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Review on the doctoral dissertation

Quantum kinetic approach to particle production in time dependent external fields

presented by

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The doctoral dissertation of Mr Lukasz Juchnowski concerns a new and challenging field of Quantum field theory, the vacuum state of quantum electrodynamics under the influence of extremely strong electromagnetic fields. According to the early works of Sauter, Euler, Heisenberg, Schwinger, et al., it is supposed that there exists a critical field strength $E_c = 1.3 \times 10^{18}$ V/m, see Eq. (2.1) of the doctoral dissertation, where the vacuum state becomes instable with respect to the creation of electron-positron pairs. At present, such strong fields are not available in laboratory experiments. Precursors of the Schwinger mechanism of pair creation may be visible already at field strengths below the critical value. This motivates the search for ways to enhance the pair-creation probability such as colliding multiple pulses or assisting the strong field with a high-energy photon. Another possibility is the dynamically assisted Sauter-Schwinger effect described by Schuetzhold et al., Phys. Rev. Lett. 101 (2008), which has become an active research field.

The dissertation of Juchnowski investigates such phenomena. Quantum kinetic equations, Eqs. (2.64), (2.74) of the doctoral dissertation, are derived and evaluated for time-dependent electrical fields. As seen from Eq. (1.2), a perturbative expansion with respect to the field strength E is not possible, and a non-perturbative approach has to be used to obtain the Schwinger source term for the kinetic equations. This is a new result of Mr Lukasz Juchnowski which is of relevance for the further research activities in this challenging field.

In detail, a non-perturbative approach has been worked out which is based on a canonical time-dependent Bogoliubov transformation of the field operators. An external classical field is considered described by a vector potential $A(t)$ in Hamilton gauge. Within a full relativistic approach, also a spacial dependence is expected. Whereas the present derivation of kinetic equations for particle production considers only homogeneous fields, the question arises whether the approach can be generalized to treat inhomogeneous, space-dependent fields.

The construction of the pair operator, Eq. (2.40), leads to similar kinetic equations for bosons. As discussed in the doctoral dissertation, the full quantum electrodynamics gives in addition to the external classical field also an intrinsic quantum field connected with the production of charged particles. For instance, a bound state, the positronium, may be formed. These back-reactions, which modify the external electric field owing to the induced fields, are neglected in the present work. Compared to the critical field strength, these induced fields are small for the parameter region under consideration. An estimation would be of interest, because they may become of relevance when the field strength approaches the critical value.

Of interest is the construction of the adiabatic vacuum state. Because of the Bogoliubov transformation, a coherent state results, and distribution functions for the occupation numbers are obtained. Induced fields are neglected so that no correlations beyond a mean-field approximation are obtained in the vacuum state. Also the Schwinger source term of the kinetic equations describing the particle production shows interesting properties. Being non-Markovian with a memory term related to the pre-history of the electron/positron distribution function, it can be transformed to a Markovian process after the introduction of two auxiliary functions. This property which was already discussed in the paper [43] of Bloch et al., allows to find numerical solutions of the particle production process in a simple way.

In the doctoral dissertation, new result are presented for the evolution of the fermionic distribution function for two cases of the time dependence, the so-called Eckert-Sauter pulse (2.141) and the harmonic pulse with Gaussian envelope (2.142). Different parameter values are discussed. The interpretation of the results is difficult. In particular, virtual electron-positron excitations should be separated from real electron-positron pairs. The entropy production is considered. In addition, the question has been touched whether there exists a field-induced phase transition. The Bogoliubov coefficients are used to construct an order parameter (2.165). The time evolution of distribution functions and the order parameter have been calculated for different parameter values of the model, the results are shown in several figures. It is discussed how the distribution functions is modified changing the parameter values.

After explaining the model and the approaches to find solutions, an inspiring part of the doctoral dissertation is the discussion of various applications of the kinetic model. An important application are the new facilities such as XFEL, HIBEF, ELI, or LCLS where high-energy short pulse lasers are produced. Being not able to reach the critical field strength, precursors as fluctuations of the vacuum properties may be found. In particular, pulse shaping may help to optimize the experimental verification of the Schwinger effect.

Pair production is also of relevance in heavy-ion collisions. Flux tubes can decay via the Schwinger process, and a model has been presented to explain the apparent thermal spectra of the produced particles. These processes may serve as a prospective application of the formalism presented in the doctoral dissertation, but need for further elaboration of the theory, for instance to inhomogeneous situations, as well as a comparison to other approaches. Also the connection between the Schwinger process and thermalization is shortly addressed. More detailed work is needed to solve these very complex problems. I estimate this last part as an outlook to show which problems may be attacked in future using the methods developed in the doctoral dissertation of Lukasz Juchnowski. His contributions to elaborate the theory are mainly collected in Section 2 of the dissertation.

The presentation of the physical problem is clearly outlined in the doctoral dissertation. The calculations are well described. Mr Lukasz Juchnowski cited the relevant literature (146 references). However, the text has also minor mistakes, in particular the English. (As example, p. 11: exapansion, explain ω_0 in Eq. (2.25), correct h_{pqs} in Eq. (2.34), integral from $-\infty$ in Eq. (2.74) should be t_0, p.25 "is define", p. 26: dot after n_{-pr} ?, p. 39 "is a reduce density matrix", "en example", p.47 "theory.[101].", p. 48: "capturapble", p. 56: "presenter".) In general the use of the articles "the" or "a" is often not clear, the punctuation at the end of the equations is in many cases not correct. This are minor defects which do not perturb the understanding of the text.

Parts of the results presented in the doctoral dissertation have been already published in peer-reviewed international journals. Coauthors are D. Blaschke, S. A. Smolyansky, T. Fischer, A. Panferov, et al., but Mr Lukasz Juchnowski made essential work for analytical calculations and numerical evaluations.

In conclusion, the doctoral dissertation contains new and interesting results in a fast developing field of research, the properties of the vacuum under the influence of ultra-strong fields. Based on a quantum statistical approach which is carefully worked out, the reaction on a time-dependent external field is treated within a non-perturbative approach. The results are already recognized in the international discussion, for instance the frequently cited publication [68]. The dynamically assisted Sauter-Schwinger effect may become observable in next future because of new facilities which produce ultra-strong laser fields, and pulse shaping may enhance the creation of electron-positron pairs. The discussion of other fields of research where pair creation is possible, shows the broad applicability of the theory to different phenomena, which have to be worked out in future investigations.

I recommend the doctoral dissertation of Mr Lukasz Juchnowski for acceptance by the Faculty of Physics and Astronomy of the University of Wroclaw. I valuate the doctoral dissertation with "cum laude" (good).

Sincerely yours

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