Appl. Phys. B 36, 167–169 (1985)

Applied Physics B Photophysics and Laser Chemistry

Interference of Atom, and Atomic Spatial Lattices in Light Fields

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Received 20 September 1984/Accepted 2 October 1984

Abstract. A scheme is proposed to observe interference of atoms by using a weakly coherent atomic beam scattered at two standing light waves. It is shown that atoms can transfer spatial coherence over rather large distances.

PACS: 32; 42.50; 42.60

Diffraction effects that are due to wave properties of particles are observed during scattering at crystal lattices of solids, when the de Broglie wavelength of particles is comparable with the lattice period. Interference effects are more difficult to be observed, as this requires coherent beams of particles. Interference arising during the neutron scattering on a sequence of silicon slabs formed the foundation for neutron interferometry [1].

In the present work we examine, for the first time, the possibility of atom interferometry. We should note that atomic coherent beams may be produced in the scattering of a particle beam on a resonant standing wave (Kapitsa-Dirac resonant effect) [2]. It is, however, impracticable to observe interference during the scattering at one standing wave even with a highly coherent beam, as the wave is localized at very small distances from the light field. Here we examine the possibility of observing interference with the aid of a weakly coherent atomic beam (with thermal spread over longitudinal velocities, large aperture and high divergence $\theta \sim 10^{-3}$) scattered at two standing light fields (Fig. 1). Owing to processes of the echo type [3] the Doppler effect is eliminated and the interference pattern may be localized at great distances from the region of interaction of atoms with the field. Interference is manifested classically in the formation of a periodic structure in the spatial distribution of atoms. It should be noted that the elimination of the Doppler effect at the interaction with two standing waves results in a macroscopic polarization transfer [3, 4] and the appearance of a narrow resonance due to interference.

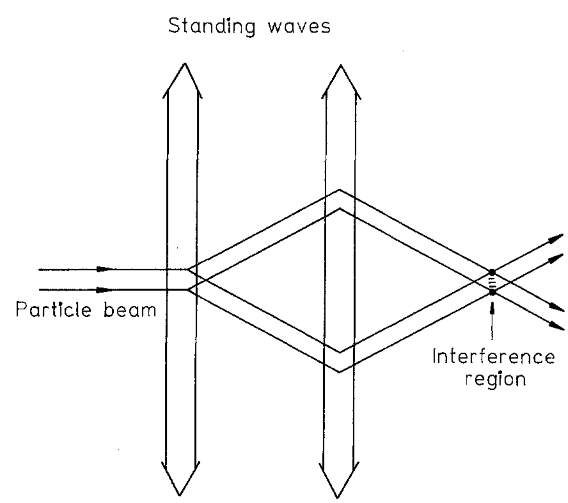

Fig. 1. Schematic of the atomic interferometer. For the sake of simplicity, the scattered beams after interaction are shown to not overlap

As calculations show, the structure of the interference pattern and the region of its localization depend on the nature of interaction of particles with the fields and on the lifetime of the excited states. Two qualitatively

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different cases are possible. Atoms with strong allowed transitions (e.g., Na) are virtually excited by the fields of a standing wave detuned from resonance by a great amount $\Delta \gg \gamma$, γ being the decay rate of an upper level. There is no real population of this level, and the spatial phase memory is transfered only through the ground state. The interference shows itself in the spatial density modulation. Atoms with weakly allowed transitions (e.g., Ca) interact with the field near exact resonance. Here a coherent mixture of states arises and is spatially transferred. The mixture may be controlled by a little change of the detuning Δ [3, 4]. This results in interference effects not only in the polarization of atoms [5] but also in the resulting density of particles.

Atoms with Short-Lived Excited State

Consider the interaction of a beam of resonant atoms with two standing light fields $E_{1,2}(y)\sin kx$, whose size a along the y axis is far less than the distance L between them. An incident atomic beam propagates along the y axis and is an incoherent mixture of flat waves with small transverse pulses ($p_x \ll p_y$). The interference of these atoms is best described when $\Delta\tau \gg 1$, where $\tau = a/v$ is the time of flight through the field. We shall assume that $\Delta \gg \gamma$.

An incident plane wave $\exp(\mathrm{i}\mathbf{pr}/\hbar)$, after the interaction with the first field placed near $y=0$, is converted into a superposition of plane waves [6]

$$\sum_n \mathrm{J}_n(\xi_1)\exp(\mathrm{i}\mathbf{p}_n\mathbf{r}/\hbar), \quad p_{nx} = p_x + 2n\hbar k, \qquad p_{ny} = p - p_{nx}^2/2p, \quad \xi_1 = \frac{(dE_1)^2}{2\hbar^2\Delta} \tag{1}$$

with pulses satisfying the law of conservation of energy: $p_n^2 = p^2$. Here $\mathrm{J}_n(\xi)$ is the Bessel function of the n^{th} order. In this expression the transferred transverse pulse is associated with induced transitions, and is divided by $2\hbar k$. Transitions with the odd number of pulses $\hbar k$ arise because of spontaneous emission and are of an incoherent nature, their contribution is small in the parameter γ/Δ. Further we are interested in atomic beams with a considerable angular divergence $\theta = p_x/p \gg \hbar k/p \sim 10^{-4}$ and a large aperture. Spatial modulation of the atomic density corresponding to the wave function (1) remains only at small distances $1/k\theta$, which is 10^{-2} cm for, $\theta \sim 10^{-3}$. However since the atoms are in the ground state with no irreversible spontaneous relaxation, the phase memory of the wave function (1) remains at large distances. This permits obtaining an interference pattern in the condition of echo.

Similarly to (1) one can calculate the influence of the second wave with parameter ξ_2 at $y = L$. Then, at the distance $y = 2L + l$ ($l \ll L$) the atom distribution density takes the form

$$1 + \sum_{n \neq 0} A_n(l)\mathrm{e}^{2\mathrm{i}nkx}.$$

The amplitude of the first harmonic is

$$A_1 = \langle \mathrm{J}_1(8\xi_1\Delta_0 l/v)\mathrm{J}_1^2(\xi_2)\exp(\mathrm{i}\varphi)\rangle, \qquad \varphi = 2klv_x/v, \tag{2}$$

where $\hbar\Delta_0 = (\hbar k)^2/2m$ is the recoil energy, m is the atomic mass, the angle brackets denotes averaging over the velocity distribution $\mathbf{v} = \mathbf{p}/m$ in an atomic beam. Note that the field parameters ξ_i also depend on velocity.

Thus the spatial density modulation (diffraction grating) exists in the vicinity of the $y = 2L$ point with width $l \sim 1/k\theta$. With exact fulfilment of the condition of echo ($l = 0$) the amplitude is $A_1 = 0$. The modulation depth is of the order of unity, if the relations $\xi_1\hbar k/p\theta \sim 1$ and $\xi_2 \sim 1$ are satisfied for thermal velocities. With a sufficiently strong effect of the first wave ($\xi_1 \gg 1$) one may use atomic beams with large angular divergence $\theta \sim \xi_1\hbar k/p \gg 10^{-4}$. With large values of the parameter ξ_1 ($\xi_1 > p_x/\hbar k$) the region of localization of the diffraction pattern decreases.

Similar gratings also arise at large distances divided by L.

Atoms with Long-Lived States

In this case of most interest small detunings from resonance arise, when atoms interfere, being in the superposition of the ground and excited states that is described by a two-component wave function.

With $\Delta\tau \ll 1$ the field effect on an atom is determined by the matrix [5]

$$\sum_n \exp(2\mathrm{i}nkx)\begin{pmatrix} \mathrm{J}_{2n}(\eta) & -\mathrm{J}_{2n+1}(\eta)\mathrm{e}^{\mathrm{i}kx} \\ -\mathrm{J}_{2n+1}(\eta)\mathrm{e}^{\mathrm{i}kx} & \mathrm{J}_{2n}(\eta) \end{pmatrix}, \tag{3}$$

where $\eta = dE\tau/\hbar$, and the lower and upper states are $\begin{pmatrix}0\\1\end{pmatrix}$ and $\begin{pmatrix}1\\0\end{pmatrix}$, respectively.

We shall assume that $\gamma L/v < 1$. Then the atoms in the ground state and also the excited atoms participate in the interference, which increases the number of interferences and that of the diffraction gratings. The atomic wave function in the entire space is obtained by using the matrix (3) for each field, the law of conservation of energy and by taking into account the dephasing of the atom-field system under free motion. As a result we can see that the interference pattern is localized at the distance y such that

$$\frac{y-L}{L} = \frac{2s+1}{2r}, \tag{4}$$

where s and r are integers. It is known [7] that spatial harmonics of level population are localized at the same distance. However, only with allowing for quantum scattering (recoil effect) the harmonics appear not only in the populations but also in the resulting density of particles. With y taken from (4) it is for a monovelocity beam

$$\varrho(x,y)=\varrho(x)\left\{1+\sum_{n=0}(-1)^{n+s+r+1}\cdot\cos[2r(2n+1)kx]\varrho_n\right\}, \quad (5)$$

$$\varrho_n=\sin(\Delta L/v)\mathrm{J}_{(2n+1)(2s+1)}(\eta_1)\cdot\mathrm{J}_{(2n+1)(2(s+r)+1)}[\eta_2\sin(2n+1)(2s+1)\Delta_0 L/v],$$

where $\varrho(x)$ is the spatial distribution of atoms in an unperturbed beam.

It is seen that, for example, with $y=1.5L$ ($r=1$, $s=0$) the 2nd, 6th (and so on) harmonics are localized. With $y=1.25L$ the 4th, 12th (and so on) harmonics appear.

Discussion

The examined effects may be observed in the fields of tunable lasers with intensity of 10^{-4} to 10^{-2} W for Na atoms and 10^{-3} to 1 W for Ca atoms. The angular divergence θ of an atomic beam can amount to 10^{-3} and more.

If coherence is transferred through the long-lived excited state, then, on the one hand, the length of the spatial coherence is limited by the free path length $L\sim v/\gamma$, which is about 10 cm for Ca. On the other hand, here the effects arise at the distances (4), the region of localization is determined by the angular divergence of the beam. At the same time, as can be seen from (5), in the maxima the harmonic amplitudes are independent of the angular distribution of atoms in the beam. Since there is no spontaneous relaxation in the ground state, the distances at which coherence can be transferred in a collision-free beam are not limited. The harmonics appear at high saturation due to the first wave field $\xi_1\gg 1$. Exactly in the point of echo $y=2L$, the amplitudes become zero, their magnitudes are usually sensitive to the angular distribution of the atoms.

The spatial interference of the atomic structure may be observed on a deposited plate placed at a distance $\sim L$ from the exciting fields, by scattering a probe wave on the lattice and so on. Atom interferometry in the wavelength region of about 10^{-9} cm may become a new instrument when carrying out various precise experiments. Achievement of coherent atomic beams makes it possible to develop atom holography. The phenomenon under examination may be of interest for obtaining submicron structure on a surface.

Acknowledgements. The authors thank E. V. Baklanov, I. M. Beterov and M. N. Skvortsov for valueable discussions.

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