Interference of atoms and formation of atomic spatial arrays in light fields

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A method for observing an interference of atoms is proposed. A slightly coherent atomic beam is scattered by two standing waves. The atoms can transfer a spatial coherence over an extremely large distance.

1. Diffraction effects due to the wave properties of particles are observed in scattering by the crystal lattices of solids when the de Broglie wavelength of the particles is comparable to the lattice constant. To observe interference effects is a more complicated matter, since coherent beams of particles must be produced. The interference which arises upon the scattering of neutrons by an array of silicon plates is the basis of neutron interferometry.[1]

In this letter we take up the possibility of atomic interference for the first time. We point out that coherent beams of atoms can be produced in the scattering of particles by a resonant standing wave (the resonant Kapitsa-Dirac effect[2]). Observation of the interference of these particles is complicated by the finite divergence of an atomic beam. As a result of the interaction with a second standing-wave field, the coherent beams are scattered again and interfere with each other (Fig. 1). Echo processes[3] eliminate the effect of the beam divergence, and an interference occurs at large distances. The interference pattern is seen as the formation of a periodic structure in the spatial distribution of the atoms. Calculations show that the structure of the interference pattern and the region in which it occurs depend on the nature of the interaction of the particles with the fields and on the lifetimes of the excited states.

2. The interference among atoms with a short-lived excited state can be described

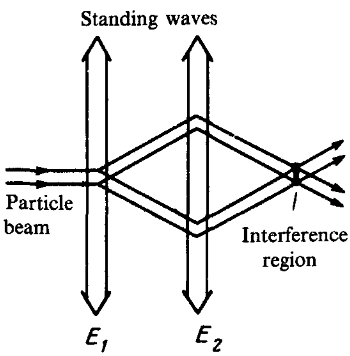

FIG. 1. An atomic interferometer. For simplicity, the scattered beams are not shown as overlapping after the interaction.

most simply in the case $\tau\Delta \gg 1$, where $\tau = a/v$ is the time required to traverse the field region, and Δ is the deviation of the wave frequency from the resonant frequency. We also assume $\Delta \gg \gamma$, where γ is the decay rate of the upper level.

After interaction with the first field (at $y = 0$), the incident plane wave $\exp(i\mathbf{pr}/\hbar)$ becomes a superposition of plane waves,[4]

$$\sum_n J_n(\xi_1)\exp(i\mathbf{p}_n\mathbf{r}/\hbar), \qquad \xi_1 = \frac{(dE_1)^2\tau}{2\hbar^2\Delta} \tag{1}$$

$$p_{nx} = p_x + 2n\hbar k, \qquad p_{ny} = p - p_{nx}^2/2p$$

with momenta that satisfy energy conservation: $p_n^2 = p^2$. Here d is the dipole matrix element of the transition between the levels, E_1 is the amplitude of the first field, J_n is a Bessel function, and the x and y axes run along the propagation directions of the wave and the beam, respectively. The transverse momentum which is transferred is related to stimulated transitions and is a multiple of $2\hbar k$. Transitions with momenta, which are odd multiples of $\hbar k$, arise from spontaneous emission and are incoherent; their contribution is small, on the order of the parameter γ/Δ.

The spatial modulation of the density of atoms which corresponds to wave function (1) is preserved only over small distances, $\sim(k\theta)^{-1}$, or on the order of 10^{-2} cm if the angular divergence of the atomic beam is $\theta \sim 10^{-3}$ and the wave number is $k \sim 10^5$ cm^{-1}. However, since the atoms are in the ground state, where there is no irreversible spontaneous relaxation, a phase memory is retained in the wave function over large distances. This memory makes it possible to produce an interference pattern under "echo" conditions.

Working by analogy with (1), we can calculate the effect of the second wave, with the parameter ξ_2, at $y = L$. In the atomic density distribution $1 + \Sigma_{n\neq 0} A_n \exp(2inkx)$ the amplitude of the first harmonic at the distance $y = 2L + l$ $(l \ll L)$ is then

$$A_1 = \langle J_1(8\xi_1\Delta_0 l/v)J_1^2(\xi_2)\exp(i\varphi)\rangle, \tag{2}$$

where $\varphi = 2klv_x/v$, $\hbar\Delta_0 = (\hbar k)^2/2m$ is the recoil energy, m is the mass of the atom, and the angle brackets denote an average over the distribution of the velocity $v = p/m$ in the atomic beam.

A spatial density modulation (a diffraction grating) thus exists in a neighborhood of the point $y = 2L$ with a width $l \sim (k\theta)^{-1}$. The modulation index is on the order of unity if the conditions $\xi_1\hbar k/p\theta \sim 1$ and $\xi_2 \sim 1$ hold for thermal velocities. If $\xi_1 \gg 1$, one could use atomic beams with a substantial angular divergence, $\theta \sim \xi_1\hbar k/p \gg 10^{-4}$; at $\theta \sim 10^{-3}$ we would need $\xi_1 \sim 10$. Similar gratings arise at larger distances which are multiples of L.

3. We turn now to some results for the case of a nearly exact resonance and an excited state with a long lifetime. After the field has acted in this case, both states are populated, and the wave function becomes a two-component wave function. In (1) we should replace J_n by the perturbation matrix calculated in Ref. 5, and we should take into account the dephasing of the atom-field system over the transit time between the waves. We find that the interference pattern is localized at distances

$$\frac{y-L}{L} = \frac{2s+1}{2r}, \tag{3}$$

where s and r are integers. Spatial harmonics of the level populations are localized at the same distances.[6] Even if quantum-mechanical scattering (the recoil effect) is taken into account, however, harmonics appear not only in the populations but also in the overall particle density. Taking y from (3), and assuming a beam with a uniform velocity, we find this density to be

$$\rho(x,y) = \rho(x)\left[1 + \sum_{n=0}^{\infty} (-1)^{n+s+r+1}\cos(2r(2n+1)kx)\rho_n\right],$$

$$\rho_n = \sin(\Delta L/v)J_{(2n+1)(2s+1)}(\xi_1)$$

$$\times J_{(2n+1)(2(s+r)+1)}(\xi_2 \sin((2n+1)(2s+1)\Delta_0 L/v)), \tag{4}$$

where $\rho(x)$ is the spatial distribution of atoms in the unperturbed beam, and $\xi_i = dE_i\tau/\hbar$. We see that at $y = 1.5L$ $(r = 1,\ s = 0)$, for example, the second, sixth, etc., harmonics would appear, while at $y = 1.25L$ $(r = 2,\ s = 0)$ we would find the fourth, twelfth, etc., harmonics.

4. An interference spatial atomic structure can be observed by arranging deposition on a plate at a distance $\sim L$ from the exciting fields, by scattering a probing wave by the grating, etc. The laser power level required for observing effects in beams of Na, Ca, etc., would be in the range 10^{-4}–1 W.

5. Atomic interferometry in the range of thermal de Broglie wavelengths $\sim 10^{-9}$ cm may become a new tool for a variety of precision experiments. This effect is also of interest for producing submicron structures.

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