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超相対論レーザー電子相互作用における量子効果を含む放射の反作用モデル
Radiation Reaction with Quantum Effects in Ultrarelativistic Laser Electron Interactions

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With the rapid progress of the ultra-short pulse laser technologies, the maximum intensities of these lasers have reached the order of 10^{22}W/cm^2 [1, 2]. One laser facility which can achieve such ultra-high intensity is LFEX (Laser for fast ignition experiment) at Institute of Laser Engineering (ILE), Osaka University [3] and another is the next laser generation project, the Extreme Light Infrastructure (ELI) project [4] in Europe. If an electron is in the strong fields caused by a laser which intensity is larger than 10^{18}W/cm^2, the dynamics of the electron should be described by relativistic equations. The most important phenomenon in this regime is the effect of the ponderomotive force, where an electron is pushed in the propagation direction of laser. When a charged particle is accelerated, it proceeds in a trajectory accompanied with bremsstrahlung. If the laser intensity is higher than 10^{22}W/cm^2, strong bremsstrahlung might occur. Accompanying this, the “radiation reaction force (or damping force)” works on the charged particle. Therefore, it is necessary to study the radiation reaction effects in the ultra relativistic laser-electron interaction regime. We can consider this effect as a “self-interaction”. In the laser electron-interaction at this intensity level, one of the important equations is the equation of motion with the reaction force. This field is based on H. A. Lorentz’s work [5]. The purpose of his study was research of the electron’s characteristics via classical physics. After this work, P. A. Dirac updated Lorentz’s theory with the relativistic covariant equation of motion, as the Lorentz-Abraham-Dirac (LAD) equation in Minkowski spacetime [6]. Dirac suggested the covariant form of the radiation reaction force should be described with, not only the retarded potential, but the advanced potential. This method resulted in an equation on which covariance is. The starting point of discussion is this LAD equation as follows.

$$m_0 \frac{dw^\mu}{d\tau} = F_{\mathrm{ex}}{}^{\mu} + f_{\mathrm{reaction}}{}^{\mu} \tag{1}$$

$$f_{\mathrm{reaction}}{}^{\mu} = m_0 \tau_0 \frac{d^2 w^\mu}{d\tau^2} + \frac{m_0 \tau_0}{c^2} g\left(\frac{dw}{d\tau}, \frac{dw}{d\tau}\right) w^\mu \tag{2}$$

Where $\tau_0 = e^2 / 6\pi\varepsilon_0 m_0 c^3$, w, τ and g is the relativistic 4-velocity, proper time and Lorentz metric. This equation is named the Lorentz- Abraham-Dirac (LAD) equation, which has the run-away (infinite value) solution. It is assumed to be pre-renormalization (not renormalized equation). When we solved Eq.(1), we need to treat as something trick like the renormalization in the quantum electrodynamics (QED).

However, an electron is a basic particle which has the charge, the mass and the spin 1/2. The property of the spin, in particular, is important in the quantum dynamics, but the normal theory of relativistic doesn't contain it. In QED, the spin is used like the label which distinguishes physical state. The Dirac equation is the electron equation which has the spin information [7].

$$\left[i\hbar\gamma^\mu \left(\partial_\mu - \frac{ie}{\hbar} A_\mu \right) - mc\,\mathbb{I} \right] \psi = 0 \tag{3}$$

The equation (3) contains electron-electromagnetic field interactions. But, this equation cannot back to the relativistic relation as $\left(m_0 w_\mu\right)\left(m_0 w^\mu\right) - m_0{}^2 c^2 = 0$, becomes

$$\left(m_0 w_\mu\right)\left(m_0 w^\mu\right) - m_0{}^2 c^2 - \frac{\hbar e}{2} \sigma^{\mu\nu} F_{\mu\nu} = 0\,. \tag{4}$$

The Dirac equation of Eq.(3) has additional term of $-\hbar e/2 \times \sigma^{\mu\nu} F_{\mu\nu}$ [8]. This term means the interaction of spin-electromagnetic field. Dirac considered this LAD theory for the classical theory of the electron. Therefore, the spin didn't treat in this classic theory. Therefore, the radiation reaction with spin dipole momentum should be prepared for the ultrarelativistic laser-high γ electron interactions. We will discuss about how to treat the spin in the radiation reaction via the Stern-Gerlach's spin theory.

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