Silicene superconductivity due to the Kapitza-Dirac effect

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Abstract

We consider the Kapitza-Dirac configuration for the generation of the standing waves. Electrons are then diffracted by standing waves and Bragg equation is valid. The situation is considered also in a plane and in the three dimensions. The electron-photon system forms the electron-photon superconductor. The Kapitza-Dirac effect is then applied to silicene.

1 Introduction

The Kapitza-Dirac effect is the difraction of an electron beam from a standing wave of light. This process may be considered as an analogue of the optical diffraction of light on a grating, but with the roles of light and matter interchanged. The effect was predicted in 1933 (Kapitza et al. 1933; Berestetzkii et al., 1989), and clear experimental confirmation of this effect has been achieved only recently using laser technique. A successful experiment observed the (classical) scattering of electrons in a standing laser wave (Bucksbaum et al., 1988).

The effect proposed is the equivalent of von Laue scattering as observed first for neutrons penetrating a crystal, where the grating is formed by the periodic structure of the atoms in a crystal. Both von Laue scattering and (reflective) Bragg scattering can be observed for thick crystals in contrast to observation of diffraction scattering for thin crystals.

In case of the Bragg scattering it is well known the Bragg equation for the interference maxima of the reflected x-rays.

$$2d \sin\theta = n\lambda; \quad \lambda \leq 2d, \tag{1}$$

where n = 1, 2, 3, ..., λ is the wave length of x-ray and d is the distance between atomic planes, which can be graphically expressed as $| \leftarrow d \rightarrow |$. The angle θ is measured from the lattice plane (Kittel, 1996). In case of the Kapitza Dirac effect d is the minimal distance between interference nods.

For a crystalline solid, the waves are scattered from lattice planes separated by the interplanar distance d. When the scattered waves interfere constructively, they remain in phase since the difference between the path lengths of the two waves is equal to an integer multiple of the wavelength.

The effect of the constructive or destructive interference intensifies because of the cumulative effect of reflection in successive crystallographic planes of the crystalline lattice. Moving particles, including electrons, protons and neutrons, have an associated wavelength called de Broglie wavelength.

A diffraction pattern is obtained by measuring the intensity of scattered waves as a function of scattering angle. Very strong intensities known as Bragg peaks are obtained in the diffraction pattern at the points where the scattering angles satisfy Bragg condition. A fully relativistic treatment of the process within the Dirac theory, can be formulated using the Volkov solution (Berestetzkii et al., 1989) of the Dirac equation for two counterpropagating light waves (Pardy, 2004a; 2004b). Let us still remark that the existence of the light standing waves in vacuum is the experimental proof of the constant light velocity, being equivalent to the Michelson Morley famous experiment.

2 From the Wiener experiment to the Kapitza-Dirac effect

Otto Wiener visualized light waves in steady conditions. He obtained the light from a carbon arc light, entering the darkroom through a slit. Then, the light was filtered through a prism, discarding most of the red part of the spectrum. Monochromatic light with a uniform wavelength, then formed a regular standing waves pattern, parallel to the mirror surface. The Wiener orthochromatic film was transparently thin, about 20 nm, measured by interference, which is much less than the wavelength of the sodium doublet which is 589 nm. It was laid on the mirror, over an equally thin slice of gel. That way, by applying pressure on one side of the film only, Wiener

could slightly tilt it so as to make it traverse several standing waves. The standing waves were revealed by exposing the film from 20 to 35 minutes, after development and printing.

3 The Kapitza-Dirac effect in a plane

While Kapitza and Dirac considered the one-dimensional situation, it my be easy to show that there is possible generalization to the two-dimensional situation in order to form the two-dimensional photon-electron crystal. The construction is in considering some rectangle ABCD. Let be AB and CD mirrors. The light ray from A is reflected by CD and AB to form the so called zig-zag trajectory of light. If at point C is reflecting mirror in the opposite direction of the last light ray, then after reflection at C, the standing waves are created in the area of ABCD and the rectangle ABCD forms in such a the two-dimensional electron-photon crystal. Then, the Kapitza-Dirac effect can be applied in the ABCD.

4 The three-dimensional Kapitza-Dirac effect

This effect is only the generalization of the one-dimensional Kapitza-Dirac effect. In this case the nodes of the standing waves form the three-dimensional crystal with the system of bundles in some volume box and the validity of the Bragg equation is sure. If the used coherent light is sufficiently strong, as an analogy with the Lebedew experiment with the pressure of light on a solid body (Lebedew, 1989), then the so called electron-photon crystal enables the existence of the superconductivity of this crystal. It may be easy to verify the superconductivity by some RLC circuit, where the resistance element R is the electron-photon crystal.

5 Superconductivity

The superconductivity in crystals, or, in the condensed medium has its origin in Cooper pairs which can overlap (Cooper, 1956). In condensed matter physics, a Cooper pair is a pair of electrons (or other fermions) bound together at low temperatures in a specific manner. Cooper showed that an arbitrarily small attraction between electrons in a metal can cause a paired state of electrons to have a lower energy than the Fermi energy, which implies that the pair is bound. In conventional superconductors, this attraction is due to the electron-phonon interaction. The Cooper pair state is the basic ingredient of the BCS theory developed by Bardeen, Cooper, Schrieffer (Feynman, 1972).

With regard to the pedagogical clarity of Wikipedia, we can say that the electron is repelled from other electrons due to their negative charge, but it also attracts the positive ions. This attraction distorts the ion lattice, moving the ions slightly toward the electron, increasing the positive charge density of the lattice in the vicinity. This positive charge can attract other electrons. At long distances, this attraction between electrons due to the displaced ions can overcome the repulsion of electrons due to their negative charge, and cause them to pairing. The rigorous quantum mechanical explanation shows that the effect is due to electron-phonon interactions, with the phonon being the collective motion of the positively-charged lattice.

6 The London explanation of superconductivity

According to quantum mechanics (Feynman, 1972), the current of electrons is given by equation

$$\mathbf{j} = -\frac{\hbar e}{2im}\left(\psi^*\nabla\psi - (\nabla\psi)^*\psi - \frac{e^2\mathbf{A}}{mc}\psi^*\psi\right). \tag{2}$$

If $\mathbf{A} = 0$, then we have from the last equation

$$\mathbf{j} = -\frac{\hbar e}{2im}\left(\psi_0^*\nabla\psi_0 - (\nabla\psi_0)^*\psi_0\right) = 0. \tag{3}$$

If the wave function is stiff, or $\psi \approx \psi_0$ for $\mathbf{A} \neq 0$, we get the London equation

$$\mathbf{j} = -\frac{e^2\mathbf{A}}{mc}\psi^*\psi = -\Lambda\mathbf{A}. \tag{4}$$

There is, on the other hand, the quantum mechanical formula following from the perturbative quantum mechanics, namely (Feynman, 1972)

$$\psi = \psi_0 + \sum_{n\neq 0}\frac{\langle n|H_{int}|0\rangle}{E_n - E_0}|n\rangle, \tag{5}$$

where E_n, E_0 are excited and basic states of the system. If $E_n \gg E_0$, then $E_n - E_0$ is big and the wave function is stiff, or, $\psi \approx \psi_0$ and we get the London equation. So, in other words, superconductive system is a such one, where there is an energetic gap $\Delta E = E_n - E_0$. The quantity ΔE follows rigorously fro the Bardeen-Cooper-Schriefer theory, or from the Bogolyubov theory of superconductivity and it is given by the formula

$$\Delta = 2\hbar\omega_D e^{-\frac{1}{\lambda}}, \tag{6}$$

where ω_D is the Debye frequency and $\lambda = N(0)V_{ef}$, where $N(0)$ is the density of the electron states on the Fermi level and V_{ef} is the two-body interaction potential of the phonon interaction of electrons with the lattice. In our case of the photon-electron crystal, we can identify the usual crystal lattice by the lattice formed from the nods of the standing photon waves and electrons.

7 Superconductivity of the electron-photon crystal due to the Kapitza-Dirac effect

The superconductivity in electron-photon crystals has its origin also in Cooper pairs which can overlap. While Cooper showed that an arbitrarily small attraction between electrons in conventional superconductors, is due to the electron-phonon interaction, we easily show that there are Cooper pairs in the electron-photon crystal. We use here the idea of the deformation of the electron-photon lattice by individual electrons.

The substantial idea of gravity attraction is that a body of mass M deforms the Minkowski space-time. Because of the validity of this idea, we write the Newton gravitational law in the form (D = deformation)

$$D_1 + D_2 \to -\kappa \frac{M_1 M_1}{r^3}\mathbf{r}, \tag{7}$$

where the quantities in the last equation have the standard textbook physical meanings. Let us only remark, that every deformation create new metrics and it means that the last equation can be transformed to the Einstein metric form. In our case every electron of the electron-photon crystal deforms it and in such a way two electrons create the Cooper pair. It means that the superconductivity of the electron-photon crystal is established.

8 Silicene superconductivity due to the Kapitza-Dirac effect

Silicene is a two-dimensional allotrope of silicon, with a hexagonal honeycomb structure similar to that of graphene. Contrary to graphene, silicene is not flat, but has a periodically buckled topology; the coupling between layers in silicene is much stronger than in multilayered graphene.

In 2015, a silicene field-effect transistor made its debut (Tao, et al. 2015) that opens up new opportunities for two-dimensional silicon for various fundamental science studies and electronic applications (Peplow, 2015).

Silicene and graphene have similar electronic structures. Both have a Dirac cone and linear electronic dispersion around the Γ point. Both also have a quantum spin Hall effect. Both are expected to have the characteristics of massless Dirac fermions that carry charge, but this is only predicted for silicene and has not been observed, likely because it is expected to only occur with free-standing silicene which has not been synthesized.

Compared with graphene, silicene has several prominent advantages: (a) a much stronger spin-orbit coupling, which leading to the quantum spin Hall effect in the experimentally accessible temperature, (b) a better tunability of the band gap, which is necessary for an effective field effect transistor operating at room temperature, (c) an easier valley polarization and more suitability for electronics study (Zhao, et al., 2016). In our case every electron of the electron-photon crystal deforms it and in such a way two electrons create the Cooper pair. It means that the superconductivity of the electron-photon crystal in silicene is established.

9 Discussion

We have discussed the possibility to create to so called electron-photon superconductive two-dimensional and three-dimensional crystal due to the Kapitza-Dirac effect. While the two-dimensional superconductivity can be realized for instance in silicene, the three-dimensional superconductivity can be realized in glass, diamond, Wigner crystal and so on. Such crystals was not still prepared by the Bell Laboratories, Silicon Valley and other laboratories, nevertheless there is no doubt on the existence of the superconductive properties of the such electron-photon crystal. The application of the 2D superonductive crystal in computer electronics is with no doubt effective and represents revolution in computer physics. The question is not how to find the better theory of such crystal, but what optical laboratory including the Silicon Valley will be the first laboratory to confirm the practical ability of such superconductive crystals.

References

Berestetzkii, V. B., Lifshitz, E. M. and Pitaevskii, L. P. (1989). *Quantum Electrodynamics*, Moscow, Nauka, (in Russian).

Bragg, W. H. and Bragg, W. L. (1913). The Reflexion of X-rays by Crystals, Proc R. Soc. Lond. A. **88** (605), 428-38.

Bucksbaum, P. H., Schumacher, D. W. and Bashkansky, M. (1988). High-intensity Kapitza-Dirac effect, Phys. Rev. Lett. **61**, 1182 .

Cooper, L. N. (1956). Bound electron pairs in a degenerate Fermi gas, Phys. Rev. **104**, (4), 1189-1190.

Feynman, R. *Statistical mechanics*, (W. B. Benjamin, Inc., Reading, Massachusetts, 1972).

Kapitza, P. L. and Dirac, P. A. M. (1933). The Reflection of Electrons from Standing Light waves, Math. Proc. Cambridge Philos. Soc. **29**, 297.

Kittel, Ch. *Introduction to Solid State Physics*, 7-th edition, (John wiley & Sons, Inc. New York, 1996).

Lebedew, P. (1901). Untersuchungen über die Druckkräfte des Lichtes, Annalen der Physik. **311**, (11), 433-458.

Pardy, M. (2004a). Massive photons and the Volkov solution, *International Journal of Theoretical Physics* **43**(1), 127.

Pardy, M. (2004b). Volkov solution for an electron in two wave fields, e-print hep-ph/0408288.

Peplow, M. (2015). Graphene's cousin silicene makes transistor debut, Nature News & Comment, 2-nd February.

Tao, L.; Cinquanta, E.; Chiappe, D.; Grazianetti, C.; Fanciulli, M.; Dubey, M.; Molle, A.; Akinwande, D. (2015). Silicene field-effect transistors operating at room temperature, Nature Nanotechnology **10** (3), 227.

Wiener, O. (1890). Stehende Lichtwellen und die Schwingungsrichtung polarisirten Lichtes, Ann. Phys., **276** (6), 203-243.

Zhao, Jijun; Liu, Hongsheng; Yu, Zhiming; Quhe, Ruge; Zhou, Si; Wang, Yangyang; Zhong, Hongxia; Han, Nannan; Lu, Jing; Yao, Yugui; Wu, Kehui (2016). Rise of silicene, A competitive 2D material, Progress in Materials Science. **83**, 24.