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# RESONANCE PHENOMENA IN HEAVY NUCLEI COLLISIONS AND STRUCTURIZATION OF THE POSITRON SPECTRUM

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## Abstract

A consistent unified quantum mechanical and quantum-electrodynamical approach (operator perturbation theory and gauge-invariant quantum-electrodynamical perturbation theory) is used for numerical calculation of the electron-positron pair production cross-section. Resonance phenomena in the nuclear subsystem lead to the structurization of the positron spectrum produced. The positron spectrum narrow peaks are treated as resonance states of the compound superheavy nucleus. Calculation results for the differential cross-sections  $d\sigma(\varepsilon s, E_1)/d\varepsilon s$  for U-U collision energies  $E_1$  ( $E_1 = 162.0$  keV – the third  $s$ -resonance and  $E_1 = 247.6$  keV – the fourth  $s$ -resonance) are presented.

## 1 Introduction

Upon collisions of atomic ions or nuclei with energy  $E > 1$  MeV the electron-positron pair production is allowed. The cross-section  $\sigma(\varepsilon, E)$  of this process depends on the collision energy  $E$  and the positron energy  $\varepsilon$ . It is of a great interest the energy region close to the Coulomb barrier (it corresponds to the energy of several MeV per nucleon). Presently such collisions are under extensive theoretical and experimental study (c.f. refs. [1–12]). Especial attention attract the narrow peaks in the differential cross-section  $d\sigma(\varepsilon, E)/d\varepsilon$ . The nature of these peaks has not yet any acceptable reasonable interpretation. In principle, the positron spectrum structure can be related with the resonances phenomena of different nature (resonances in the residual electron shell of colliding ions or resonances of the compound nucleus which is created

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by the colliding nuclei or resonances of new non-identified particles etc.) [3–7]. In general it should be noted that the modern physics of the heavy atoms inner shells deals with the processes which energy and time scales are comparable with those of the low-energy nuclear processes. From this point of view the possibilities of systematic study of the co-operative electron-nuclear processes are appeared. We mean the situation where the interaction of the inner nuclear and electronic degrees of freedom open new reaction channels in both subsystems or leads to appreciable corrections to observable. The correct approach to 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-electrodynamics properties of the electron subsystem. The quality of the modelling of inner-nuclear dynamics may have decisive importance. A striking example of such kind presents the electron-positron pair production in the nuclei collision and in strong electromagnetic field (c.f. ref. [3]). The variation of parameters of the inter-nuclear potential within the reasonable limits leads to the qualitative changing of positron spectra [6, 7, 11]. The nuclear subsystem and electron subsystem have been considered on the equal foot as two parts of the complicated system interacting one with another through the model potential. The inner-nuclear dynamics has been treated due to Schrödinger (Dirac equation) with the model potential. The solution of the total electron-nuclear system quantum-mechanical equation is based on the formally exact perturbation theory with the zeroth order Hamiltonian  $H$  of the total system being determined by its energy spectrum and the set of the eigenfunctions without specifying analytic form of zero order potential [6–9, 10]. The subsequent corrections of the perturbation theory can be expressed in terms of the matrix elements of total Hamiltonian, calculated between the zeroth order state functions. All the spontaneous decay or the new particle (particles) production processes are excluded in the zero order [6, 7, 11]. The approach treats the widely known distorted waves approximation as the zeroth order approximation in the formally exact quantum-mechanical perturbation theory allowing for successive refinement of calculations [11]. Here we will use a consistent unified quantum mechanical and quantum-electrodynamical approach (operator perturbation theory method and quantum-electrodynamical perturbation theory) [6–8, 10–15] for numeric calculation of the electron-positron pair production cross-section and treat the positron spectrum narrow peaks as resonances states of the 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 modified versions of the relativistic energy approach, based on the  $S$ -matrix Gell-Mann and Low formalism, and perturbation theory method.

The calculation is carried out for the case of U–U collision (total nuclear system charge being  $Z = 184$ ) with using the two-pocket nuclear potential.

## 2 Energy approach to calculation of the EPPP cross section

The formulae of EPPP' cross-section can be obtained on the basis of the energy approach [6–11]. As in refs. [6, 7, 11], a one-center model is chosen as a zero-order approximation. Energy approach allows the use of the well developed stationary-state methods to the collisional problem with variable number of particles. In such approximation the calculation of the EPPP' cross-section is reduced to the solution of the ordinary differential equation system. The latter includes: (1) equations for the potentials  $V(R)$ ,  $U(r)$  (internuclear potential and electric potential of the compound nucleus), (2) relativistic quantum-mechanical equations for nuclear system– and electron system–state functions, equations for all matrix elements of perturbation theory. The nonstationary feature of our problem manifests itself in the way of the normalization of the nuclear system initial state function and in the principle of the electron system bound state quantization when this state dives into the lower continuum. The motion of nuclear system is described by the Dirac equation whose radial part is represented by

$$\begin{aligned} F' &= -F(\varkappa + |\varkappa|)/T - G(E + 2M\tilde{\alpha}^{-2} - V)\tilde{\alpha}, \\ G' &= G(\varkappa - |\varkappa|)/T + F(E - V)\tilde{\alpha}, \end{aligned} \quad (1)$$

where  $\varkappa$  is the Dirac angular quantum number,  $E$  is the state energy,  $F$ ,  $G$  being the large and small radial components correspondingly. The two-pocket nuclear potential  $V(R)$  is in further used. It is defined by the following differential equation [10]:

$$dV(R) = z \times (R_B/2 - R) \times (3R_B/4 - R) \times (R_B - R) \times R^3(V_B + 8R^8). \quad (2)$$

This potential has the same asymptotics at  $R \rightarrow 0$ ,  $R \rightarrow \infty$  as the one-pocket potential used in calculation [6, 7]. Its model parameters are found from the physical conditions: potential generates five  $S$ -resonances, the difference  $V(R_B) - V(\infty)$  coincide with the experimental energy of the near-barrier collision. It is supposed that  $R_B = R_U \approx 6$  fm (radius of compound nucleus charge distribution). It corresponds to the internuclear distance  $2R_B \approx 12$  fm. The potential generates the under-barrier  $s$ -resonances, whose positions and level widths are listed in the Table 1. The widths of the NS'

Table 1: Energies  $E$  and width  $\Gamma$  of  $s$ -resonances of the compound U-U nucleus, generated by the potential  $V$

$E$ , keV	25.9	85.8	162.0	247.6	225.2
$\Gamma$ , eV	$0.20 \times 10^{-3}$	$0.12 \times 10^{-1}$	0.86	$0.42 \times 10^2$	$0.16 \times 10^4$

states, related to the purely nuclear process, were calculated by the same method as the width of the quasi-stationary state of the electron-positron vacuum with a dived atomic level. The correct procedure was developed earlier and is in the following. In zeroth order of perturbation theory it is used the Hamiltonian generating the same energy spectrum as the potential  $V(R)$  but possessing only stationary states. Further note that contrary to the case of the stationary states we use the alternative principle of quantization of the quasi-stationary states [11]. It can be realized by the following procedure: (i) let the trial NS' state energy to be  $E$  and preset the function norm by the condition  $F(T = 0) = 1$ . (ii) Let's integrate the system (1) under this conditions up to asymptotically large  $T$  with the simultaneous evaluation of [6, 7]:

$$X(E) = \lim_{T \rightarrow x} T^{2|x|} ((E + 2M\tilde{\alpha}^2 - V)G^2 + (E - V)F^2). \quad (3)$$

This value defines the norm of the state function of the asymptotically free motion [4]. (iii) The value  $X$  must be minimized as a function of state energy  $E$ . According to our assumption, the stationary points of  $E$  correspond to the resonances of the system. The quantization principle for the electron slate dived into continuum is described in [4, 7]. The principle is equivalent to the above described principle of the quantization in the case of potential  $V(R)$  with a barrier. The main difference is that the role of the potential plays here another function:

$$U_{eff} = (\varepsilon s + 2\tilde{\alpha}^2 - U)(\varepsilon s - U). \quad (4)$$

The effective potential has two turning points  $T_1$ ,  $T_2$ , dividing the whole integration region into three parts, where  $U < \varepsilon s$  ( $T < T_1$ ),  $\varepsilon s < U < \varepsilon s + 2\tilde{\alpha}^2$  ( $T_1 < T < T_2$ ), and  $U > \varepsilon s + 2\tilde{\alpha}^2$  ( $T > T_2$ ). The quasi-stationary state function must decrease in the second region and oscillate in the third one. The quantization principle implies the minimization of the following function of the trial electron system energy

$$\lim_{T \rightarrow \infty} T^{2|x|} ((\varepsilon s + 2M\tilde{\alpha}^2 - U)G^2 + (\varepsilon s - U)F^2). \quad (5)$$

When having found state energy  $\varepsilon(1s)$  one must define all the ES' state functions for the zero-order potential  $U_0$ . All the level positions in the potential

$U_0$  coincide with those in the potential of the compound nucleus electric field  $U$ . Functions of all states above the lower continuum are preserved too, the restructuring concerns only the  $1s$ -state and the lower continuum states.

The cross-section of the EPPP is connected with the imaginary part of the energy for our system. In the lowest perturbation theory order the second-order diagram describing the polarization of the electron-positron vacuum is calculated as follows [6, 7, 10]:

$$\text{Im}E = -\Gamma/2 = \text{Im}\Sigma(M_{1s,1,F,\varepsilon s})^2/(E_F + \varepsilon(ns) - E_1 - \varepsilon s). \quad (6)$$

The differential cross-section is 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 details of numeric procedure are described in refs. [6–13].

### 3 Results and conclusion

In Ref. [10] we have presented the results of calculation of the differential cross-section for the nuclear subsystem collision energy  $E_1 = 352.2$  keV (fifth upper  $s$ -resonance). Here we consider calculation results for the differential cross-section  $d\sigma(\varepsilon s, E_1)/d\varepsilon s$  (plotted against  $\varepsilon(1s) - \varepsilon s$ , in B/MeV) for the nuclear subsystem collision energies  $E_1$ : (a)  $E_1 = 162.0$  keV (the third  $s$ -resonance) and (b)  $E_1 = 247.6$  keV (the fourth  $s$ -resonance). The main difference of present calculation from analogous calculations [6, 7] is connected with two moments. We use the two-pocket nuclear potential and more correct procedure for account of the perturbation theory higher-order diagrams, describing the additional attraction in the final state of the nuclear subsystem due to the bound electron. The calculation results for  $d\sigma(\varepsilon, E_1)/d\varepsilon$  at two different collisional energies  $E_1 < V_B$  are presented in Fig.1. It is important to note that the calculation leads to principally the same physical picture as one with one-pocket potential besides appearance of some additional peaks. Naturally, not all processes accompanying the electron-positron pair production are taken into account and considered in this paper. This problem will be considered in the separated paper.

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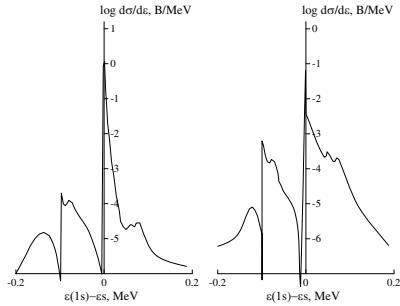


Figure 1: The differential cross-section  $d\sigma(\varepsilon s, E_1)/d\varepsilon s$  plotted against  $\varepsilon(1s) - \varepsilon s$  (in B/MeV) for the nuclear subsystem collision energies: (a)  $E_1 = 162.0$  keV; (b)  $E_1 = 247.6$  keV.

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## 4 References

### References

- [1] H.Gould, in: *Photonic, Electronic and Atomic Collisions* eds. F.Aumayr, H.Winter, Singapore: World Scientific, 465 (1997).
- [2] J.C.Wells, B.Segev, in: *Photonic, Electronic and Atomic Collisions* eds. F.Aumayr, H.Winter, Singapore: World Scientific, 487 (1997).
- [3] A.A.Gryb, S.G.Mamaev, V.M.Mostepanenko, *Quantum Effects in Intensive External Fields*, Moscow (1980).
- [4] J.Reinhardt, B.Muller, W.Greiner, *Phys.Rev.A* **24**, 103 (1981).
- [5] J.M.Bang, V.V.Flambaum, J.M.Hansteen, *Z. Phys. A* **330**, 431 (1985).
- [6] L.N.Ivanov, T.V.Zueva, *Phys.Scr.* **43**, 374 (1991).
- [7] L.N.Ivanov, A.V.Glushkov, S.V.Malinovskaya, S.V.Ambrosov, *Preprint of Institute for Spectroscopy AN*, No. AS-5, Troitsk: ISAN, (1991).

- [8] A.V.Glushkov, L.N.Ivanov, *J.Phys.B* **26**, L379 (1993).
- [9] L.N.Ivanov, E.P.Ivanova, L.V.Knight, *Phys.Rev.A* **48**, 4365 (1993).
- [10] A.V.Glushkov., S.V.Ambrosov, A.V.Loboda, in: *it New Projects and New Lines of Research in Nuclear Physics* eds. G.Fazio, F.Hanappe, Singapore: World Scientific, 126 (2003).
- [11] A.V.Glushkov, in *Low Energy Antiproton Phys.*, AIP Serie. **796**, 206 (2005).
- [12] A.V.Glushkov, S.V.Ambrosov, A.V.Loboda, Yu.G.Chernyakova, O.Yu.Khetselius, A.A.Svinarenko, *Nucl.Phys.A* **734**, e21 (2004).
- [13] A.V.Glushkov, S.V.Ambrosov, A.V.Loboda, Yu.G.Chernyakova, G.P.Prepelitsa, *Int.J.Quant.Chem.* **104**, 562 (2005).
- [14] A.V.Glushkov, L.N.Ivanov, *Phys.Lett.A* **170**, 36 (1992).
- [15] E.P.Ivanova, L.N.Ivanov, A.V.Glushkov, A.E.Kramida, *Phys.Scr.* **32**, 524 (1985).
- [16] A.V.Glushkov, E.P.Ivanova, *J.Quant.Spectr.Rad.Transfer* **36**, 127 (1986).