QED effects exploration based on ultra-intensity lasers

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Abstract. With the development of the laser technology, the interaction between laser and matter is expected to enter the field of strong field QED, which has become as one of the hottest research directions. In this paper, we present the development of laser technology and the realization of ultra-intense ultra-short laser. Specifically, we demonstrate the progress of laser strong field QED and the laser-plasma interaction. Especially, the frontier progress of Laser-plasma QED, as well as its results of numerical simulation and the related QED process are demonstrated. Additionally, some relevant interesting strong field QED effects are also discussed. Besides, the frontier development of vacuum-related QED effects is evaluated, e.g., the vacuum birefringence. These results have important practical significance for some applications related to precision measurement, for example the optical clock. Moreover, they shed light on testing the basic theory of QED from a higher precision and guiding for new generation of laser development.

Keywords: laser technology, strong field QED, Laser-plasma interaction, vacuum birefringence.

1. Introduction

In retrospect, the development of laser, in 1916, Einstein proposed the stimulated emission and the spontaneous emission, in which the concept of stimulated emission provided an important theoretical basis for the birth of laser [1]. In 1924, after analysing the probability of stimulated radiation, Tolman put forward the important concepts of population inversion and negative temperature [2]. In 1937, Fabrikant proposed the idea of using population inversion and stimulated emission to manufacture microwave amplifier, that is, the concept of stimulated radiation amplification [3]. Since then, the theoretical basis of laser has been basically established. In 1950, Towns, et al. proved microwave stimulated radiation, proposed the principle of Maser (microwave amplification by stimulated emission of radiation), and manufacture the Maser in 1954 [4]. In 1958, Townes and Schawlow discussed the possibility of laser Invention [5]. In 1959, Gordon proposed that stimulated emission could be used to amplify light. He described an optical resonator that can form a narrow beam of coherent light and called it laser, it means “light amplification by stimulated emission of radiation” [6]. In 1960, Maiman observed the population inversion of chromium atoms when irradiating ruby with 560nm wavelength light. In 1960, Maiman manufactured the world's first working laser, and obtained a laser with good monochromaticity, good directivity, high brightness and good coherence [7]. In the same year, Basov manufactured the world's first semiconductor laser. After the laser is manufactured. People are starting to focus on improving the intensity of the laser. There are two breakthroughs in the improvement of laser intensity. One is the development of Q-switched technology [8] and phase locking of laser modes technology in the 1960s [9], and the other is the development of the CPA (Chirped pulse amplification) technology in 1985, which is epoch-making significance [10]. Strickland and Mourou introduced the idea of "chirped" in radar technology into the design of laser [10]. The two breakthroughs make the laser intensity increase exponentially. Later, in 1992, Dubiets and others proposed OPCPA (optical parameter chirped pulse amplification), which combined CPA technology with optical parametric amplification technology [11]. Contemporarily, new technologies continue to emerge, e.g., the proposal of QPCPA technology [12]. At present, the peak intensity of $10^{23}W/cm^2$ has been reached experimentally [13]. With the continuous improvement of laser field intensity, where the upper limit of laser field intensity is considered has become a question. Compared with the upper limit of laser field intensity of $\sim10^{29}W/cm^2$ in perfect vacuum, which is the Schwinger field, the intensity an upper threshold at the level of $\sim10^{26}W/cm^2$ in nonideal vacuum [14].When the laser intensity reaches the order of $10^{22}\sim10^{24}W/cm^2$, which can be comparable to the Schwinger field, which can readily support the research on strong-field QED physics (e.g., the radiation-reaction effects, electron-positron pair production, QED cascade) [14].

In the late 1940s, Feynman et al. co-established the theory of QED. Later, Dirac, Heisenberg, Pauli laid the Quantum theory of radiation. Now QED is the earliest, most mature and most accurate branch of quantum field theory, which mainly studies the interaction between electromagnetic fields and charged particles. Gamma ray radiation is one of the basic processes in the study of QED theory of intense laser field. Compton scattering is the most widely studied way of gamma ray production. Since Sengupta et al began to study the scattering of free electrons in electromagnetic waves in 1949 [13], multi-photon Compton scattering in intense laser field has been studied for many years, and the calculation of radiation spectrum under the framework of quantum theory. The amplitude of the radiation process is obtained mainly through the Feynman diagram of QED. The generation of electron-positron pairs is also concerned by the laser strong field QED. Due to the quantum fluctuation effect, real particles will be produced when there is a huge force field around, which is one of the most important theoretical predictions of QED. In 1951, Schwinger obtained the probability of producing electron pairs in a constant electric field by proper-time method [14]. According to the Schwinger theory, the theoretical field intensity must reach the critical field intensity of Schwinger ($1.3\times10^{18}V/m$, the corresponding laser intensity is $10^{29}W/cm^2$) to produce electron-positron pair [14]. With the development of laser intensity, it is possible for the laboratory to produce positive and negative electron pairs, thus many theoretical supporting studies have emerged. Fig. 1 presents the recent progress of applications for different laser intensities [15].

The main motivation of this paper is to review the technological development of ultra-intense ultra-short laser, summarize the high-field QED effect based on laser to review the development of related theories, the rest part of the paper is organized as follows. The second part of the article mainly talks about the technical realization of ultra-intense ultra-short laser. The third part will briefly describe the strong field QED effects of laser plasma. The fourth and the fifth part focus on several strong field QED effects in detail. Then, the paper will introduce the interesting effects of the strong field QED effect related to vacuum.

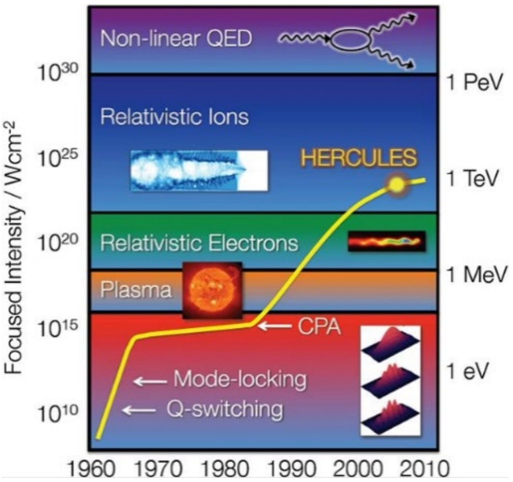

Figure 1. The development of laser focusing intensity and the corresponding research process of physical problems [15].

2. Ultra Short Ultra intensity lasers

The ultrashort light pulses generate by the lasers usually has a wave period of 2.5 femtoseconds that is equivalent to $1 \times 10^{-15}s$. For observing the phenomenon, it is impossible to use the standard electronics to be done therefore a petahertz oscilloscope is needed which is one million times faster than the normal oscilloscope. The type of lasers used to generate this type of pulses is called "mode-locked lasers" which makes it to have a high peak power and a high resolution.

2.1. The "Mode-Locked" lasers

A "Mode-Locked" laser could emit up to one million colors and the same time in order to boost its intensity, therefore we have to make sure that the different wavelengths of colors are synchronized by using nonlinear optics. Since waves are infinite the mode lock lasers fire a continues of pules what we called "Pulse train". Here, we are basically compacting the energy into a very short bursts and as the pulses become shorter, the intensity will be larger therefore the power would also be larger. In addition, the wavelength would also become shorter which could be described as when increases the number of colors:

$$\frac{P_{ml}}{P_{cw}} = N \tag{1}$$

where P_{ml} is the power of mode locked lasers and P_{cw} is the power of same lasers operating at a single frequency mode and the N is the number of colours. For example if we have one miliion colours with 100mW of a normal colours, the power of the actual laser will now be 100 kilo watts, that's how intense "mode-locked" lasers are. A short pulse laser noramally has a broad spectrum; or if one wants a monochromatic laser, the pulse usally will be very long.

2.2. The effects of dispertion on the intensity of the lasers

After the dispertion, the red light travels approximately 1.65 faster than the violet light. When the white light passes through the dispersive medium, the red travels faster and the light becomes more spread out and the light becomes chirped. Therefore if we shine a white llight through the glass or through the microsopic lens, the peak power drops dramitically and this is the challenge that we need to over come when we are producing a ultra instensive laser.

2.3. The generation of the ultra short lasers

To produce a broad spectrum of laser unlike a monochromatic laser, one needs a gain meduim which is a contiunous laser pump source, but the medium would be destroyed if the intensity is too strong. Hence, it is important to have device that could maintain the short pulse without it being destroyed (i.e., a "Pulse-Shortening device"). A pulse shortening device could usually be consisted of a saturable absober, a phase moderator or a despersion conpensator. When we shine a pulse through the gain medium, the material absorbs the photon and also amplifies it. Whereas, the dispersion will cause the increase in length of the pulse in which the red light travels faster than the violet light. Therefore, a pulse-shortening device is also needed to be nagative dispersed and eventually it would pass through the outpout mirror and a pulse is generated.

2.4. Nagative dispertion

As mentioned above, a negative dispersion is needed in order to counter the effect of dispersion in pulse-shortening device, and one example for this could be using a prism pulse compressor. This is a relatively easy method to do which does required lots of technology. Nowadays, the more advanced method called "chirped mirror" is used. Chriped mirror is a special type of mirror and the key idea behind it is still increasing the length that red light travels. Here the blue frequency of light would be reflected in the early layer whereas the red frequency would be reflected later than the blue light; so, the blue light would be delayed. The advantage of this type of mirror is it is more precise than prim pulse compressor but requires higher technology in order to achieve.

2.5. Extreme laser powers using Chirped-Pulse-Amplification (CPA)

As disscused ealier, one could simply increase the power of the laser by adding more and more colours; however, we could not achieve the extreme laser powers simply doing that because in praticle we discovered that the lasers would be destroyed. Therefore, the way to fix the problem is using Chirped-Pulse-Amplification which is known as CPA. This technology was invented in 1985 and it was a revolution of the power of the laser. The way we could achieve the extreme laser power is where we take a pulse from the oscillator which is a short pulse with low energy, and we could use different dispertions to manipulate the laser light (as shown in Fig. 2).

To obtain a ultra short and ultra short laser with, one could have a pulse which has a broad spetrum which has been diluted in time first. Subsequently, an amplifier can be used to boost the amplitude with a relative large duration and which is diluted in time. Afterwards, we could use a nagative dispersion to make the pulse short again which has a really high peak and high energy in a short period of time.

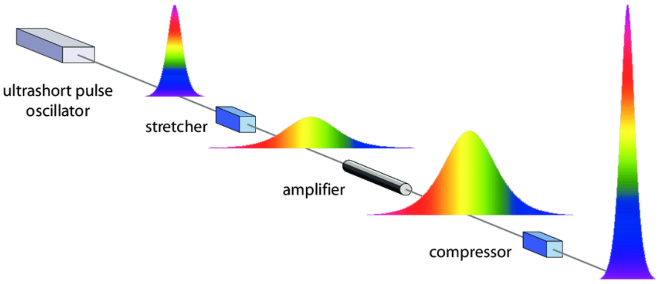

Figure 2. The steps of CPA [12].

3. Laser plasma interaction

In the study of strong field QED effect of laser-plasma interaction, the problems must be considered are the physical process of strong field QED effect itself, the effects of laser-plasma interaction on QED effect, as well as QED effect on laser-plasma interaction. Considering these factors and the simulations of laser-plasma interaction itself, there have been some simulation results using various numerical simulation methods, for example the PIC simulations.

3.1 The physical process of QED effect

The generation of gamma rays and the generation of electron-positron pairs. The generation of gamma rays is one of the most basic processes in the study of strong field QED theory. We know that when the velocity of electrons changes, electromagnetic waves will radiate outward. Due to the difference of electron energy and velocity or different external fields, there will be different types of radiation, such as synchrotron radiation, Bremsstrahlung and Compson scattering. The main way to produce gamma rays is Compton scattering (the interaction between laser field and electrons). The spectrum of radiation should be calculated under the framework of QED theory. The amplitude of the radiation process can be obtained from the Feynman diagram. The electron-positron pairs theory is one of the most important theoretical predictions of QED. We know that due to the quantum fluctuation effect, when there is a huge force field around, real particles will be produced, and there are three principles that can produce electron-positron pairs. One is the Bethe-Heitler (BH) process [16], i.e., the electron-positron pairs are obtained by colliding with laser photons through the photons of the Coulomb field. The other is Breit-Wheeler (BW) [17] process, i.e., the generation of electron-positron pairs, which are obtained by the collision of high energy photons (Gamma photons) with laser photons. It should be mentioned another standing wave field case, which is the Schwinger mechanism.

3.2 The influence of laser-plasma interaction on the QED effect:

In this part, we mainly consider the impact of some physical parameters of laser-plasma interaction on the strong field QED effect, e.g., the characteristics of the laser (intensity, polarization, etc.), the characteristics of the target (density, shape, etc.) and other characteristics can influence on the strong field QED effect. For example, in 2014, Brady et al analysed the effects of laser intensity and electron density of the target in a certain range on the conversion efficiency of gamma rays produced by synchrotron radiation and the electron-positron pairs produced by the BW process [18]. In 2015, Liu et al. investigated various forms of targets as illustrated in Fig. 3. The positron production of conical hollow targets can be increased by 5 orders of magnitude at the same laser intensity [19]. The composite target composed of nitrogen and gaseous aluminium can increase the yield of electron-positron pairs [20].

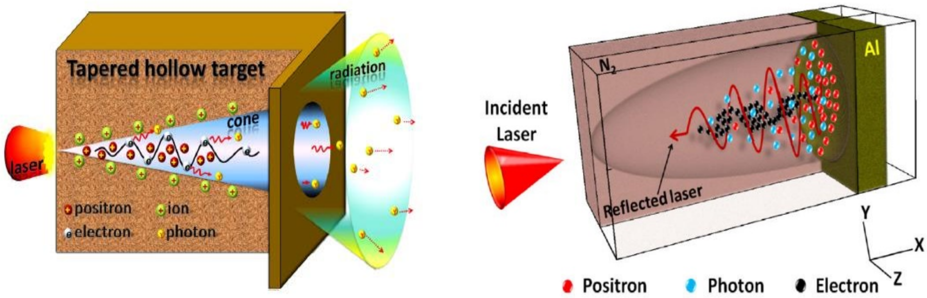

Figure 3. Target morphologies can increase the yield of electron-positron pairs yield. The conical hollow targets (left panel) [19] and the composite target composed of nitrogen and gaseous aluminium (right panel) [20].

3.3 The influence of QED effect on laser-plasma interaction:

This part mainly introduces the influence of strong field QED effect on laser-plasma interaction. In 2015, Sarri et al showed that using a compact laser-driven setup, ion-free electron–positron plasmas with unique characteristics can be produced [21]. In 2017, Wang et al. found that the laser hole boring and relative transparency are restrained by the generation of electron-positron pairs and gamma rays [22]. In 2018, Sorbo et al. simulated that when the next generation laser intensity interacts with the solid target, the strong field QED effect will lead to the generation of a critical density pair-plasma which will absorb laser energy. Thus, the energy of ion acceleration will be reduced, and the ion acceleration efficiency of laser will be reduced by 30-50% [23].

4. Gamma ray generation

This Section will introduce several research progresses of the generation of ultra-bright gamma radiation source generation based on QED effect in strong laser fields.

4.1 Gamma ray generation using ultra-intense laser

Until now, there have been a lot of researches about utilizing laser to generate gamma ray, most of the schemes are included in these two ways:

1) Interacting plasma with strong laser, the electrons that got accelerated can produce high-energy polarized gamma light by bremsstrahlung. However, wide energy dispersion and large size put a restrict on peak brightness. Nevertheless, it does not mean that the mechanism has no use at all while it is actually playing an important role in other aspects. It offers us a new scene where the process works and give more understanding and inspiration about it. It is worth mentioning that according to Seipt et al. QED-cascades will cause highly polarized particle generation and the spin-dynamics can decrease the growth rates, leading to orders of magnitude differences in particle yield compared with calculations with unpolarized rates under certain conditions and this raises the

prospect of generating polarized lepton beam maybe useful for the production of highly polarized γ-photons [24].

2) Interacting electrons sprightly with laser can also generate high energy gamma light. It was studied that using the linear polarized plane wave to interact with electron beam under weak nonlinear mechanism can generate gamma rays with polarization up to 91%. when a0>>1 the scattering mechanism become strong nonlinear mechanism which means electron spin should also be taken into consideration. Xue et al. have done research about mechanism about nonlinear Compton effect [25], it shows that the electrons in the plasma are accelerated by the tail field excited by a linearly polarized laser, the accelerated relativistic electron beam is colliding with the reflected laser produces linearly polarized gamma light as shown in the Fig 4. [26].

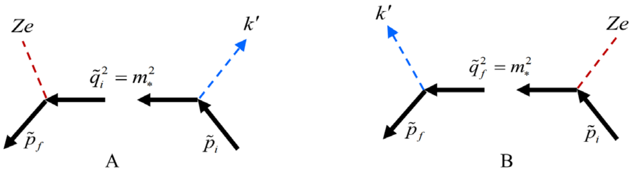

Figure 4. Resonant spontaneous bremsstrahlung of an electron in the field of a nucleus and a plane electromagnetic wave [26].

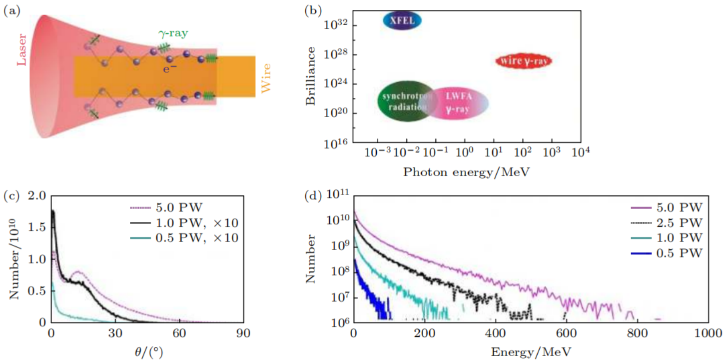

Figure 5. Schematic diagram of wire target scheme (a), range of photon energy and peak brightness of gamma ray source (b) and angular distribution and energy spectrum distribution of gamma ray source (c) (d) [27].

4.2 Ultra-intense laser field interact with fine target wire

With the arrival of a new generation of 10 beat watt ultra-intense laser device, researches about plasma based on ultra-intense laser fields have raised the curiosity of scientists from all over the world, however, it is still a huge challenge to gain ultra-bright γ ray pulse which energy is larger than 1 MeV.

A new scheme which utilizes petawatt intense laser pulse interacting with fine target wire whose order of magnitude is in the order of laser wavelength to generate γ ray in Fig. 5 [27]. It was discovered that when ultra-bright laser field interact with fine target wire (or microchannel which is the same thing), on the one hand, the surface of the target will speed up the electrons to the order of the GeV. On the other hand, strong transverse electromagnetic field will be excited on the surface of the wire, thus, electrons will make a strong lateral oscillation and then excite ultra-intense synchrotron radiation and radiate out plenty of γ photons. It will trigger QED effect then generate high energy and ultra-intense γ ray efficiently.

5. Electron-positron generation

Electron-positron could be seen as plasma that represent a special form of matter, which can be found near the high energy or powerful object in the universe (black hole and pulsars etc.), and these plasmas play an important role in the dynamics of supermassive objects. However， Positron, as one of the basic QED effects and products of another QED process, has many applications in medicine, large-scale industry, material engineering and scientific measurement such as PET-CT, Ps-TOF spectrum etc. Although it was confined that there are plenty of electron positron pairs near pulsar and black hole, it still difficult to be created in laboratory environment. It is of vital importance to find out generation mechanism of positive and negative electron pairs.

5.1 QED cascade

Reference to a lot of research QED cascade is such a process that firstly ultra-intense laser field interacting with electrons to generate gamma ray (Compton scattering) then gamma photon immediately interacts with the laser filed to generate electron-positron pairs (nonlinear B-W process), the generated photons, electrons and positrons will be accelerated to continue to generate gamma ray then go and return in following a circle [36, 37].

With the increasing development of laser technology, it is going to be possible to reach intensities of the order of $10^{23\text{-}24}$W/cm^2. Martin Jirka et al recently done research about QED cascade with 10PW-class lasers [29]. The research pointed that they studied the influence of tight focusing and original target density on cascade pair generation efficiency by performing 2D simulations with the particle-in-cell code EPOCH. It is said that the problem that as the pulse is focused more tightly, the seed particles will be expelled more quickly, can be solved by increasing the target density exhibited in the Fig. 6. Besides, the pair production efficiency can also be influenced by the relativistic critical plasma density. It is worth mentioned that Daniel et al have done research about polarized QED cascades and they found that the growth rate of QED cascade in super intense laser field can be greatly reduced [24].

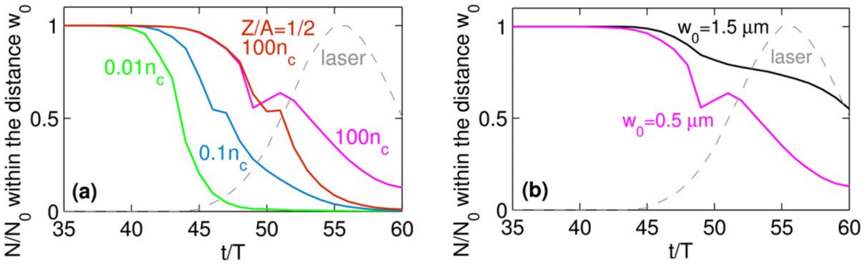

Figure 6. The effect of target density on expelling the seed particles from focal spot region [29].

5.2 Generation of polarized positron beam by ultra-intense laser

Until now there are a lot of research about EP pairs such as using SLAC device to verify the weak nonlinear Compton scattering process and Breit-Wheeler process when high energy electrons interacting with laser which offer the evidence to generate EP pairs by laser. However, in the case of relatively low intensity driving light field, the way to obtain a collimated dense GeV electron positron pair source with quasi neutral beam characteristics and controllable beam structure is still a great challenge. A new method is proposed by Zhu et al [27, 28] that generate dense GeV electron-positron pairs by lasers in near-critical-density plasma. The whole thing is that utilizing the interaction of two laser pulses with adjustable polarization state and critical density plasma can effectively generate dense GeV electron positron pairs beam. In the mechanism the plasma plays the role of transformation medium, then high energy electrons acquire energy and angular momentum and generate gamma photons through nonlinear Compton scattering. γ photons gain corresponding angular momentum followed by collision of γ photons and ultra-intense scattering laser field and then generate high energy electron positron pairs through Breit-Wheeler process as shown in Fig. 7 [28].

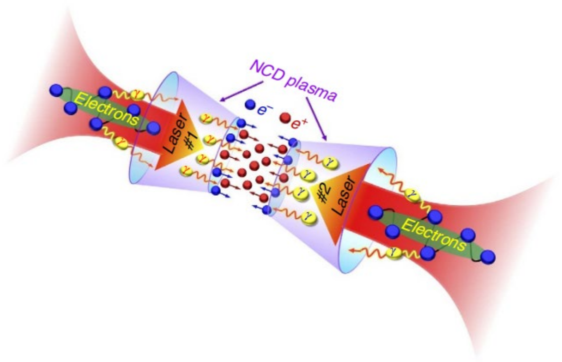

Figure 7. Schematic diagram of QED cascade [28].

6. Vacuum structure

6.1 Dirac Sea

In 1927, Dirac used the wave function of four components to describe the electron and proposed the Dirac equation satisfying the relativistic covariance. The solutions of these equations contain electrons with negative energy. It is suggested that every negative state is occupied by an electron, the vacuum is considered as a sea that is full of electrons with negative energy. Meanwhile, electrons with positive move on the surface of this sea. Fig. 8 depicts the sketch of Dirac sea. If there is a high energy γ ray incident into the Dirac Sea, an electron will be excited to the surface of the sea, and a positive hole will be left in the sea. The discovery of a particle with the same mass as an electron but opposite charge (positron) in the cloud chamber proved the theory of Dirac.

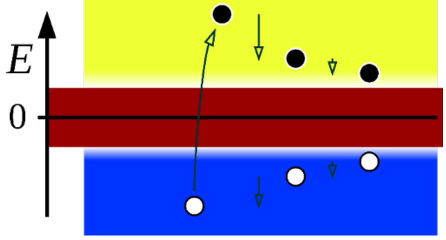

Figure 8. A sketch of Dirac sea.

6.2 Vacuum fluctuation

The main research object of quantum electrodynamics is the quantum properties of electromagnetic interaction: emission and absorption of photons; generation and annihilation of charged particles, etc. Fig. 9 presents the Feynman diagram of the collision between two electrons can the two electrons interact by exchanging virtual photons as well as vacuum polarization. The virtual photons emitted by electrons are able to become a pair of virtual electrons, then this pair of electrons annihilate into a virtual photon again. This virtual process is called vacuum polarization. Thus, it can be seen that virtual particle pairs are constantly generated, annihilated, and transformed in the vacuum. This phenomenon is called vacuum fluctuation.

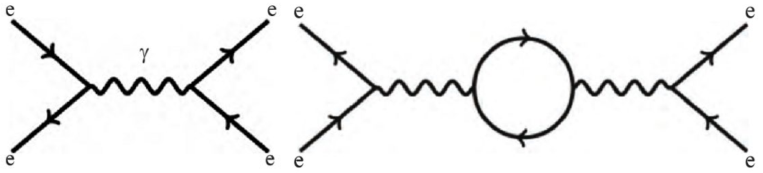

Figure 9. The Feynman diagram of collision between electrons and vacuum polarization.

6.3 Lamb Shift

In 1947, the Lamb–Retherford experiment proved the vacuum fluctuation [30]. Since the spaces inside the atoms are vacuum, so the vacuum fluctuation happens and affects the energy level of atoms.

According to the theory from Dirac, the hydrogen atoms with the same n and j quantum number have the same energy. Willis Lamb and Robert Retherford used microwave technology to stimulate hydrogen atoms' radio-frequency transitions between ${}^2S_{1/2}$ and ${}^2P_{1/2}$. Based on the analysis, there was a difference of the energy between these two states, and this difference called Lamb Shift. The Lamb Shift can be written as:

$$\Delta E_{Lamb} = \alpha^5 m_e c^2 \frac{k(n,0)}{4n^3} \tag{2}$$

where α is the fine-structure constant. The theoretical value of Lamb shift is 1057.864 MHz, and the measurement is very similar to the theoretical value, it is 1057.862 MHz [31]. To sum up, the vacuum in QED is a complex fluid with virtual photons and electron-positron pairs.

6.4 Casimir effect

There is another experiment that can prove the Vacuum fluctuation. 1948, Casimir proposed that there is a weak attraction between two neutral metal plates placed parallel in a vacuum. This effect is called the Casimir effect, the attraction force called the Casimir force. Every point in the vacuum between two plates is a simple harmonic oscillator, and the space can be considered as a cavity. The vibrational modes have positive zero-point energy:

$$E = \frac{1}{2}\hbar\omega \tag{3}$$

The vibration modes that form cavity resonance are strengthened, and those that do not conform to cavity resonance are suppressed, which results in the radiation pressure of electromagnetic field in cavity being less than that outside cavity, this causes the cavity to contract inward. The attraction increases when the distance between two metal plates decreases, [32].

7. Conclusion

In summary, this paper introduced several QED effects based on strong laser, including the achieve of ultra-intense and ultra-short laser, the development of laser technology. Specifically, we introduce the frontier progress, as well as the state-of-art simulation results and the related QED process of laser plasma interaction, gamma ray generation, electron-positron generation and vacuum polarization. In addition, the frontier developments of vacuum-related QED effects are evaluated (e.g., the vacuum birefringence). According to the analysis, it is expected to realize the SFQED effect in laboratory and explore the QED vacuum in the future. Contemporarily, countries around the world are making great efforts to build a new generation of high-power laser devices of 10 petawatt (PW) level and actively preparing to build the next generation of ultra-high-power laser devices of 100 petawatt level, which is expected to push the laser intensity to more than 10^{23} w/cm^2. This will provide an unprecedented high intensity light field to study QED effect and super relativistic nonlinear physics, and provide energy for discovering and verifying new physics under extremely strong field and exploring its application. Overall, with the continuous development of high-power laser technology and experimental conditions, it is reasonable to believe that the experimental research on the physics of extremely strong field QED plasma will be realized rapidly.

References

[1] Einstein, Strahlungs-emission und-absorption nach der Quantentheorie, J. Verh. Deutsch. Phys. Gesell. 18 (1916) 318-323.

[2] Tolman, Richard C, Duration of molecules in upper quantum states, J. Physical Review 23.6 (1924) 693.

[3] Gallardo, Mario O., and Eduardo Jaime Quel. "Una nueva historia del láser." Charla-seminario" Hacia una nueva historia del láser"(CIOp, 12 de noviembre de 2019). 2019.

[4] Aleksandr M. Prokhorov – Facts. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 7 Apr 2022. https://www.nobelprize.org/prizes/physics/1964/prokhorov/facts/

[5] Schawlow, Arthur L., and Charles H. Townes, Infrared and optical masers, J. Physical Review 112.6 (1958) 1940.

[6] Gould, R. Gordon, The LASER, Light Amplification by Stimulated Emission of Radiation, In Franken, P.A.; Sands R.H. (eds.). The Ann Arbor Conference on Optical Pumping, the University of Michigan, June 15 through June 18, (1959). p. 128.

[7] Maiman T H, Stimulated optical radiation in ruby, J. Nature, 1960, 187: 493.

[8] Früngel F B A, Optical pulses-lasers-measuring techniques, M. Academic Press, (2014)

[9] P. W. Smith, Phase locking of laser modes by continuous cavity length variation, J. Appl. Phys. Lett. 10 (1967) 51-53

[10] Strickland, D. and G. Mourou, Compression of amplified chirped optical pulses, Optics Communications 55.6(1985):447-449.

[11] Dubietis A, Jonušauskas G, Piskarskas A, Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal, J. Opt. Commun. 88.4-6 (1992) 437-440.

[12] J. G. Ma, J. Wang, P. Yuan, G. Q. Xie, H. Y. Zhu, K. N. Xiong, Y. F. Tu, X. N. Tu, E. W. Shi, Y. Q. Zheng, and L. J. Qian, Quasi-parametric amplification of chirped pulses based upon a Sm3+-doped yttrium calcium oxyborate crystal, Optica 2 (2015) 1006.

[13] N. D. Sengupta. On the Scattering of Electromagnetic Waves by Free Electrons. I. Classical Theory, J. Bulletin of the Calcutta Mathematical Society, 41(5) (1949) 1911-1912.

[14] Wu Y, Ji L, Li R., On the upper limit of laser intensity attainable in nonideal vacuum, J. Photonics Research, 9(4) (2021) 541-547.

[15] Mourou G A, Tajima T, Bulanov S V, Optics in the relativistic regime, J. Rev. Mod. Phys., 78(2) (2006) 309.

[16] H. Bethe, W. Heitler. On the Stopping of Fast Particles and on the Creation of Positive Electrons. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 146(856) (1934) 83-112

[17] G. Breit, J. A. Wheeler. Collision of Two Light Quanta. Physical Review, 46(12) (1934) 1087-1091.

[18] C. S. Brady, C. P. Ridgers, T. D. Arber, et al. Synchrotron radiation, pair production, and longitudinal electron motion during 10-100 PW laser solid interactions. Physics of Plasmas, 21(3) (2014) 9

[19] J.X. Liu, Y.Y. Ma, J. Zhao, et al. High-flux low-divergence positron beam generation from ultra-intense laser irradiated a tapered hollow target. Physics of Plasmas, 22(10) (2015) 103102.

[20] J. X. Liu, Y. Y. Ma, T. P. Yu, et al. Enhanced electron-positron pair production by ultra-intense laser irradiating a compound target. Plasma Physics and Controlled Fusion, 58(12) (2016) 9.

[21] Sarri, G., et al. "Generation of neutral and high-density electron–positron pair plasmas in the laboratory." Nature Communications 6(2015) 6747.

[22] W. M. Wang, P. Gibbon, Z. M. Sheng, et al. Laser opacity in underdense preplasma of solid targets due to quantum electrodynamics effects. Physical Review E, 96(1) (2017) 013201

[23] S. Dario Del, R. B. David, C. Remi, et al. Ion acceleration with radiation pressure in quantum electrodynamic regimes. Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers III, Eurospan, (2017) 102411.

[24] D. Seipt et al. Polarized QED cascades. New Journal of Physics, 23(5), (2021), 053025.

[25] Ting Sun et al. The progress of polarized high-energy Gamma rays and electron-positron driven by intensity laser. Acta Physics in China, 70(08), (2021), 111-122.

[26] S. P. Roshchupkin, et al. Resonant production of high-energy electronpositron pairs and gamma quanta in the quantum electrodynamics processes in strong laser fields," Proc. SPIE 11777, High Power Lasers and Applications, 117770M (18 April 2021).

[27] Zhu Xing-Long, et al. Research progress of ultrabright γ-ray radiation and electron-positron pair production driven by extremely intense laser fields. Acta Phys. Sin.,70(8), (2021), 085202.

[28] Zhu X L, Yu T P, Sheng Z M, et al. Dense GeV electron–positron pairs generated by lasers in near-critical-density plasmas, Nature communications, 7(1), (2016), 1-8.

[29] Jirka M, Klimo O, Vranic M, et al. QED cascade with 10 PW-class lasers[J]. Scientific Reports, 7(1), (2017), 1-7.

[30] Lundeen, S. R., & Pipkin, F. M. Measurement of the Lamb Shift in Hydrogen, n=2. Physical Review Letters, 46(4), (1981), 232–235.

[31] Hughes, V. W., & Kinoshita, T. Anomalous g values of the electron and muon. In More Things in Heaven and Earth (pp. 223-233). Springer, New York, NY, 1999.

[32] Gambassi, A. The Casimir effect: From quantum to critical fluctuations. In Journal of Physics: Conference Series (Vol. 161, No. 1, p. 012037). IOP Publishing, 2009, April.