Kapitza-Dirac effect with lasers and non-resonant interaction for quantum modulation of electron beams (Schwarz-Hora effect)

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Abstract: The initial Kapitza-Dirac effect for crossing energetic electron beams with laser beams had been generalized for quantum modulation of the electrons. The recent developments provide advanced insights with the initial experimental facts where consequences are leading to results about non-resonant laser interaction with condensed media including nonlinearities with applications to quantum 1/f noise theory in electronic devices.

Key words: Laser Interaction with electron beams; Kapitza-Dirac effect; Schwarz-Hora effect; non-resonant nonlinear excitation; virtual electron states.

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The final detailed experimental demonstration[1] of the Kapitza-Dirac effect[2] for scattering of an electron beam when crossing a laser beam by standing wave nodes and antinodes is related to the basic understanding of laser interaction with electrons. This refers to both, to electrons in the unbound-free state in vacuum and also in high temperature plasmas, as well as to electrons in the bound states in a condensed medium. For the free electrons, the Kapitza-Dirac effect – now demonstrated[1] - is a very early[2] theoretical approach to the problem of nonlinearity which came later into the focus of attention with the laser. The question of the electron interaction in the bound state was touched by quantum modulation effect[3] where a condensed medium was located into the crossing area of the beams as a generalization of the Kapitza-Dirac effect. This generalization did realize from the beginning that this is a quantum modulation process[3] for the electron beam.

At the time when the measurement of the quantum modulation by using crystals as medium[3] and the repetition of the experiments and reproduction of the effect with molecules as medium[4,5] were performed, the nonlinearity of the interaction process was just at the begin to be clarified. This question was opened by realizing that the interaction of electrons with lasers could not happen by linear physics but needed nonlinear physics[6]. Before, the linear description was based on the exactly derived result that a free electron can never gain energy[7] from a laser field of a plane wave electromagnetic pulse. In contrast, after realizing the nonlinearity, acceleration of free electrons by lasers can produce beams of measured GeV energy and may lead to beams with PeV electrons using Exawatt (EW) laser pulses in the range of femtosecond (fs) duration[8].

The Kapitza-Dirac effect was predicted in 1933 for the interaction of electron beams with optical beams in a modified way going beyond the knowledge of linear interaction. In view of these facts, the following clarifies the position of the quantum modulation process under the aspect of the Kapitza-Dirac experiment[1]. For the quantum modulation, in the first part, the results about the long beating wave length of the electrons and the fit with the theory of Peierls[9] is shown, then the agreement of the initial quantum model[3] is supported by the later performed quantum modulation experiments of Weingartshofer et al.[5], and finally an updating of the early reported consequences[10] to the 1/f noise theory for applications to electronics elements is presented.

Clarification of the long wave length beating. The initial experiment demonstrated the scattering of the electrons[3] if a crystal in the crossing area of the electron beam with a transport of photons to a nonluminescent screen. The modulation of the photons in the electron beam was directly shown with a neon laser interacting with argon atoms using a CO_2 laser to show an up- or down shift of the electron energy by the laser photons as measured in the electron energy spectrum[4]. The first experiment[3] was leading to the measured long wave length beating[11] for demonstration of the effect. This is different to the later demonstration of the effect by using and argon atoms in the crossing area where the modulation could be directly measured from the electron spectrum with the shift of the energy $\hbar\omega$ by the energy of photons of the laser with the frequency ω[5,6] using Planck's constant h and $\hbar = h/2\pi$.

Following the initial publication[3], the beating in the electron beam[12] was studied. In first order, electron and light waves show the same beating for which the necessary coherence is fulfilled[13]. In contrast for electron waves, the second order showed a basic difference to optical waves. This was used before e.g. to calculate exact solutions for the Goos-Haenchen effect[14,15] while the optical case could be treated only by approximations. Salat discovered a second order bunching for electrons[13] having a wave length λ_e

$$\Lambda_{beo} = 8\lambda_e(E_o/\hbar\omega)^2 = 1.6858 \text{ cm} \qquad (1)$$

When Schwarz got the paper for refereeing, he immediately used his experiment with motion of the non-luminescent screen and measured this second order bunching[11], Fig. 1 with a wave length

$$\Lambda_{be} = 1.73(0.01) \text{ cm.} \qquad (2)$$

The theory[12] was 3% lower than the measured long beating wave length. The computation was non-relativistic. A relativistic approximation[16] arrived even at a shorter wave length 1.51 cm. This raised questions to the experiment of Schwarz. Using an exact derivation with the Dirac equation for the electrons[17], the problem was what dielectric response should be applied for the crystals used by Schwarz[3,11]. An initially used dispersion led still to a difference with the experiment. When the later theory of Peierls[9] arrived at the ratio of the speed of light c_M in the medium with a refractive index n = 1.58 of the crystal and the speed of light in vacuum c

$$c_M/c = (n^2 -1)[1 + (n^2 - 1)/5]/n, \qquad (3)$$

the theoretical long beating wave length was

$$\Lambda = 1.740 \text{ cm.} \qquad (4)$$

This exact fit was an immediate proof of the correctness of the Peierls[9] theory and also confirmed the very accurate measurement of the motion of the non-luminescent screen by Schwarz[11].

Theory of quantum limit. The initial paper on the Schwarz-Hora effect[3] included a rather obvious but nevertheless hypothetical theoretical assumption. When the electrons of the beam are moving through the condensed medium (crystal or molecules), will they interact with the laser field as if they are free electrons, as being in vacuum or in a high temperature plasma? Or will there be an interaction with the electrons in the medium? In the first case, the electrons are picking up oscillations in the laser field and returning this "quiver energy" when leaving the laser field, independently from any polarization direction. This corresponds to the exact theoretical solution requiring that free electrons in a laser field should not absorb optical energy or receive an acceleration[7] based on linear theory. It changes by inclusion of nonlinear effects. Energy from a laser field to free electrons can be transferred by nonlinear mechanisms[6] as well known now from electron acceleration in laser fields[6,18]. The fact that energy from laser photons is exchanged with the electrons within a medium[3-5] can only happen by inclusion of nonlinear processes within the medium. Its electrons, however are not free and assuming that these behave in a similar way as free electrons can be considered only as a hypothetical virtual process.

Such virtual motion is considered similar to that of free electrons. One obtains then a displacement x along the direction of the electric field E, determined by the laser intensity I of the laser for the oscillation and maximum momentum p = m(dx/dt). It was postulated[3] that if xp is less than $\hbar$ this should be a range of quantum interaction and if larger than $\hbar$ it should be classical. The laser intensity I between these two ranges, expressed in a modified formulation[3] using the fine structure constant α

$$I = I^* = m\omega^3/(8\pi\alpha) = \pi^2 mc^3/(\alpha\lambda^3), \quad (5)$$

Where λ is the laser wave length. Converting (5) from cgs units to Watts/cm^2 results for CO_2 lasers in

$$I^* = 1.403x10^9 \ \ W/cm^2 \quad (6)$$

For cw lasers in the experiments, this condition is fulfilled with intensities $I < I^*$ within the quantum range[3] both for argon lasers and the subsequent experiments with[4,5] CO_2 lasers.

It was interesting, to measure the scattering intensity of the modulation effect from the electron spectra by varying the laser intensity. Fig. 2 shows a typical results of Weingartshofer et al.[5]. From a series of experiments the strength of the modulation can be evaluated as shown in Fig. 3 resulting in a decrease of the scattering intensity with increasing laser intensity I, down to no scattering when reaching the threshold intensity I* of Eq. (6). This is a proof of the correct conditions of Weingartshofer's et al. rather sophisticated experiments, and of the intensity threshold I* with the limit of the quantum range towards the classical range demonstrated for the basic use in initial experiments[3] and the ones following[4,5].

Interpretation and application to 1/f noise. After the final experimental establishment and demonstration of the Kapitza-Dirac effect[1], this is also proof of its generalization by adding a medium in the crossing area, when crossing an electron beam with the laser beam (Schwarz-Hora effect)[3-5]. What is remaining is the further understanding of the non-resonance of the medium aspect and the necessary involvement of the medium that provides the essential nonlinear mechanism. This can be realized on the basis of achievements, during the recent years, in the theory of target interactions with a laser field. In linear physics, the exact solution did not permit a final energy transfer from a laser beam to an electron in vacuum. In contrast, the basic result was[6] that nonlinearity resulted in electron acceleration in laser fields in vacuum, that now has been achieved[8,18]. A connection exists, and is mentioned here, to the quantum mechanical theory of the fundamental 1/f noise[10,.19,20] and to quantum coherence[21].

For the fundamental understanding of quantum mechanics it has to be realized that the interaction is a non-resonance process differing from the well-known optical resonances in the medium. Heisenberg aimed to base quantum mechanics purely on observable quantities, such as the exactly measured energy levels of spectral lines. He connected these levels with matrix elements of non-commutative operators to elegantly obtain quantization. Together with Dirac and others he defined Poisson brackets and also described the hydrogen atom relativistically, recovering line shift of fine structure, predicting antimatter and more. This was a method with directly and transparently observed quantities. The way introduced by Schrödinger, following DeBroglie's result with wave functions Ψ, was more indirect. It obtained the same results through solutions of differential equations, from eigenvalues of spherical functions and Laguerre associated functions. This was a quite transparent treatment for the hydrogen atom. The wave functions Ψ however were not directly observable values of measurements, but only indirect expressions of distribution functions from where the real observable values of measured quantities had to be derived as expectation values.

Dirac mentioned some incompleteness in quantum mechanics[22]. The absence of a matrix element in Quantum Electro Dynamics QED due to the long range of the Coulomb potential was an incompleteness that was removed by the introduction[23] of the long range Coulomb interaction into the unperturbed hamiltonian. It led to a more complex notion of a free charged particle of indefinite energy that is never exactly free, with its field in a non-stationary coherent state, and with the asymptotic QED propagator[27,28] of Faddeev, Kulish, Zwanziger and Kibble for large times or low frequencies. This non-stationarity with implicit de-coherence allowed us to explain[10.26,27] the ubiquitous fundamental 1/f noise with the simple universal formula $2\alpha/\pi fN$ for the spectral density of fractional fluctuations of current carried by N charge carriers. It brought us a basic aspect[28,29] of quantum physics, with the notions of "physical" cross sections and process rates that still contain the mezo/macroscopic "infrared" genuine quantum fluctuations, with great practical importance in the optimization of most hi-tech applications[29,30], for ultra-low 1/f noise and phase noise close to carrier. It is applicable with coherent and conventional contributions for any system of quanta with infrared-divergent coupling to any current, including also gravitons, transversal piezo- phonons, etc., by just replacing the fine structure constant a with the right coupling constant. For nanotechnology applications and devices the conventional part is dominant.

On the other hand, the example of non-resonance and the principle realization of nonlinearity[31] for the electron beam interaction with laser photons occurring in condensed media within the defined quantum range for the laser intensity I < I* may also be one avenue to access exploring more subtle properties of these processes.

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Figure Captions

Fig. 1. Optical emission intensity from the non-luminescent screen for varying the distance D = r between crystal and screen (see Ref. 14). The minima correspond to the long beating wave length according to Eq. (3).

Fig. 2. Schwarz-Hora effect measured by Weingartshofer et al. (from Fig. 5 of Ref. 5) of the energy spectrum of the electron beam after interaction from where the height of the intensity of the scattered first maximum could be related to that of the incident laser intensity I, see following Fig. 3 with cases A, B and C for different laser intensities an no laser, D.

Fig. 3. Measured intensity ratios of the scattered radiation of the electrons on the irradiated CO_2 laser intensity I decaying to zero at the threshold intensity I*, Eq. (6), separating quantum interaction ($I < I^*$) from the classical case ($I > I^*$) defining a correspondence principle for electromagnetic interaction.

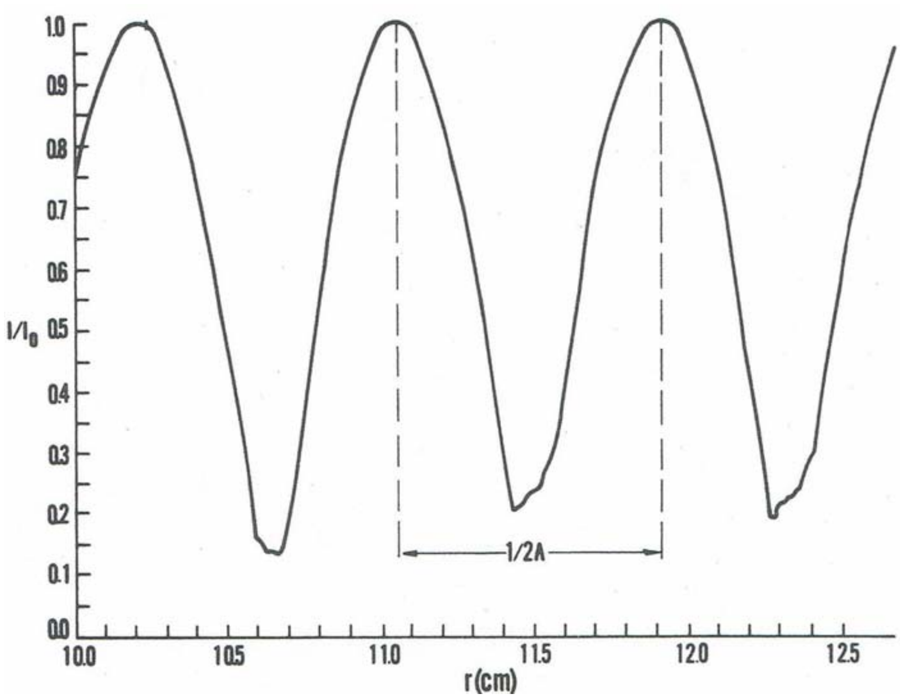


Fig. 1

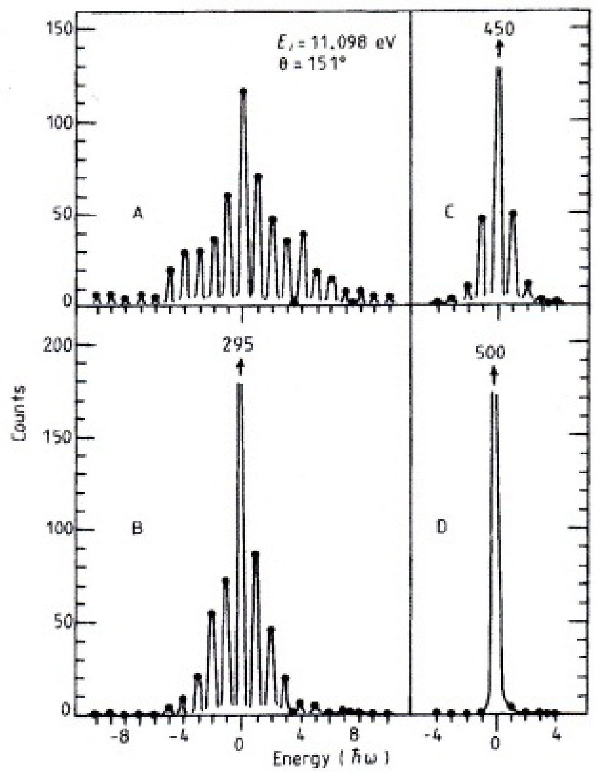
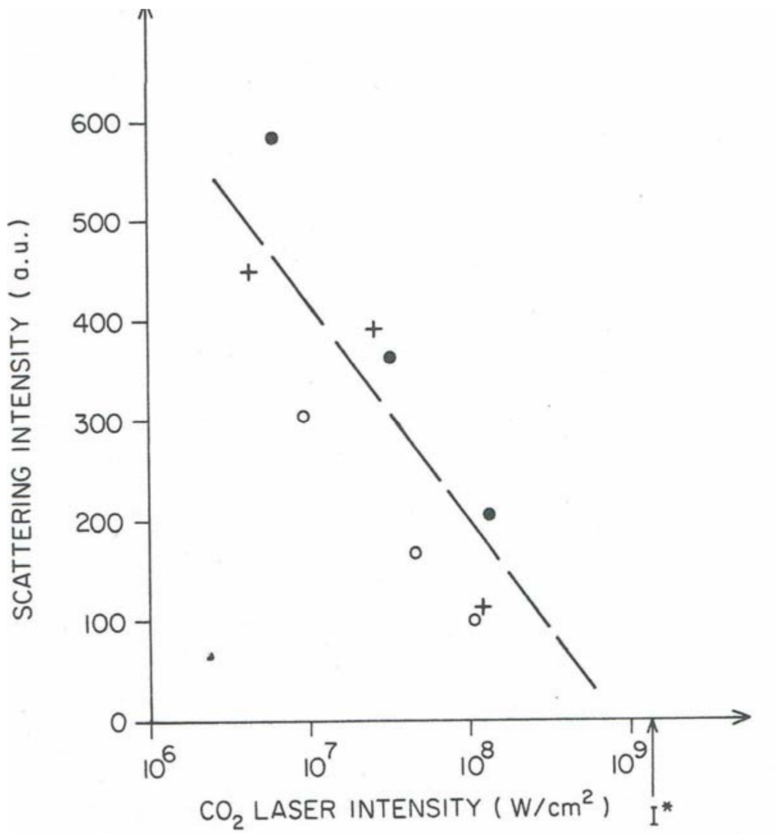


Fig. 2



SCATTERING INTENSITY (a.u.)
600
500
400
300
200
100
0
10^6
10^7
10^8
10^9
CO2 LASER INTENSITY (W/cm^2)
I*

Fig. 3