Re-shaping Bose-Einstein condensates with complex light for atomic persistent currents and trapping

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ABSTRACT

We numerically model the propagation of far-detuned optical beams through a Bose-Einstein condensate (BEC) using coupled nonlinear Schrödinger and Gross-Pitaevskii equations. For red atom-field detuning, we show that light carrying orbital angular momentum (OAM) can lead to coupled light-atom solitons carrying angular momentum. We demonstrate the formation of azimuthally rotating wavepackets, toward an atomic persistent current without trapping requirements. For blue atom-field detuning, we show highly exotic BEC distributions, with the atoms trapped in dark regions of the optical field. Our results provide a novel means of atomic transport and of sculpting a BEC into unique transverse distributions.

Keywords: Angular momentum of light, Atom optics, Optomechanics, Bose-Einstein condensates, Solitons

1. INTRODUCTION

The reliable manipulation of ultracold atoms has many possible applications, including in the field of atomtronics, where atoms are guided as an analogue of an electric current,[1,2] and in atomic transport, where ultracold atoms are used to probe quantum mechanical properties.[3] Generally such approaches use static magnetic or optical trapping fields to control the behaviour of the atoms.

Recently, we outlined an alternative approach to atomic manipulation. We reported that a co-propagating, far-red-detuned optical field that carries OAM[4] may re-shape a BEC into coupled atom-light solitons that carry angular momentum,[5] a realisation of the BEC's ability to behave as an effective Kerr superfluid[6] as observed previously in a number of other media.[7–9] Here, we extend this work, exploring both the rotational characteristics of the atomic medium under such a setup, and also, under far-blue-detuned conditions, the ability of the system to transport and trap atoms within dark optical field regions.

2. THEORY

We consider co-propagating far-detuned ultracold atomic and optical beams, with the optical field structured in both intensity and phase. We numerically model the propagation along ζ of both atomic (ψ) and optical (F) fields by employing coupled nonlinear Gross-Pitaevskii and Schrödinger equations, respectively, given by[5,10]

$$\partial_\zeta \psi = i\nabla_\perp^2 \psi - i\left(s|F|^2 + \beta_{col}|\psi|^2 - iL_3|\psi|^4\right)\psi, \tag{1}$$

$$\partial_\zeta F = i\nabla_\perp^2 F + i\left(\frac{-s|\psi|^2}{1+\sigma_{sat}|F|^2}\right)F. \tag{2}$$

In Eqn. (1), there are terms representing the atomic kinetic energy ($\nabla_\perp^2$), interatomic scattering (β_{col}), and three-body loss (L_3). In Eqn. (2), there are terms corresponding to diffraction ($\nabla_\perp^2$), and saturation (σ_{sat}). The two fields are dipole coupled through the parameter s, which represents the sign of the atom-light far detuning. If s is positive (negative), this represents blue (red) detuning, and the atoms may be described as dark (light) seeking. The transverse and longitudinal dimensions are scaled according to $(\xi,\eta) = \sqrt{2}(x,y)/w_F$ and $\zeta = z/(2z_R)$, respectively, where $z_R = \pi w_F^2/\lambda$ is the Rayleigh range of the optical field of beam waist w_F.

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3. LIGHT-SEEKING ATOMS

We start by considering light-seeking atoms ($s = -1$), as in Ref. 5, where we demonstrated the formation of coupled atom-light solitons arising from mutual ring fragmentation. Here, we use the probability flux to quantify the azimuthal velocity of the atoms before soliton formation, allowing us to explore if such a scheme would be suitable for use as an atomtronic superconducting quantum interference device (SQUID).[1,2]

We consider a weakly repulsive BEC with $\beta_{col} = 3.5$ and an initially Thomas-Fermi distribution. If the input light takes the form of a Laguerre-Gaussian (LG) mode with OAM m, the atoms move to the ring of maximum optical intensity, before this ring mutually fragments in both fields, forming $2|m|$ coupled atom-light solitons. The solitons are subsequently tangentially ejected, thereby conserving angular momentum. In Fig. 1, we show in 3D the BEC's optically induced reshaping during propagation from $\zeta = 0$ to $1.5z_R$ (here $z_R \approx 0.44$mm) for an optical beam with $m = 1$.

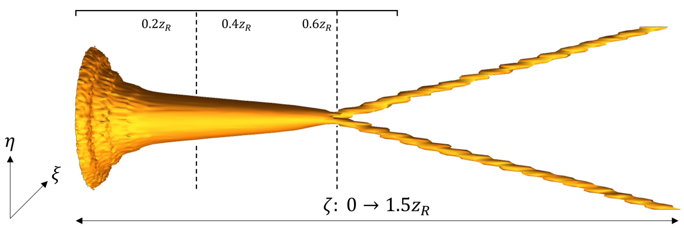

Figure 1. Transverse (ξ, η) re-shaping of a BEC between $\zeta : 0 \to 1.5z_R$ (left to right) by an optical LG mode with $m = 1$. Parameters as Ref. 5. Upper square bracket corresponds to ζ-domain of Fig. 2, with dashed lines highlighting the start and end of atomic flux growth.

After the atoms have moved onto the optical field, we find that the BEC follows the dynamics of the light. To demonstrate that both fields rotate azimuthally due to the OAM, we calculate the flux of probability, a quantity that defines the amount of flow present in a quantum mechanical field:[11]

$$j(s, \zeta) = \frac{\hbar}{2m_\Phi i} \left(\Phi^* \partial_s \Phi - \Phi \partial_s \Phi^*\right). \tag{3}$$

Here s is the circumference of the ring of maximum intensity, Φ is the complex field around this circumference, and $m_\Phi = |\Phi|^2$ is the total field density along s. In Fig. 2, we track the evolution of the average value of the probability flux for both the atomic (blue) and optical (black) fields during propagation within the region of Fig. 1 indicated by the upper square bracket.

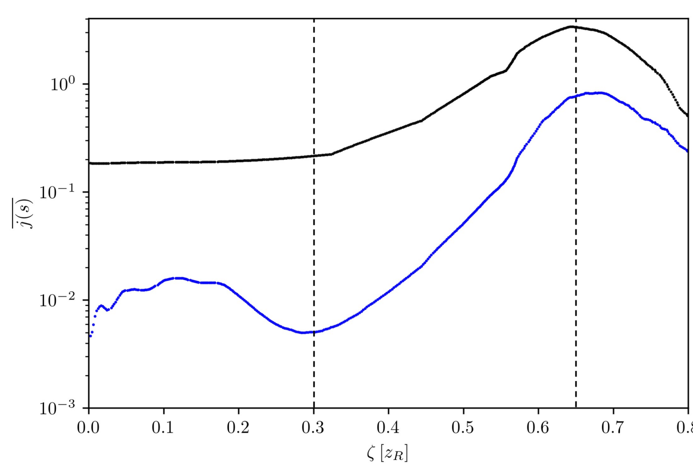

Figure 2. Average flux of probability $j(s, \zeta)$ around coupled atomic (blue, lower) and optical (black, upper) ring during propagation between $\zeta : 0 \to 0.8z_R$, indicated by the square bracket in Fig. 1. Dotted lines correspond to start and end of atomic flux growth.

The optical field, which rotates with OAM, begins with a far greater flux than the atomic field, which has flux at the noise level. However, following its channelling into a ring, it too begins to rotate, and the value of its probability flux dramatically increases. This growth begins shortly after a ring of maximum intensity forms in the atomic field, around $\zeta = 0.3z_R$, as indicated on Figs. 1-2. The increase of flux in both fields is reflective of the continual narrowing of the ring size, which leads to an increased rotation speed as expected from the $\omega = 2m/R^2$ dependence outlined in Ref. 12.

By $\zeta = 0.65z_R$, indicated in the second dotted line on Figs. 1-2, fragmentation begins in both fields. This causes the dynamics to be less confined to an effective 1D ring, and therefore the flux measurements become less representative of the 2D dynamics. The clear development of atomic flux around the ring of maximum intensity before fragmentation indicates that the co-propagating optical field causes the BEC to rotate azimuthally. By tuning the parameters, or optimising the optical field, we expect that it may be possible to find a region where the fragmentation is delayed, or even avoided altogether, providing an alternative method of realising atomic currents for atomtronic SQUID devices.[1,2] Such a method has the advantage of not requiring trapping potentials, and by using a spatial light modulator would be easily reconfigurable, adjusting the selected LG mode profile to realise atomic currents of many rotation rates, directions, and transverse sizes.

4. DARK-SEEKING ATOMS

If we instead consider far-*blue* atom-field detuning ($s = 1$) the atoms now seek dark optical field regions and we obtain markedly different dynamics. As discussed by Franke-Arnold et al.,[13] atoms trapped in darkness are less subject to optically induced heating than in bright regions.

For the setup of Figs. 1-2 a large proportion of the dark-seeking atoms become confined within the central phase singularity of the optical LG mode. However, if the transverse complexity of the initial optical field is increased through the scalar superposition of two LG modes, then the resulting optical field will gain additional off-axis points of singularity (darkness) which are also capable of trapping ultracold atoms. This allows us to obtain any number of atomic clusters simply by refining the optical mode superposition, a means of reliably creating tailored atomic distributions.

To demonstrate this, we consider now a superposition of two LG modes with OAMs of $m = 2$ and $m = 8$. If the beam waists of the two modes are similar, then the overlapping rings will produce six additional off-axis optical vortices, as shown in the bottom left corner of Fig. 3. When the amplitude of the initial optical field is sufficiently high that the dipole force felt by the atoms from the light is the dominant effect, we find that atoms become trapped in all seven optical vortices. Once trapped in their clusters, the atoms again rotate around a central fixed point, this time being 'pushed' by the optical field surrounding each cluster.

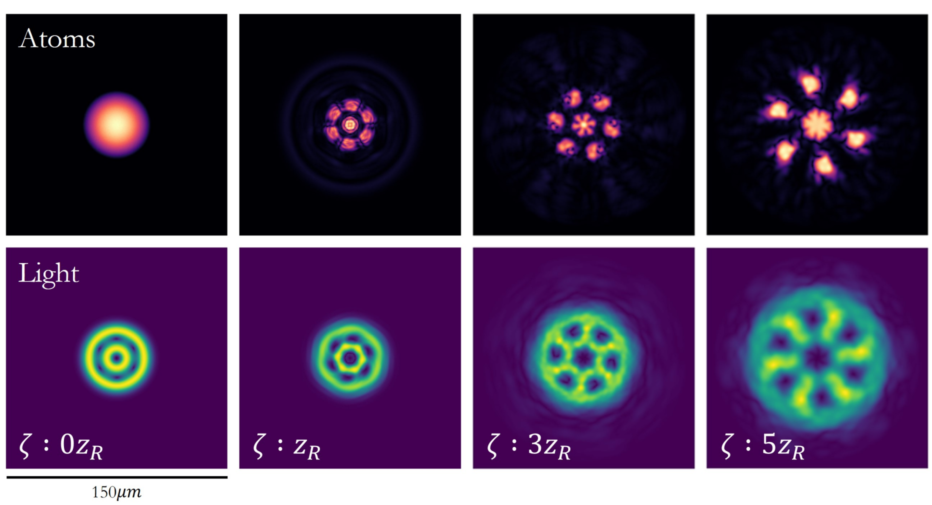

Figure 3. Optically induced re-shaping of a BEC by an optical LG mode superposition with $m = 2, 8$, under blue atom-field detuning, between $\zeta : 0 \rightarrow 5z_R$. Upper (lower) row shows atomic (optical) transverse distributions at marked z_R values.

The mechanism outlined in Fig. 3 provides a powerful realisation of atomic transport to dark regions, with the trapped atoms less subject to coincident optical heating.[13] As mentioned, the approach outlined here provides a straightforward method of designing complex atom-light configurations: simply by altering the OAM indices of each optical mode, and therefore the number of phase singularities within the initial optical field, one may readily realise a range of cluster atomic field configurations.

5. CONCLUSIONS

We have used coupled nonlinear Schrödinger and Gross-Pitaevskii equations to describe co-propagating ultracold atomic and optical fields. With structured optical fields, we outlined two applications of the system depending on the atom-field detuning: for bright-seeking atoms, the realisation of a uniformly rotating atomic persistent current, with analogues to atomtronics;[1,2] and for dark-seeking atoms, the thermal-free trapping of any number of atomic clusters in a tailored transverse form, with analogues to atomic trapping and transport for the probing of fundamental quantum mechanical properties.[3,13]

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