World Academy of Science, Engineering and Technology
International Journal of Nuclear and Quantum Engineering
Vol:12, No:05, 2018

Non-Perturbative Vacuum Polarization Effects in One- and Two-Dimensional Supercritical Dirac-Coulomb System

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Abstract : There is now a lot of interest to the non-perturbative QED-effects, caused by diving of discrete levels into the negative continuum in the supercritical static or adiabatically slowly varying Coulomb fields, that are created by the localized extended sources with Z > Z_cr. Such effects have attracted a considerable amount of theoretical and experimental activity, since in 3+1 QED for Z > Z_cr,1 ≈ 170 a non-perturbative reconstruction of the vacuum state is predicted, which should be accompanied by a number of nontrivial effects, including the vacuum positron emission. Similar in essence effects should be expected also in both 2+1 D (planar graphene-based hetero-structures) and 1+1 D (one-dimensional 'hydrogen ion'). This report is devoted to the study of such essentially non-perturbative vacuum effects for the supercritical Dirac-Coulomb systems in 1+1D and 2+1D, with the main attention drawn to the vacuum polarization energy. Although the most of works considers the vacuum charge density as the main polarization observable, vacuum energy turns out to be not less informative and in many respects complementary to the vacuum density. Moreover, the main non-perturbative effects, which appear in vacuum polarization for supercritical fields due to the levels diving into the lower continuum, show up in the behavior of vacuum energy even more clear, demonstrating explicitly their possible role in the supercritical region. Both in 1+1D and 2+1D, we explore firstly the renormalized vacuum density in the supercritical region using the Wichmann-Kroll method. Thereafter, taking into account the results for the vacuum density, we formulate the renormalization procedure for the vacuum energy. To evaluate the latter explicitly, an original technique, based on a special combination of analytical methods, computer algebra tools and numerical calculations, is applied. It is shown that, for a wide range of the external source parameters (the charge Z and size R), in the supercritical region the renormalized vacuum energy could significantly deviate from the perturbative quadratic growth up to pronouncedly decreasing behavior with jumps by (-2 x mc^2), which occur each time, when the next discrete level dives into the negative continuum. In the considered range of variation of Z and R, the vacuum energy behaves like ~ -Z^2/R in 1+1D and ~ -Z^3/R in 2+1D, exceeding deeply negative values. Such behavior confirms the assumption of the neutral vacuum transmutation into the charged one, and thereby of the spontaneous positron emission, accompanying the emergence of the next vacuum shell due to the total charge conservation. To the end, we also note that the methods, developed for the vacuum energy evaluation in 2+1 D, with minimal complements could be carried over to the three-dimensional case, where the vacuum energy is expected to be ~ -Z^4/R and so could be competitive with the classical electrostatic energy of the Coulomb source.

Keywords : non-perturbative QED-effects, one- and two-dimensional Dirac-Coulomb systems, supercritical fields, vacuum polarization
Conference Title : ICQESP 2018 : International Conference on Quantum Electrodynamics and Statistical Physics
Conference Location : Amsterdam, Netherlands
Conference Dates : May 10-11, 2018

Open Science Index, Nuclear and Quantum Engineering Vol:12, No:05, 2018 publications.waset.org/abstracts/82860.pdf