер урану. В роботі розвинуто послідовну КЕД теорію збурень для розрахунку характеристик (енергетичних рівнів, амплітуд E1, M1 переходів) важких та надважких атомів, зокрема, виконано розрахунок амплітуди E1 переходу 6s-7s без збереження парності в атомі Cs.