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Kapitza–Dirac diffraction of atoms

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Abstract. Kapitza and Dirac predicted the diffraction of an electron on a standing optical wave. The roles of light and matter here changed places relative to classical optics. Later, ideas about the diffraction of matter on an electromagnetic wave were developed in atomic physics. The diffraction of atoms has been observed in various forms and is used in atomic interferometers.

Keywords: interference of matter waves, stimulated scattering, photon recoil momentum

In 1933, Kapitza and Dirac predicted the diffraction of an electron by a standing light wave [1]. The effect resembles the diffraction from a thick grating known in optics, but the substance and light have swapped places. The authors pointed out the weakness of the effect. In 1966, it was calculated in [2] that the effect is much stronger for atoms. Since then, the ideas of Kapitza and Dirac have been developed in atomic physics — the diffraction of atoms on a standing light wave has been observed in various variants and applied in practice.

In this paper, the original Kapitza–Dirac effect is first discussed, and then most of the paper is devoted to the varieties of the effect that have appeared in atomic physics. Diffraction by thin and thick gratings, in an atomic beam and in a nearly motionless cloud of atoms, combined with Stern–Gerlach and Talbot effects, and as applied in atomic interferometry are considered.

Figure 1 shows a diagram of electron diffraction, adopted from original paper [1]. Light can be described in both a quantum and a classical way. From the quantum point of view, in the illuminated region, the electron redistributes photons between modes $\mathbf{k}_1$ and $\mathbf{k}_2$. Since the process is stimulated, an even number of photons are scattered, which leads to the transfer of momentum $n2\hbar k$, where $k = |\mathbf{k}_1|$ is the wave vector of light, and n is an integer. In diffraction by a thick grating, conservation of energy leads to the selection of one specific n and the appearance of only one diffraction maximum, as shown in Fig. 1. From the point of view of classical physics, the electron is driven by the spatially periodic Gaponov–Miller potential [3]

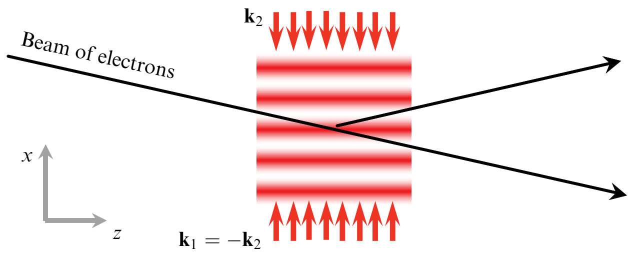

Figure 1. Bragg diffraction of an electron by a standing optical wave. (Adopted from paper by Kapitza and Dirac [1].)

$$U_{\rm GM}(x) = \frac{e^2 E_0^2}{4m\omega^2}\cos^2(kx)\,, \tag{1}$$

where E_0, ω, and $k = \omega/c$ are the amplitude at the antinode, the frequency, and the wave vector of the light wave, and e and m are the charge and mass of the electron.

Instead of electrons, we can consider a beam of atoms. They are affected by a dipole potential $U_{\rm dipole}$. Representing an atom as an electron on a spring, which corresponds to a frequency ω_0, we get

$$U_{\rm dipole}(x) = \frac{e^2 E_0^2}{4m(\omega^2-\omega_0^2)}\cos^2(kx)\,. \tag{2}$$

Near resonance, $\omega \sim \omega_0$, the potential becomes multiply amplified compared to a free electron. Due to the periodicity of $U_{\rm dipole}(x)$, the standing wave is often called an optical grating.

For atoms, signs of Kapitza–Dirac diffraction were observed in [4, 5]. The atomic beam broadened after crossing the standing wave, the observed broadening corresponding to the transfer of momentum $\simeq 200\hbar k$ [5].

Since the interaction of light and an atom can be rather strong, as can be seen from Eqn (2), the thick grating mode is not at all necessary. In 1980, diffraction by a thin grating was calculated [6], and its qualitative result is shown in Fig. 2. In contrast to the thick grating mode, several diffraction maxima arise, corresponding to a shift of the initial momentum by $n2\hbar k$. Such diffraction was observed in 1986 [7]. In this experiment, a collimated atomic beam crossed a standing wave; the result is shown in Fig. 3. The data distinguish the diffraction orders corresponding to a given number of transferred photon recoil momenta $\hbar k$, and this number is always even.

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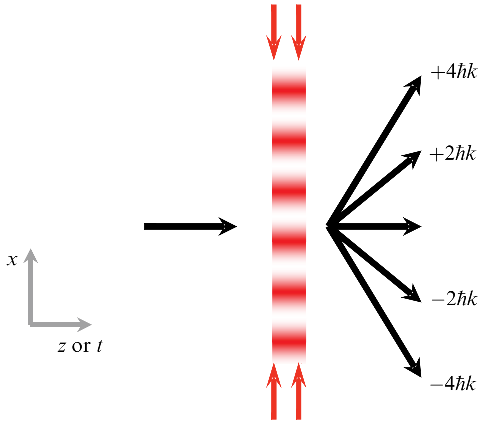

Figure 2. Kapitza–Dirac diffraction using a thin light grating. Optical fields are shown in red, atomic trajectories and corresponding momentum additives are shown in black.

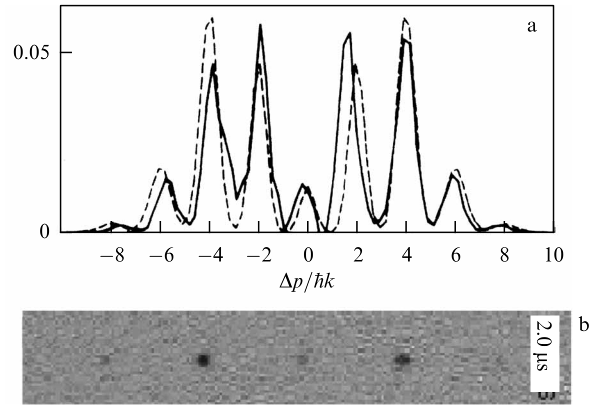

Figure 3. (a) Kapitza–Dirac diffraction of an atomic beam by a thin light grating (adopted from [7]). Flux distribution in atomic beam at a distance from the grating is shown. (b) Diffraction of a Bose condensate whose center is stationary in laboratory frame of reference (adopted from [8]). Two visible dark dots are diffraction orders corresponding to momenta $\pm 2\hbar k$. Between them is a weakly noticeable zero order.

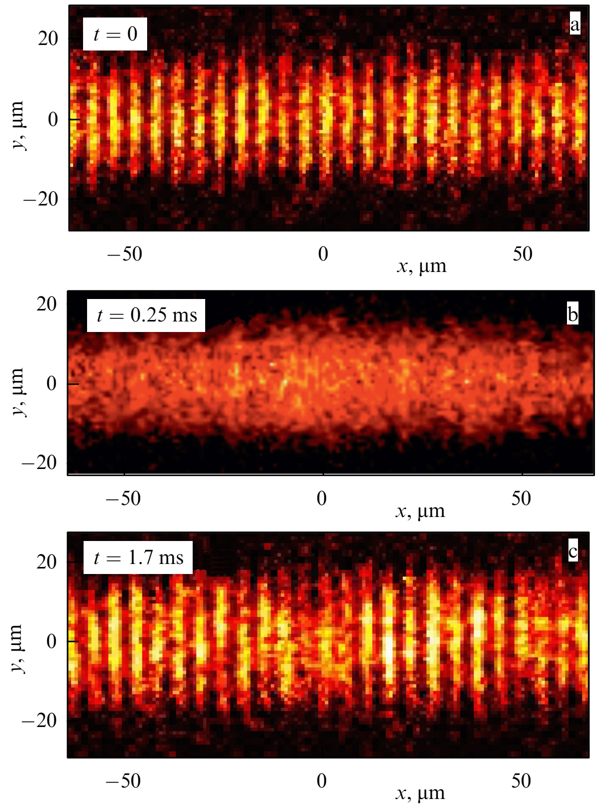

Figure 4. (a) Chain of Bose condensates trapped in antinodes of a standing wave. (b, c) Subsequent diffraction and interference after switching off standing wave at $t = 0$. Published (a, c) and unpublished (b) data from experiment [14].

For a thin grating, diffraction allows analytical calculations [6, 9]. Let us describe the state evolution of the atom's center of mass in a reference frame that moves across the standing wave with the same velocity as the atom. Passage through the standing wave is observed as its switching on for a short time τ. The internal state of the atom is preserved. At the initial time $t = 0$, let the atom be described by a plane wave $\psi(x, 0) = \exp(\mathrm{i}p_0 x)$; the rays of the standing wave are switched on for a short time, creating a potential $U(x, t) = U_0(t)\sin(2kx)$. Let us ignore the motion of the atom during time τ, equivalent to disregarding the kinetic energy in the evolution operator, which thus has the form $\exp(\mathrm{i}\varphi\sin(2kx))$, where $\varphi \equiv -(1/\hbar)\int_0^{\tau} U_0(t)\,\mathrm{d}t$ is the area of the pulse. The impact of the standing wave transfers the atom to the state

$$\psi(x, \tau) = \exp\left(\mathrm{i}\varphi\sin(2kx)\right)\exp(\mathrm{i}p_0 x) = \sum_{n=-\infty}^{\infty} J_n(\varphi)\exp\left(\mathrm{i}(2nk + p_0)x\right), \qquad (3)$$

where J_n is the Bessel function of the first kind. The atomic density remains uniform, and phase modulation appears. In the far zone, the phase modulation transforms into density modulation and the flux is divided into several maxima, the density in which is $\sim |J_n(\varphi)|^2$. The maxima are symmetric with respect to replacing n with $-n$. It is possible to enhance or suppress a specific pair of maxima $\pm n$ by varying the pulse area φ. The result does not depend on p_0.

Besides the atomic beam conditions, the diffraction of atoms by a thin optical lattice was also observed in a cloud of almost motionless atoms [8, 10]. The standing wave is switched on for a short time τ, which, in the atomic reference frame, is identical to the passage of the beam through the standing wave. After some time, the phase modulation transforms into the observed density modulation. The result of the diffraction of the Bose condensate of atoms can be seen in Fig. 3b. Atoms are mainly scattered into states with momenta $\pm 2\hbar k$. The width of the diffraction is $\ll 2\hbar k$, which reflects the extremely narrow initial distribution of momenta in the condensate. In experiment [10], diffraction was observed in a cloud with a momentum distribution wider than $2\hbar k$ due to the selective sensitivity of the detector to the density harmonic $\sim \exp(\mathrm{i}2kx)$. Kapitza–Dirac diffraction is most frequently used for a cloud of atoms. This is facilitated by cooling methods developed for localized systems [11, 12].

In the case of a thick grating mode, one dominant diffraction maximum can be distinguished. The splitting of the initial and deflected states by an angle of up to $24\hbar k$ is achieved [13]. The experiment is performed with a cloud of atoms, without crossing the standing wave. For Bragg diffraction, the atomic beam must be incident at an angle different from 90°, which is shown in Fig. 1. For a stationary cloud of atoms, an exact analogue of such a difference is a

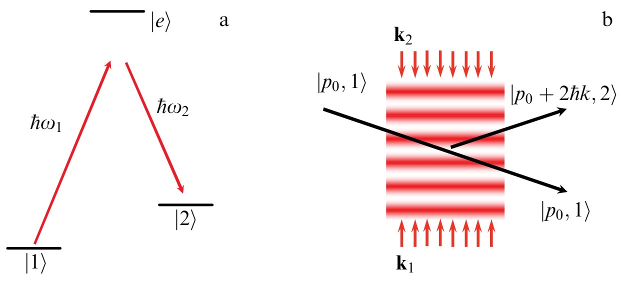

Figure 5. Diffraction of an atom in combination with a change in its internal state: (a) diagram of levels and frequencies of modes $\mathbf{k}_1$ and $\mathbf{k}_2$; (b) diffraction result.

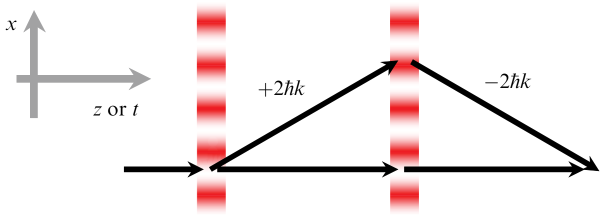

Figure 6. Schematic diagram of an atomic interferometer (based on Ref. [9]). Interfering trajectories of atom and corresponding momentum shifts along x are shown in black, and regions of interaction of the atom with the standing wave or corresponding time intervals are shown in red.

slow movement of the standing wave along x, which is achieved by a small imbalance between the moduli of the wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$.

Purely amplitude modulation as an initial condition for diffraction can also be created using a standing wave. An example can be seen in Fig. 4a — a chain of Bose condensates of molecules is prepared in the antinodes of a standing wave, which are the minima of the dipole potential (2). Approximate phase homogeneity is achieved by tunneling particles between the wells. The experiment is also performed without propagation of particles across the standing wave. At the time moment $t = 0$, the standing wave is switched off, after which diffraction and interference occur. Figure 4b shows the beginning of diffraction with individual clouds overlapping. In Figure 4c, after a longer time, the initial density modulation is restored due to interference, which is also a manifestation of the quantum Talbot effect [15].

The action on the center of mass of the atom can be combined with that on the atomic internal state [16]. For this, modes $\mathbf{k}_1$ and $\mathbf{k}_2$ are detuned in frequency by approximately the splitting between two long-lived eigenstates of the atom $|1\rangle$ and $|2\rangle$, as in Fig. 5a. They can be two states corresponding to different energy levels of the hyperfine structure in an alkali metal. Interaction with the electromagnetic field leads to a transformation of the state of the atom,

$$|p_x = p_0, 1\rangle \to \alpha|p_0, 1\rangle + \beta|p_0 + 2\hbar k, 2\rangle\,, \tag{4}$$

as shown in Fig. 5b. The condition $|\mathbf{k}_1 + \mathbf{k}_2| \ll k$ is used. The spatial and internal states are entangled, so this variant of Kapitza–Dirac diffraction is similar to the Stern–Gerlach effect.

The main practical application of Kapitza–Dirac diffraction is atomic interferometry [17], proposed in [9]. The interferometer scheme is shown in Fig. 6 and is similar to the Mach–Zehnder interferometer in optics. The first interaction with the standing wave plays the role of a beamsplitter, and the second one plays the role of a mirror. In Ref. [9], diffraction was considered in the thin grating mode, for which only a pair of possible trajectories are shown in Fig. 6. In the thick grating mode, the number of interfering trajectories can be reduced to two [13]. Often, the interferometer is based on a cloud of atoms [10, 13, 18, 19], rather than a beam — the atoms do not move across the standing wave; instead, the wave is switched on for a short time. In the interferometer, diffraction can be combined with a Raman transition of the form (4) [18]. A sensitive rotation sensor [20] and the highest-precision gravimeter [19] are constructed in a similar manner. Similar gravimeters are now industrially produced in the USA [21], France [22], and China [23].

Kapitza's and Dirac's prediction was thus transferred to atoms and molecules. Analogues of the effect, initially predicted as weak, were observed in various variants and applied in practice. In atomic physics, the term "Kapitza–Dirac scattering" traditionally refers only to diffraction by a thin optical lattice [17], as shown in Fig. 2. At the same time, a significantly wider range of problems regarding the diffraction of an atom in the field of two counterpropagating waves can be considered a development of study [1].

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