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THE KAPITZA-DIRAC EFFECT

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IN a brief note published in 1933[1], P. L. Kapitza and P. A. M. Dirac demonstrated the possibility of reflecting free electrons from a standing light wave. It is remarkable that they immediately emphasized the most interesting feature of the effect—observation of induced scattering of the radiation, which at that time (and for a long time thereafter) could not be observed experimentally. Recently the Kapitza-Dirac effect has become experimentally observable by using powerful lasers[2].

The idea of the experiment proposed by Kapitza and Dirac is illustrated in the figure. An electron beam from an electron source 1 is accelerated by the potential between the source and diaphragm 2, and then crosses a standing light wave 3, produced by reflecting the light beam from mirror 4. Some of the electrons experience Bragg reflection from the standing wave acting like a three-dimensional grating with period $\lambda_{\text{light}}/2$ (λ_{light} —length of the light wave) and arrive at the point 5′ in lieu of the point 5.

Kapitza and Dirac presented the following theoretical analysis of the effect. The standing wave represents two waves of equal frequency traveling in opposite directions. Each of the traveling waves causes Compton transitions of the electrons, wherein the electrons absorb photons from the traveling wave and re-radiate them in arbitrary directions, experiencing thereby a recoil that deflects them from their initial path. For two traveling waves with definite velocity and direction

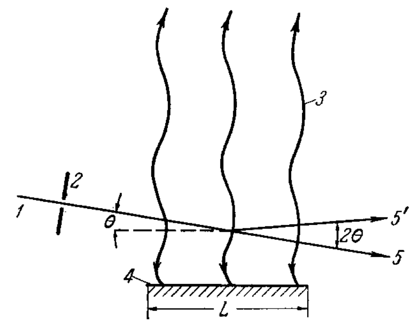

Diagram of experimental observation of the Kapitza-Dirac effect. 1 – Electron source, 2 – diaphragm, 3 – standing light wave, 4 – mirror, 5 – unscattered electron beam, 5′ – scattered electron beam.

of electron motion, a new effect is produced—induced Compton scattering, in which the photon is absorbed from one traveling light wave, and its re-radiation is induced by the other traveling wave, whereby the electron again experiences recoil. The probability of this process, unlike ordinary Compton scattering (the probability of which is proportional to the intensity of one of the traveling waves), is proportional to the product of the intensities of the traveling waves. It is clear that in a weak optical field the most probable is the ordinary Compton effect, and in a strong optical field the induced effect predominates.

The energy and momentum conservation law leads in this case directly to the Bragg condition for the scattering of electron waves. The photon re-radiated in the induced process should have the same frequency and direction as the inducing traveling wave. Consequently, the re-radiated photon should have the same frequency ν as the absorbed photon, and should move in the opposite direction. The momentum transferred to the electron is equal to $2h\nu/c$ and is directed along the light ray, while the energy transferred is equal to zero. It follows therefore that the electron waves should be reflected from the surfaces of the standing wave at a reflection angle equal to the incidence angle, and the wavelength of the electron waves λ_{el} should be connected with the angle of incidence θ (see the figure) by

$$2\frac{h\nu}{c}=2\frac{h}{\lambda_{el}}\sin\theta, \quad \text{and} \quad \lambda_{el}=2\left(\frac{\lambda_{light}}{2}\right)\sin\theta, \tag{1}$$

which is the condition of first-order Bragg reflection from a grating with period $\lambda_{light}/2$.

Kapitza and Dirac obtained also an expression for the probability of the induced process from the known cross section for the ordinary Compton scattering, using the relation between the Einstein coefficients for the induced and spontaneous emission. The expression they obtained for the probability P of electron reflection is

$$P=\frac{e^4L}{2m^2c^2h^2\nu^4v}\int I(\nu)I'(\nu)\,d\nu, \tag{2}$$

where v is the electron velocity and $I(\nu)$ and $I'(\nu)$ are the spectral energy densities of the traveling waves (in erg/sec-cm^2 Hz).

For ordinary continuous light sources, which emit not more than 1 watt in a spectral line with width ~ 0.1 Å, the probability of deflection of the electron is $\sim 10^{-14}-10^{-15}$. Although a somewhat larger probability can be obtained for pulsed light sources, nonetheless the fraction of the reflected electrons remains exceedingly small. In this connection Kapitza and Dirac emphasized that the experiment is at the borderline of feasibility and is very difficult to perform. The development of powerful pulsed lasers emitting $\sim 10^8$ W/cm^2 in a spectral region of $\sim 10^{-2}$ Å has made the Kapitza-Dirac experiment feasible with deflection of an appreciable fraction of the electrons.

The first to observe the Kapitza-Dirac effect experimentally were Bartell, Thompson, and Roskos[2]. In their experiment, a beam of 1.65-keV electrons crossed at right angle the cavity of a ruby laser emitting an energy of 30 J at a pulse intensity $\sim 10^8$ W/cm^2 inside the cavity. To attain maximum intensity of the standing wave inside the resonator, external totally-reflecting (99.9%) mirrors were used in the laser. The resultant power was therefore sufficiently high even without Q-switching. The scattering angles were measured by scanning the electrons past the slit of a scintillation detector. The scattering angle 2θ was only 10^{-4} rad. Special attention was therefore paid to collimation of the beam and to maintaining its direction during the time of the laser flash. These nontrivial requirements were satisfied, and the perturbation of the electron beam did not exceed a small fraction of 2θ per scanning.

The deflection of an appreciable fraction of the electrons was observed in 200 laser flashes. To eliminate the possibility of a false effect, the following experiments were performed. A narrow metal strip was introduced into the cavity to shield the path of the electron beam inside the cavity from the light. The effect then disappeared. It appeared again, however, when the metal strip was rotated around the axis of the laser beam in such a way that it no longer blocked the entire passage of the electron beam. The intensity of the laser beam was insufficient to obtain the observed effect by ordinary Compton scattering. All this confirms that the effect observed was indeed that of Kapitza and Dirac.

The accuracy of the experiment in [2] was insufficient for unambiguous verification of the fulfillment of the Bragg condition (1) for the scattering angle. The reason is that, first, the apparatus did not measure the time and the scattering angle independently, and second, the width of the electron beam, although allowing a resolution of 10^{-4} rad under favorable condition, was nonetheless comparable with the expected deflection angles. The authors of the experiment hope to modify the apparatus for a quantitative investigation of the Kapitza-Dirac effect.

Of great interest is the irregular clearly-pronounced structure of the scattered electron beam observed in [2]. The electrons were deflected at angles corresponding to fourth and higher diffraction orders, thus pointing to momentum exchange with four or more photons at sufficient field intensity. The scheme of the process that produced Bragg reflection of order n is

$$e^- + \overbrace{\gamma+\gamma+\ldots+\gamma}^{n} \rightarrow e^- + \overbrace{\gamma'+\gamma'+\ldots+\gamma'}^{n}. \tag{3}$$

Other processes, for example

$$\begin{aligned} e^-+\gamma &\rightarrow e^-+\gamma'+\gamma', \\ e^-+\gamma+\gamma &\rightarrow e^-+\gamma', \end{aligned} \tag{4}$$

although probable in strong fields, are kinematically forbidden in the Kapitza-Dirac experiment.

The Kapitza-Dirac effect is the first example of induced interaction between free electrons and photons. Recently a large number of experimental papers were published[3-10] dealing with possible effects of such interactions.

We note the last paper by Eberly[10], in which it is proposed to observe with the aid of the Kapitza-Dirac experiment a nonlinear Compton frequency shift of a scattered photon[6-9].

The sphere of manifestation of the Kapitza-Dirac effect will undoubtedly broaden in the future. By way of illustration we can present the following example. Electron waves in a crystal situated in the field of a strong standing light wave can be diffracted not only by the crystal lattice but also (with suitable direction and velocity of motion) by the light wave itself. This can cause splitting of the continuous spectrum of the electron energy into alternating allowed and forbidden bands.

To be sure, we are faced here with the following two circumstances. First, the bandwidths are small and, second, splitting due to the Kapitza-Dirac effect may be masked by the splitting produced by the periodic deformation of the crystal itself in the strong light field, due for example to electrostriction, since periodic deformation of the crystal lattice leads, as is well known[11], to an analogous splitting of the continuous spectrum.

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