Coherent backscattering of Bose-Einstein condensates in two-dimensional disorder potentials

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We study quantum transport of an interacting Bose-Einstein condensate in a two-dimensional disorder potential. In the limit of vanishing atom-atom interaction, a sharp cone in the angle-resolved density of the scattered matter wave is observed, arising from constructive interference between amplitudes propagating along reversed scattering paths. Weak interaction transforms this coherent backscattering peak into a pronounced dip, indicating destructive instead of constructive interference. We reproduce this result, obtained from the numerical integration of the Gross-Pitaevskii equation, by a diagrammatic theory of weak localization in presence of a nonlinearity.

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The past years have witnessed an increasing number of theoretical and experimental research activities on the behaviour of ultracold atoms in magnetic or optical disorder potentials.¹²³⁴⁵⁶⁷⁸⁹¹⁰¹¹¹²¹³¹⁴. A central aim in this context is the realization and unambiguous identification of strong Anderson localization with Bose-Einstein condensates, which was attempted by several experimental groups.¹²³ with recent success.¹⁴, and theoretically studied both from the perspective of the expansion process of the condensate¹³ as well as from the scattering perspective.⁷⁸. Complementary studies were focused on localization properties of Bogoliubov quasiparticles⁹¹⁰, on dipole oscillations in presence of disorder¹¹¹², as well as on the realization of Bose glass phases.¹³¹⁴

The above-mentioned topics mainly refer to processes that are essentially one-dimensional (1D) by nature. Qualitatively new phenomena, however, do arise in two or three spatial dimensions, due to the scenario of weak localization. The latter manifests in a slight reduction of the transmission probability of an incident wave through a disordered region as compared to the classically expected value, due to constructive interference between backscattered paths and their time-reversed counterparts. This interference phenomenon particularly leads to a cone-shaped enhancement of the backscattering current in the direction reverse to the incident beam, which was indeed observed¹⁵ and theoretically analyzed¹⁰ in light scattering processes from disordered media. Related weak localization effects also arise in electronic mesoscopic physics, leading to characteristic peaks in the magneto-resistance.¹⁷¹⁸.

In this Letter, we investigate the phenomenon of coherent backscattering with atomic Bose-Einstein condensates that propagate in presence of two-dimensional (2D) disorder potentials. An essential ingredient that comes into play here is the interaction between the atoms of the condensate. On the mean-field level, this is accounted for by the nonlinear term in the Gross-Pitaevskii equation describing the time evolution of the condensate wavefunction. Indeed, nonlinearities do also appear in scattering processes of light e.g. from a gas of cold atoms, due to the saturation of the intra-atomic transition.¹⁹²⁰²¹. In this case, however, the saturation also leads to inelastic scattering²⁰²¹ and, in addition, the nonlinearity competes with other dephasing mechanisms induced, e.g., by polarization phenomena²² or thermal motion²³. The complementary process of atomic condensates scattering from optical random potentials in the mean-field regime provides a cleaner situation where the coherence of the atomic wavefunction remains well preserved in the presence of the nonlinearity. As we shall argue below, this leads to substantial modifications of the coherent backscattering feature. In particular, the interaction turns constructive into destructive interference, leading to a negative coherent backscattering peak height. This is reminiscent of the weak antilocalization effects due to spin-orbit interaction observed for mesoscopic magneto-transport²⁴.

The starting point of our investigation is the time-dependent 2D Gross-Pitaevskii equation describing the mean-field dynamics of the condensate in presence of the disorder potential V(⃗r) [⃗r ≡ (x, y)],

\[ i\hbar \frac{\partial}{\partial t} \psi(\vec{r}, t) = \left( -\frac{\hbar^2}{2m} \Delta + V(\vec{r}) + \tilde{g}(x) |\psi(\vec{r}, t)|^2 \right) \psi(\vec{r}, t) + S(t) \delta(x - x_0) \exp(-i\mu t / \hbar), \]

where \(S(t)\) denotes a source term simulating the coherent injection of matter waves with chemical potential \(\mu\) from an external reservoir onto the scattering region.⁷ In the numerical integration of Eq. (1), \(S(t)\) is adiabatically increased from zero to a final value \(S_f\) that corresponds to a fixed incident current density \(j_{in}\). Periodic boundary conditions are imposed on the transverse boundaries (in \(y\) direction) of the numerical grid to ensure a homogeneous flow in absence of disorder, whereas absorbing boundary conditions applied at the edges of the longitudinal (\(x\)
direction allow us to inhibit artificial backreflection of outgoing waves with rather high accuracy [24].

In Eq. (1), the effective 2D interaction strength is written as $\tilde{g}(x) \equiv \hbar^2 g(x)/(2m)$, with the dimensionless nonlinearity parameter $g(x)$. In presence of a harmonic confinement of the condensate in the third spatial dimension with the oscillator length $a_\perp(x) \equiv \sqrt{\hbar/(m\omega_\perp(x))}$, we have $g(x) = 4\sqrt{2\pi a_\perp(x)}$, where $a_\perp$ denotes the $s$-wave scattering length of the atoms. We assume that $g(x)$ is adiabatically ramped on and off in front of and behind the disorder region, as shown in Fig. 1. Physically, this spatial variation of the nonlinearity, which is needed in order to avoid nonlinear effects at the position of the source and the absorbing boundaries, would correspond to a finite extent of the transverse harmonic confinement into which the condensate is propagating.

As for the disorder potential $V(\vec{r})$, we choose a Gaussian random process characterized by a vanishing mean value $\langle V(\vec{r}) \rangle = 0$ and a Gaussian correlation function $\langle V(\vec{r})V(\vec{r} + \Delta \vec{r}) \rangle = V_0^2 e^{-\Delta r^2/2\sigma^2}$ with correlation length $\sigma$. We focus in the following on the parameters $k\sigma = 0.5$, with $\sigma = \sqrt{2m\mu/\hbar}$ the wavenumber of the incident beam, and $V_0/\mu = 0.614$. The incident current density reads $j_{in} = \hbar k|\psi_0|^2/m$, where we set $\psi_0 = k$ for the amplitude of the incident wave [23].

At the above values for $\sigma$ and $V_0$, scattering in the disorder region is approximately isotropic. This is quantitatively expressed by the equivalence of the two relevant length scales that the disorder averages introduces for the transport process of the condensate: the scattering mean free path $\ell_s$, which describes the average decay of the incident coherent mode inside the disorder region according to $|\langle \psi(\vec{r}) \rangle|^2 \propto \exp(-x/\ell_s)$, and the transport mean free path $\ell_{tr}$, which characterizes the decay of the average density $|\langle \psi(\vec{r}) \rangle|^2$ (see Fig. 1). In absence of the nonlinearity, the scattering mean free path is in leading order in $V_0$ given by the Born approximation

$$(k\ell_s)^{-1} \simeq (\pi/2)(V_0/\mu)^2(k\sigma)^2 I_0(k^2\sigma^2) \exp(-k^2\sigma^2) \quad (2)$$

where $I_j(\xi)$ is the modified Bessel function of order $j$.

The transport mean free path can be extracted from the linear decrease of $|\langle \psi(\vec{r}) \rangle|^2$ with $x$ according to $|\langle \psi(\vec{r}) \rangle|^2 \propto (L + z_0\ell_{tr} - x)$, with $z_0 = 0.82$ in two spatial dimensions, and $L$ the longitudinal extent of the disorder region. In lowest order in $V_0$, $\ell_{tr}$ is given by the Boltzmann transport mean free path $\ell_B$ defined through

$$\frac{\ell_s}{\ell_B} = 1 - I_1(k^2\sigma^2)/I_0(k^2\sigma^2). \quad (3)$$

Weak localization effects lead to logarithmic corrections that yield for $k\ell_B \gg 1$ [27, 28]

$$\ell_{tr} \simeq \ell_B[1 - 2(k\ell_B)^{-1} \log(L/\ell_B)]. \quad (4)$$

As shown in Fig. 2, the expressions (2) and (3) are in good agreement with the numerically computed values of $\ell_s$ and $\ell_{tr}$ for $V_0 < \mu$. Specifically at $k\sigma = 0.5$ and $V_0/\mu = 0.614$, we find $k\ell_s \approx 9.61$ and $k\ell_{tr} \approx 9.75$.

The angle-resolved current in backward direction is numerically computed from the decomposition of the reflected wave $\psi_{ref}(x, y) \equiv \psi(x, y) - \psi_0\exp(ikx)$ at fixed position $x$ close to $x_0$ where $g(x)$ is negligibly small] into the transverse eigenmodes $\psi_n(y) \sim \exp(in\pi y/W)$, which support outgoing waves into the directions with the angles $\theta_n \equiv \text{arcsin}[2\pi n/(kW)]$. Figure 3 shows the average angular density $j(\theta)$ of the backscattered current, which is normalized such that $\int_0^{2\pi} j(\theta)d\theta = 2\pi$. In the linear
By linear transport theory. From the average density, the average density $V$ diverging from the disorder potential $g$ is negligible compared to scattering from the fluctuations $\tilde{\ell} \equiv k\ell_a$ of a classical random walk. This assumption is valid approach for weak localization in presence of a nonlinearity region in front of the disorder potential, $g > 0$. Negative cone heights $j_C(0) < 0$ leading to a dip in the angle-resolved current density $j(\theta)$ appear for $g > 0.01$.

In a second step, the coherent backscattering peak is calculated by means of crossed (Cooperon) diagrams, describing interference between reversed scattering paths. Following the diagrammatic approach presented in Ref. [30], we obtain the height of the coherent backscattering peak from the transport equations

$$C_c(x) = \langle |\psi_0|^2 e^{-ix/\ell} \rangle \left( 1 + \frac{i}{k} \int_{x_0}^L dx' g(x') C_1(x') \right),$$

$$C_1(x) = \int_0^L \frac{dx'}{\pi \ell} \left[ K_0 \left( \frac{\tilde{x} - x'}{\ell} \right) \left( C_1(x') + C_c(x') \right) + \frac{i}{k} K_1 \left( \frac{\tilde{x} - x'}{\ell} \right) \langle |\psi(x')|^2 \rangle \times \right. 
\left. \times \int_{\min(x,x')}^{\max(x,x')} dx'' g(x'') \left( C_1(x'') + C_c(x'') \right) \right].$$

for the “Cooperon intensity” $C_1(x)$ and the “coherent Cooperon intensity” $C_c(x)$, with $\tilde{x} \equiv \max(x,0)$ and $K_{0,1}$ the modified Bessel functions of the second kind. The contribution to the flux scattered in backward direction then results as

$$j_C(0) = \text{Re} \int_0^L dx \frac{dx' |\psi_0|^2}{\ell |\psi_0|^2} e^{-x/\ell} \left( C_1(x) + \frac{i}{k} \langle |\psi(x')|^2 \rangle \int_x^{x_0} dx' g(x') C_1(x') \right).$$

Note that nonlinear processes also occur for $x_0 < x < 0$ where $V(x) = 0$ but $g(x) > 0$ (see Fig. 1). Hence, the cone height $j_C(0)$ — in contrast to the background intensity $j_L(0)$ — explicitly depends on the spatial extent of the nonlinearity region in front of the disorder potential, and can therefore be tuned through the ramp-up of $g(x)$.

In the absence of nonlinearity, the above equations reduce to linear transport theory in a two-dimensional slab, yielding $C_1(x)|_{g=0} = \langle |\psi(x')|^2 \rangle - |\psi_0|^2 \exp(-x/\ell)$. We...
then obtain $j_C(0)|_{\theta=0} = j_L(0) - 1/2$, which expresses reciprocity symmetry, i.e. the equality of reversed path amplitudes (the term 1/2 describes single scattering). For $g \neq 0$, however, the nonlinearity turns $C_1(x)$ into a complex quantity, as evident from the terms proportional to $\eta$ in Eqs. (5-7). This indicates an effective phase difference between the reversed scattering paths. Consequently, the backscattered current $j_C(0)$ is expected to decrease with increasing nonlinearity, and may even become negative if this phase difference is sufficiently large.

This latter situation is indeed encountered if the set of equations (5-7) is numerically solved for the system parameters under consideration. As shown in Fig. 4, the total flux $j_L(0) + j_C(0)$ resulting from Eqs. (5-7) (solid line) agrees rather well with the average value for $j(0)$ obtained from the numerical simulation (symbols). Discrepancies are attributed to weak localization corrections in the background intensity, which would specifically lead to a reduction of the backscattered flux at $g = 0$, and to an additional contribution to the Cooperon intensity, termed $C_2(x)$ in Ref. [30], which was neglected in the derivation of the above transport equations. Details on these additional ingredients will be presented elsewhere.

At larger nonlinearities, $g \gtrsim 0.3$, the numerical propagation of the inhomogeneous Gross-Pitaevskii equation [1] does not converge to a stationary scattering state, but leads to a permanently time-dependent behaviour of $\psi(\vec{r}, t)$, as predicted in Refs. [29] and encountered also in the transport of condensates through 1D disorder potentials [7]. In this regime, the average backscattered current again displays a peak around $\theta = 0$; this peak is, however, comparatively broad and does not arise from a coherent backscattering phenomenon. This becomes obvious if we inject the incident wave with a finite angle $\theta_0 \approx 0.32$ (corresponding to the transverse eigenmode $\chi_0$) onto the disorder region. While the cone and dip structures at $g = 0$ and 0.02 appear, as shown in the inset of Fig. 3, at the expected angle of coherent backscattering, corresponding to retro-reflection of the incident beam, the broad peak at $g = 0.06$ is not affected in this way.

In conclusion, the presence of a small nonlinearity reverts the scenario of weak localization and gives rise to a cone-shaped dip, instead of a peak, in the angle-resolved backscattered current density. This phenomenon appears to be rather robust; it is numerically encountered also for disorder potentials with longer correlation lengths $\sigma$ giving rise to anisotropic scattering, and we expect its manifestation also in three spatial dimensions (as predicted by the diagrammatic theory) as well as for speckle disorder where diagrammatic approaches would have to be based on the treatment of Ref. [28]. We therefore believe that the effect would be measurable, for a reasonably large range of parameters, in state-of-the-art transport experiments with coherent Bose-Einstein condensates in well-controlled disorder potentials.

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[26] A different choice of $\psi_0$ would amount to rescaling $g$.