An Explanation of the Interactions between Waves and Electrons: Discussion of Electromagnetic Fields

Weiye Xu[1,*]

[1]*Institute of Plasma Physics, Chinese Academy of Sciences, 230031 Hefei, China*

Abstract: The interactions between waves and electrons are the basis of vacuum tubes and particle accelerators. In order to further understand the interactions, we proposed a new electromagnetic model. In this model, the photon is composed of two elementary particles – ephoton and mphoton, which are the basic particles that form the electric fields and magnetic fields, respectively. There are many ephotons around the electrons and the electrons can absorb the ephotons. The proposed electromagnetic model can well explain the electromagetic phenomena and the interactions between waves and electrons.

Keywords: Interactions between waves and electrons; Electromagnetic fields; photon.

1. Introduction

The vacuum tubes [1], such as the traveling wave tubes, the back wave tubes, klystrons, magnetrons, gyrotrons, free electron lasers, etc. are used to generate high power microwaves, and are widely used in the fields such as the nuclear fusion, communication, radar, industrial microwave heating, etc. Particle accelerators [2] are the key devices for studying high-energy physics. The interactions between waves and electrons are the basic interactions in the vacuum tubes and the particle accelerators. Now using the Maxwell's equations, the Lorentz force formula, and the energy conservation law, we can well analyze the interactions between the electromagnetic waves and the electrons. But that is just one of the correct ways to describe it. We are not really know why electrons and electromagnetic waves can transfer energy to each other. In this letter, we try to offer a new way of thinking in order to understand the interactions. Firstly, we discuss what is the electromagnetic field. A new electromagnetic model is proposed. Then we try to give the explanation of the interactions between waves and electrons according to the proposed electromagnetic model.

2. Discussion of the electromagnetic fields

Maxwell's equations do follow from the laws of electricity combined with the theory of special relativity [3]. There is a view that there is no such thing as a magnetic field, what appears to be a magnetic field is just changing electric fields. We think that the use of theory of special relativity can only explain the relationship between the electric field and the magnetic field, but can not explain that they are the same thing. The magnetic field is real. The reason is that in one coordinate system, we can simultaneously observe the existence of electric fields and the magnetic fields. We note that $B^2 - E^2/c^2$ is a Lorentz invariant quantity. If $B^2 > E^2/c^2$ at a given spacetime point in a given inertial frame, it follows that $B^2 > 0$ at that point in all inertial frames. In fact, there is a frame where the electric field vanishes but the magnetic field does not. It shows that the magnetic effects is not fictitious.

We believe that there are two kinds of virtual photons, one is ephoton (short for electric-photon), the other one is mphoton (short for magnetic-photon). The particle flow density of the ephotons is the electric field intensity E, and the particle flow density of the mphotons is the magnetic induction B. Thus, we have,

$$E = \rho_e v_e, \tag{1}$$

$$\oint_S E \cdot dS = - \int_V \frac{\partial \rho_e}{\partial t} dV. \tag{2}$$

Where, E is the particle flow density of the ephotons, i.e.,

the electric field intensity; ρ_e is the particle density of the ephotons.

$$\boldsymbol{B} = \rho_m \boldsymbol{v_m}, \tag{3}$$

$$\oint_S \boldsymbol{B} \cdot d\boldsymbol{S} = -\int_V \frac{\partial \rho_m}{\partial t} dV. \tag{4}$$

Where, $\boldsymbol{B}$ is the particle flow density of the mphotons, i.e., the magnetic induction; ρ_m is the particle density of the mphotons.

Compare Eq. (2) with Gauss's law,

$$\oint_S \boldsymbol{E} \cdot d\boldsymbol{S} = \frac{1}{\varepsilon} \int_V \rho dV, \tag{5}$$

we can find the relationship between the particle density of the ephotons ρ_e and the charge density ρ,

$$\frac{\rho}{\varepsilon} = -\frac{\partial \rho_e}{\partial t}. \tag{6}$$

That is, the charge density is actually the change of ephoton density with time.

Compare Eq. (4) with the divergence equation of magnetic field (assuming no magnetic charge exists),

$$\oint_S \boldsymbol{B} \cdot d\boldsymbol{S} = 0, \tag{7}$$

we can find that,

$$\frac{\partial \rho_m}{\partial t} = 0. \tag{8}$$

That is, the density of mphotons does not change with time, and the mphotons may be uniformly distributed in the universe.

We know that the differential form of Maxwell's equations in the isotropic medium are,

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \tag{9}$$

$$\nabla \times \boldsymbol{B} = \mu \boldsymbol{J} + \mu\varepsilon \frac{\partial \boldsymbol{E}}{\partial t}, \tag{10}$$

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon}, \tag{11}$$

$$\nabla \cdot \boldsymbol{B} = 0. \tag{12}$$

Bring Eq. (1) and Eq. (3) into Eq. (9) and Eq. (10), respectively,

$$(\nabla\rho_e) \times \boldsymbol{v_e} + \rho_e \nabla \times \boldsymbol{v_e} = -\frac{\partial \rho_m}{\partial t} \boldsymbol{v_m} - \frac{\partial \boldsymbol{v_m}}{\partial t} \rho_m, \tag{13}$$

$$(\nabla\rho_m) \times \boldsymbol{v_m} + \rho_m \nabla \times \boldsymbol{v_m} = \mu \boldsymbol{J} + \mu\varepsilon \frac{\partial \rho_e}{\partial t} \boldsymbol{v_e} + \mu\varepsilon \frac{\partial \boldsymbol{v_e}}{\partial t} \rho_e. \tag{14}$$

The above two equations and Eq. (6) and Eq. (8) can be combined to obtain the following equations,

$$(\nabla\rho_e) \times \boldsymbol{v_e} + \rho_e \nabla \times \boldsymbol{v_e} = -\frac{\partial \boldsymbol{v_m}}{\partial t} \rho_m, \tag{15}$$

$$(\nabla\rho_m) \times \boldsymbol{v_m} + \rho_m \nabla \times \boldsymbol{v_m} = \mu\varepsilon \frac{\partial \boldsymbol{v_e}}{\partial t} \rho_e, \tag{16}$$

$$\boldsymbol{J} = -\varepsilon \frac{\partial \rho_e}{\partial t} \boldsymbol{v_e} = \rho \boldsymbol{v_e}, \tag{17}$$

$$-\frac{\partial \rho_e}{\partial t} = \frac{\rho}{\varepsilon}, \tag{18}$$

$$\frac{\partial \rho_m}{\partial t} = 0. \tag{19}$$

The above five equations represent the motion of ephotons and the mphotons in the isotropic media. Similar to electromagnetic fields, the boundary relation of the ephotons and the mphotons are,

$$\mathbf{n} \times \left(\rho_{e2} \boldsymbol{v_{e2}} - \rho_{e1} \boldsymbol{v_{e1}} \right) = 0, \tag{20}$$

$$\mathbf{n} \times \left(\frac{\rho_{m2}}{\mu_2} \boldsymbol{v_{m2}} - \frac{\rho_{m1}}{\mu_1} \boldsymbol{v_{m1}} \right) = \boldsymbol{\alpha}, \tag{21}$$

$$\mathbf{n} \cdot \left(\varepsilon_2 \rho_{e2} \boldsymbol{v_{e2}} - \varepsilon_1 \rho_{e1} \boldsymbol{v_{e1}} \right) = \sigma, \tag{22}$$

$$\mathbf{n} \cdot \left(\rho_{m2} \boldsymbol{v_{m2}} - \rho_{m1} \boldsymbol{v_{m1}} \right) = 0. \tag{23}$$

Where, $\boldsymbol{n}$ is the unit normal component of the interface, which is directed to the #2 medium from the #1 medium. The σ is the surface density of the free charge. The $\boldsymbol{\alpha}$ is the line density of the free current.

As can be seen from Eq. (17), the velocity of the ephoton is the same as the velocity of the charge (that is electron) in the conductor, which means that the ephotons are bound around the electrons.

In the vacuum, we assume that the ephoton density and the mphoton density are uniform. The Eq. (15) and Eq. (16) can be written as,

$$\rho_e \nabla \times \boldsymbol{v_e} = -\frac{\partial \boldsymbol{v_m}}{\partial t} \rho_m, \tag{24}$$

$$\rho_m \nabla \times \boldsymbol{v_m} = \mu\varepsilon \frac{\partial \boldsymbol{v_e}}{\partial t} \rho_e, \tag{25}$$

From the above two equations, we can get the form of motion of ephotons and the mphotons. As shown in Fig. **1** (a), the ephoton moves at a constant velocity v_p around the center of a sphere. The planes of motion of the two particles are perpendicular to each other. As shown in Fig. **1** (e) and (f), when the ephoton moves for a half cycle, it will change the direction of rotation. The ephoton and the mphoton will

change the direction of movement, and the velocity remains constant. The pair of a ephoton and a mphoton make up a photon. The resonance frequency of the pair of an ephoton and a mphoton is the frequency of the phothon. The resonance radius is λ, i.e. the corresponding wavelength,

$$\lambda = c/f. \qquad (26)$$

The actual velocity of the ephotons in the vacuum is,

$$v_p = \pi c/2. \qquad (27)$$

The ephotons and the mphotons fill the entire universe. All the ephotons are always moving at speed v_p, but not the speed c. So, we predict that the transmission speed of the electric fields is v_p. The moving speed of the ephotons is a constant, and the propagating speed in the propagation direction changes periodically with an average value of c.

We assume that the unit energy of the ephoton-mphoton pair is h, which is the Planck's constant, then the relativistic mass of the ephoton-mphoton pair is,

$$m_\gamma = \frac{E}{c^2} = \frac{h}{c^2}. \qquad (28)$$

The centripetal force of the ephoton-mphoton pair is,

$$F = m_\gamma a = m_\gamma \frac{\lambda}{4} \omega^2 = \frac{h}{c^2} \frac{\lambda}{4} (2\pi f)^2 = \frac{hf\pi^2}{c}, \qquad (29)$$

which is proportional to the frequency and the unit energy of the ephoton-mphoton pair. It is proportional to the energy of the electromagnetic wave. That is why we usually think that the higher the frequency, the larger the photon energy.
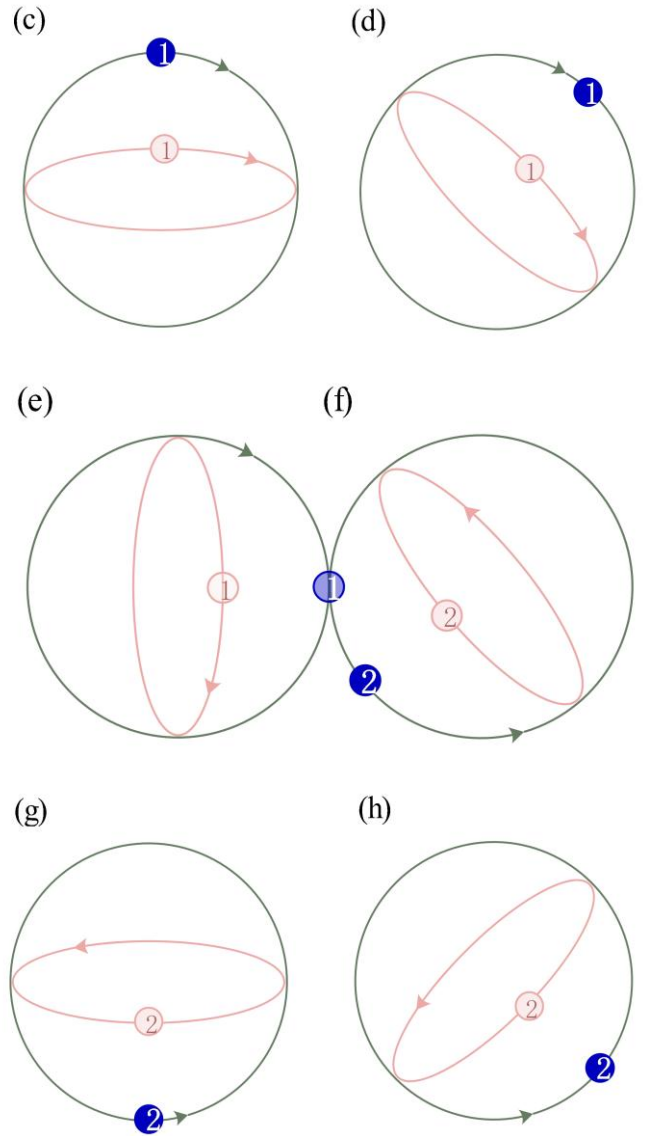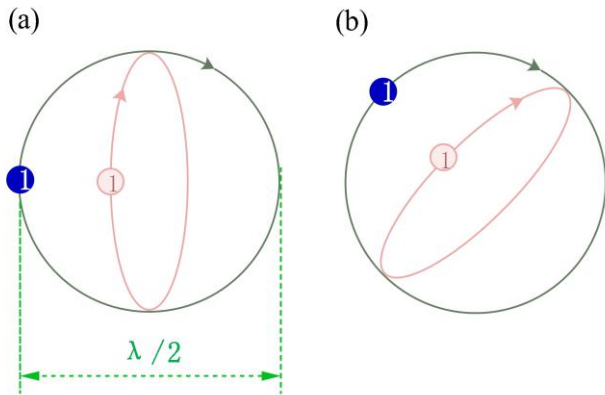

Figure 1. The schematic diagram of the ephoton-mphoton particle pairs and the propagation of plane electromagnetic wave in vacuum (a) at the initial moment, (b) after one eighth of a cycle, (c) after a quarter of a cycle, (d) after three eighth of a cycle, (e) after half a cycle, (f) after five eighth of a cycle, (g) after three quarters of a cycle, and (h) after seven eighth of a cycle. The red arrows in the figures are located on the inside of the paper.

There are some evidences shows that the fine structure constant α may not be a constant [4,5].

$$\alpha = e^2/4\pi\varepsilon_0\hbar c. \qquad (30)$$

According to Albert Einstein's special theory of relativity, the speed of light in the vacuum, c, is a constant, and we

believe that is true. And we believe $\hbar = h/2\pi$, is a constant, too. So we think that the charge of the electron, e, may be variable. The charge of the electron is not a Lorentz invariant, this is not contrary to the law of conservation of charge [6].

There is a possibility that the charges of positrons may not be exactly opposite to those of electrons [7-9]. In Ref. [7], the difference is measured using the measurements of Rydberg-energy and cyclotron-frequency ratios, which is,

$$|q_{e+} + q_{e-}|/e < 4 \times 10^{-8}. \qquad (31)$$

There is a possibility that the mass of positrons may not be exactly equal to that of electrons [10,11].

Based on Eq. (17) and the facts mentioned above, we proposed a model that is shown in Fig. **2**, in which, there are many ephotons around the electrons and the positrons, and the electrons can absorb the ephotons, the positrons can release the ephotons. Although the electrons always absorb the ephotons, it always move in high speed (around the nucleus inside the atoms) with releasing the ephotons. The absorption rate and release rate are almost equal, so that the mass of the electrons change little.

Until now, no magnetic charge has been found yet [12]. Unlike the electrons that can absorb the ephotons, we think that there are no paticles that can absorb the mphotons. But there are a lot of mphotons in the universe. And the mphotons can be attracted by the ephotons to form the ephoton-mphoton particle pairs as shown in Fig. **1**. That is the reason the electromagnetic waves can be generated.
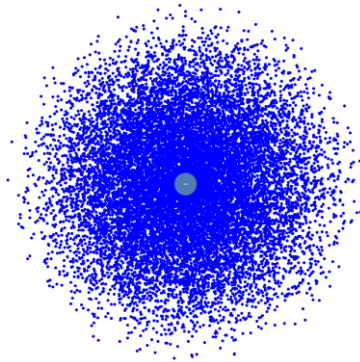

Figure 2. The model of the electron.

The proposed model can easily explain many electromagnetic phenomena. For example, we can explain why electrons have magnetic moment. In order to maintain stability, electrons must spin. The electron spin drives the ephoton around the electrons to move circularly along the spin direction (motion in the z-y plane shown in Fig. **3** (a)), thereby generating a magnetic field and generating a magnetic moment.

As shown in Fig. **3** (b), when the electrons move in the z direction, more ephotons will cluster in the front, resulting in a magnetic field in the x-y plane (perpendicular to the direction of motion). That is why the DC current can generate a stable magnetic field.
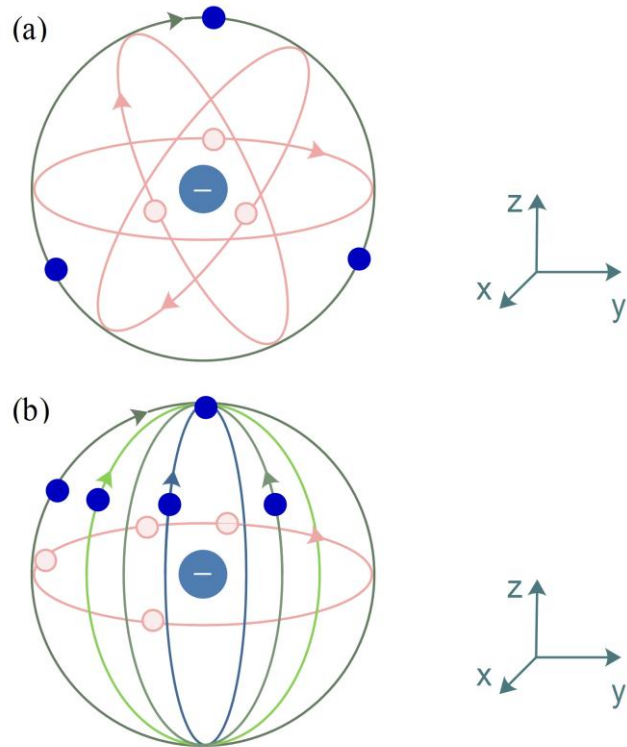

Figure 3. Particle motion model around the electron when (a) the electron just spin without any axial movement, and (b) the electron move along the z direction.

The electron orbital magnetic moment and the nucleus spin magnetic moment have the same mechanism of generation as the electron spin magnetic moment. The molecular magnetic moment is constituted by the electron orbital magnetic moment, the electron spin magnetic moment, and the nucleus spin magnetic moment. The magnetization of the magnetic medium is a result of external magnetic field effects the magnetic moment of the molecule.

3. Interaction between waves and electrons

Some kinds of high-power microwave sources [1] have

been developed for many years to generate coherent electromagnetic radiation using the interaction between the waves and the electrons. The waves and electrons will interact to produce coherent radiation when the resonance happens between the waves and the electrons, which is,

$$\omega \cong k_z v_z + s\Omega. \tag{32}$$

Where, ω and k_z are the wave angular frequency and axial wavenumber, v_z is the electron axial velocity and s is the cyclotron resonance harmonic number (s=1, 2, …).

For devices utilizing Cherenkov radiation, like the traveling wave tubes, the back wave tubes, etc., s=0. That is, $\omega \approx k_z v_z$, i.e., $v_p \approx v_z$, i.e., when the electron axial velocity close to the phase velocity of electromagnetic wave, the interaction happens between the waves and the electrons.

For devices utilizing bremsstrahlung radiation, like the gyrotrons [13], $k_z << \omega$/c, Ω=eB$_0$/m$_e$, where B_0 is the magnetic induction of the center of the gyrotron, m_e is the relativistic mass of electron. The resonance condition is, $\omega \approx s\Omega$, i.e., when the electron cyclotron frequency close to the electromagnetic frequency, the interaction happens between the waves and the electrons, too.

For free electron lasers [14], $k_z \approx \omega/c$, $\Omega=k_w v_z=2\pi v_z/\lambda_w$, where λ_w is the period of a spatially varying undulator or wiggler magnetic field. The above two kinds of interactions happen at the same time.

When the electron axial velocity close to the axial phase velocity of electromagnetic wave, $\omega \approx k_z v_z$, i.e, $\omega/k_z \approx v_z$. For devices with $\omega/k_z \approx c$, the way to make the waves-electrons interactions is to accelerate electrons to speed c. Another way to make the waves-electrons interactions happen is to decrease the axial phase velocity of the electromagnetic waves using the slow wave structure. In the slow wave structure, the minimum inner diameter is close to (or less than) the half wavelength. When the ephotons hit the metal wall, they will be absorbed by the electrons in the metal wall, and the electrons will move to release the new ephotons. Because the electrons absorb ephotons and release ephotons slower than the speed of light, so the axial phase velocity of the electromagnetic waves in the slower wave structure will be slower than the velocity of the light. When $v_p=\omega/k_z=v_z$, and the electromagnetic waves and the electrons resonate. When the velocity of the electrons v_p is a little faster than the phase velocity of the electromagnetic

waves, the speed of electrons will decrease, so as to tend to return to the resonance state. We assume that the faster the electron speed, the more the number of ephotons around. It may be the reason why the greater the speed, the greater the quality according to the special theory of relativity. When electrons move in the opposite direction of the electric field, which is shown in Fig. **4** (a), the electrons will accelerate and therefore absorb more ephotons, that is the progress of the electromagnetic energy converts into electronic kinetic energy in the accelerators. When electrons move in the same direction of the electric field, which is shown in Fig. **4** (b), the electrons will slow down and therefore release more ephotons, that is the process of the electronic kinetic energy converts into the electromagnetic energy in some electric vacuum devices such as the traveling wave tubes.
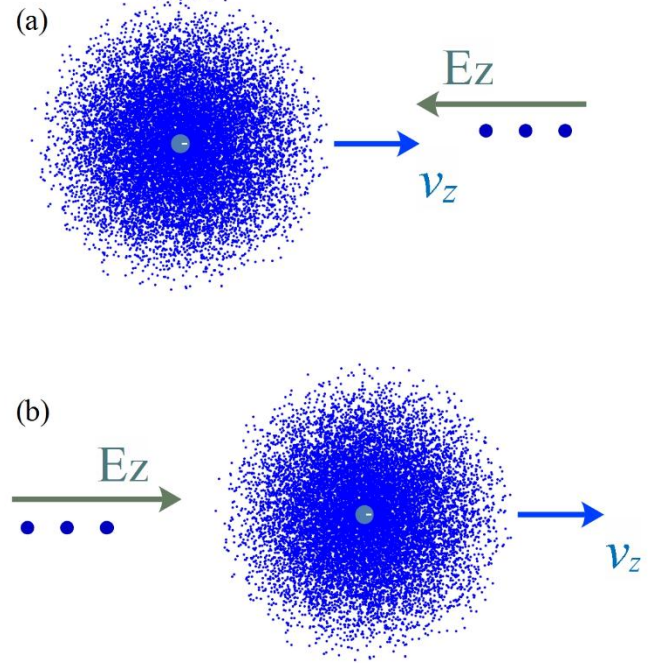

Figure 4. Interactions between waves and electrons when (a) the direction of the electron movement is opposite to the electric field, (b) the direction of the electron movement is the same as the electric field.

When the electrons do uniform circular motion, the ephotons around the electrons will be thrown away. Due to inertia, the cyclotron frequency of the ephotons will be almost same with the cyclotron frequency of the electrons. The cyclotron motion of the ephotons will attract the mphotons to form the ephoton-mphoton pairs, i.e. the photons, which are the basis particles of the electromagnetic

wave. That is the interaction process between the waves and the electrons in the devices utilizing bremsstrahlung radiation.

4. Discussion and conclusion

A new electromagnetic model is proposed to explain the interactions between waves and electrons. In this model, the photon is composed of two elementary particles – ephoton and mphoton, which are the basic particles that form the electric fields and magnetic fields, respectively. There are many ephotons around the electrons and the electrons can absorb the ephotons. According to this model, the particle flow density of the ephotons is the electric field intensity E, and the particle flow density of the mphotons is the magnetic induction B. The charge density is actually the change of ephoton density with time. The density of mphotons does not change with time. Using the ephoton-mphoton pair assumption, a numerical algorithm may be developed in the future to simulate the propagation of the electromagnetic waves and the interactions between waves and electrons.

*xuweiye@ipp.cas.cn

1 Gold, S. H. & Nusinovich, G. S. Review of high-power microwave source research. *Rev. Sci. Instrum.* **68**, 3945-3974, doi:10.1063/1.1148382 (1997).

2 Chao, A. W. & Tigner, M. Handbook of Accelerator Physics and Engineering.   (World Scientific, 1999).

3 PURCELL, E. M. & MORIN, D. J. Electricity and Magnetism. Third edn,   (Cambridge University Press, 2013).

4 Pickering, J. C. et al. Accurate laboratory wavelengths of some ultraviolet lines of Cr, Zn and Ni relevant to time variations of the fine structure constant. *Monthly Notices of the Royal Astronomical Society* **319**, 163-167, doi:10.1046/j.1365-8711.2000.03808.x (2000).

5 Webb, J. K. et al. Further Evidence for Cosmological Evolution of the Fine Structure Constant. *Phys. Rev. Lett.* **87**, 091301 (2001).

6 Ai, Xiaobai. What is the physical meaning of "running" fine structure constants? - To discuss with Mr. Guangjiong Ni. *Physics* **26**, 244-246 (2000).

7 Hughes, R. J. & Deutch, B. I. Electric charges of positrons and antiprotons. *Phys. Rev. Lett.* **69**, 578-581 (1992).

8 Müller, B. & Thoma, M. H. Vacuum polarization and the electric charge of the positron. *Phys. Rev. Lett.* **69**, 3432-3434 (1992).

9 Schäfer, A. & Reinhardt, J. Vacuum polarization as a test of C and CPT invariance. *Phys. Rev. A* **51**, 838-840 (1995).

10 Fee, M. S. et al. Measurement of the positronium 1 3S1-2 3S1 interval by continuous-wave two-photon excitation. *Phys. Rev. A* **48**, 192-219 (1993).

11 Chu, S., Mills, A. P. & Hall, J. L. Measurement of the Positronium 1 3S1-2 3S1 Interval by Doppler-Free Two-Photon Spectroscopy. *Phys. Rev. Lett.* **52**, 1689-1692 (1984).

12 Milstead, D. & Weinberg, E. J. Magnetic Monopoles http://pdg.lbl.gov/2017/reviews/rpp2017-rev-mag-monopole-searches.pdf (2017).

13 Nusinovich, G. S., Thumm, M. K. A. & Petelin, M. I. The Gyrotron at 50: Historical Overview. *J. Infrared Millim. Te.* **35**, 325-381, doi: 10.1007/s10762-014-0050-7 (2014).

14 Manfred, T. State-of-the-Art of High Power Gyro-Devices and Free Electron Masers. Report No. KIT-SR 7575, (Karlsruhe Institute of Technology 2010).

Additional Information