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Study on the Quantum Electrodynamic Phenomena with Femtosecond High-Power Laser

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The advance in the femtosecond high-power laser technology [1,2] enables one to study the laser-plasma interactions in relativistic (>10^{18} W/cm^2) and ultra-relativistic (>10^{24} W/cm^2) regimes and to seek opportunities to study striking phenomena related to quantum electrodynamics (QED). According to the QED picture, the vacuum tends to have nonlinear features with respect to the electromagnetic field as the field strength approaches the Schwinger field ($E_S \simeq 1.32\times10^{16}$ V/cm). These phenomena cannot be treated by classical electrodynamics in which the Lagrangian contains only the E^2 - B^2 term. The Euler-Heisenberg (EH) Lagrangian describes QED features under high but constant field strength conditions, and in the weak field limit where the fields are much less than the Schwinger field it can be Taylor-series expanded, successively yielding higher order terms describing QED phenomena. As a result, under an ultra-strong field, the vacuum behaves like a nonlinear medium, showing vacuum birefringence, light-light scattering and electron-positron pair production via the Schwinger mechanism.

Such an ultra-strong field can be achieved by tightly-focusing or 4π-spherically focusing a femtosecond high-power laser pulse [3,4]. From an optical point of view, the 4π-spherical focusing scheme can be regarded as the extreme case of either multiple laser beam focusing (in which the number of beams approaches infinity) or a tight focusing (in which the f-number approaches zero) scheme. Thus, the 4π-spherical focusing scheme provides the theoretical limit to the highest field strength achievable for a given laser power. According to the recent analysis [5], such an ultra-strong field strength as ~1.5×10^{15} V/cm can be achievable by 4π-spherically focusing a radially-polarized 100 PW laser pulse at 0.2 μm wavelength within an FWHM volume of ~$\lambda^3/20$ (λ: wavelength).

In this talk, we first present the electromagnetic field distribution when cylindrical vector (CV) beams (radially-polarized and azimuthally-polarized beams) [6] are focused by the 4π-spherical focusing scheme. There are two different polarization states known as the transverse magnetic (TM) and transverse electric (TE) modes depending on the polarization state. The spatial distribution of the field is expressed by the product of spherical Bessel functions and the associated Legendre polynomials. The exact solution for the electromagnetic field distribution under the 4π-spherically focusing condition allows us to explicitly express the EH Lagrangian with the field distribution and to describe vacuum birefringence, light scattering of a probe beam, and electron-positron pair production in the laser power range of 10 - 1000 PW.

In order to introduce the nonlinear birefringent behavior to the vacuum, the intensity-dependent electric permittivity and magnetic permeability tensors for vacuum are calculated by the EH Lagrangian. A probe laser pulse propagating through a nonlinear birefringent vacuum (NBV) is scattered by a scattering potential expressing the NBV. The scattered field is calculated by a perturbation method using the Born approximation. The scattering properties of the probe laser pulse, such as the differential cross section for scattering and the number of scattered photons, are investigated based on a semi-classical approach [7]. As another example of QED phenomena, the e-p pair production rate is investigated with the electromagnetic field distribution obtained by the 4π-spherically focusing scheme, and the minimum laser power required for the pair production is estimated from the derived formulas and compared to previous results.

These calculations can be applied to investigate the nonlinear QED processes in the intensity range over 10^{24} W/cm^2 obtained by an exawatt (EW, 1000 PW) power laser facility, which will be available in the near future.

References

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