A Bose-Einstein Condensate in a Uniform Light-induced Vector Potential

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We use a two-photon dressing field to create an effective vector gauge potential for Bose-condensed $^{87}$Rb atoms in the $F = 1$ hyperfine ground state. The dressed states in this Raman field are spin and momentum superpositions, and we adiabatically load the atoms into the lowest energy dressed state. The effective Hamiltonian of these neutral atoms is like that of charged particles in a uniform magnetic vector potential, whose magnitude is set by the strength and detuning of Raman coupling. The spin and momentum decomposition of the dressed states reveals the strength of the effective vector potential, and our measurements agree quantitatively with a simple single-particle model. While the uniform effective vector potential described here corresponds to zero magnetic field, our measurements agree quantitatively with a simple single-particle model. Therefore, this approach is limited to modest effective fields, too small for FQHE physics [5, 6].

Most recent proposals to create significantly larger effective magnetic fields without rotation [7, 8, 9, 10, 11] involve optical coupling between internal (spin) states and differing in linear momentum. The effective magnetic field in such a system with neutral atoms requires an effective vector potential, and our measurements agree with a simple single-particle model. We define $E_r = h^2 k_r^2 / 2m$ as the recoil energy. The family of three states coupled by the Raman field, $\Psi(\tilde{k}_x) = \{ -1, \tilde{k}_x + 2k_r, \tilde{k}_x, 1, \tilde{k}_x - 2k_r \}$, are labeled by the quasi-momentum, $\tilde{k}_x$. The Raman beams have frequencies of $\omega_L$ and ($\omega_L + \Delta \omega_L$) ($\Delta \omega_L > 0$), and a bias field $B_0 y$ produces a Zeeman shift $\hbar \omega_Z = g_J B_0 \approx h \omega_L$ (see Fig. 1b). Since the momentum transfer is only along $\hat{x}$, the single-particle Hamiltonian can be written as $\mathcal{H} = \mathcal{H}_1(k_x) + \hbar^2 (k_y^2 + k_z^2) / 2m + V(\vec{r}) \otimes 1$, where $\mathcal{H}_1$ is the Hamiltonian for the Raman coupling, the Zeeman energies and the motion along $\hat{x}$, and 1 is the $3 \times 3$ unit matrix acting on the spin space. $V(\vec{r})$ is the state-independent trapping potential (arising from a far-off-resonance dipole trap and the scalar light shift of the Raman beams), and $m$ is the atomic mass. In the rotating wave approximation for the frame rotating at $\Delta \omega_L$, $\mathcal{H}_1 / h$ expressed in the state basis of the family $\Psi(\tilde{k}_x)$ is

\[
\begin{pmatrix}
\frac{h^2}{2m} (\tilde{k}_x + 2k_r)^2 - \delta & \frac{h \Omega_R}{2} & 0 \\
\frac{h \Omega_R}{2} & \frac{h^2 \tilde{k}_x^2 - \epsilon}{2m} & \frac{h \Omega_R}{2} \\
0 & \frac{h \Omega_R}{2} & \frac{h^2}{2m} (\tilde{k}_x - 2k_r)^2 + \delta
\end{pmatrix}
\]

Here $\delta = (\Delta \omega_L - \omega_Z)$ is the detuning from Raman resonance, $\Omega_R$ is the resonant Raman Rabi frequency, and $\epsilon$ accounts for a small quadratic Zeeman shift (Fig. 1b). For each $\tilde{k}_x$, diagonalizing $\mathcal{H}_1$ gives three energy eigenvalues $E_j(\tilde{k}_x)$ ($j = 1, 2, 3$). For dressed atoms in state $j$, ultracold atoms are an appealing system for the study of many-body correlated states relevant to condensed matter physics. These widely tunable systems in nearly disorder-free potentials have already realized one-dimensional Tonks-Girardeau gases [1], and the superfluid to Mott-insulator transition of a Bose-Einstein condensate (BEC) in an optical lattice [2]. The implementation of these simple iconic condensed matter systems paves the way for more interesting systems with exotic correlations and excitations, as in the fractional quantum Hall effect (FQHE) of a two-dimensional electron system in a strong magnetic field [3]. Simulating such a system with neutral atoms requires an effective Lorentz force, which is associated with a vector gauge potential. Current experimental approaches involve rotation of trapped BECs [4, 5], where low field effects, such as the formation of an Abrikosov vortex lattice, have been observed. For technical reasons, this approach is limited to modest effective fields, too small for FQHE physics [3, 5]. Most recent proposals to create significantly larger effective magnetic fields without rotation [7, 8, 9, 10, 11] involve optical coupling between internal atomic states, where the atoms are dressed in a spatially dependent manner. The effective magnetic field in such light-induced gauge potentials can be understood as a consequence of changing into a spatially varying basis of internal states. This is similar to the effective magnetic field in a rotating BEC arising from changing into the frame rotating with the BEC.

Here we report a first step toward using light-induced vector potentials to simulate magnetic fields. By dressing a BEC with two counter-propagating Raman laser beams, we realize a spatially uniform vector gauge potential. The Raman beams couple internal (spin) states with linear momenta differing by twice the photon momentum. This gives rise to a spatial gradient (along the Raman beam direction) of the phase difference between spin components of the dressed state. As we will show, this spatially varying state leads to a non-zero vector potential when the coupling is detuned from Raman resonance. We adiabatically load the BEC into the dressed state, and measure properties of the dressed-state dispersion relation by probing its spin and momentum decomposition. Although the atoms are stationary in the lab frame (having zero group velocity), the momenta of the individual spin components composing the dressed state show a non-zero phase velocity which depends on the strength and detuning of the Raman coupling. Our measurements agree with a simple single-particle model, and demonstrate the presence of an effective vector potential.

We dress a $^{87}$Rb BEC in the $F=1$ ground state with two Raman laser beams counter-propagating along $\hat{x}$. Together these beams couple states $|m_F, k_x\rangle$ differing in internal angular momentum by $\hbar (\Delta m_F = \pm 1)$, and differing in linear momentum $k_x$ by $2k_r$. Here, $k_r = 2\pi / \lambda$ is the single-photon recoil momentum, and $\lambda$ is the wavelength of the Raman beams. We define $E_r = h^2 k_r^2 / 2m$ as the recoil energy. The family of three states coupled by the Raman field, $\Psi(\tilde{k}_x) = \{ -1, \tilde{k}_x + 2k_r, \tilde{k}_x, 1, \tilde{k}_x - 2k_r \}$, are labeled by the quasi-momentum, $\tilde{k}_x$. The Raman beams have frequencies of $\omega_L$ and ($\omega_L + \Delta \omega_L$) ($\Delta \omega_L > 0$), and a bias field $B_0 y$ produces a Zeeman shift $\hbar \omega_Z = g_J B_0 \approx h \omega_L$ (see Fig. 1b). Since the momentum transfer is only along $\hat{x}$, the single-particle Hamiltonian can be written as $\mathcal{H} = \mathcal{H}_1(k_x) + \hbar^2 (k_y^2 + k_z^2) / 2m + V(\vec{r}) \otimes 1$, where $\mathcal{H}_1$ is the Hamiltonian for the Raman coupling, the Zeeman energies and the motion along $\hat{x}$, and 1 is the $3 \times 3$ unit matrix acting on the spin space. $V(\vec{r})$ is the state-independent trapping potential (arising from a far-off-resonance dipole trap and the scalar light shift of the Raman beams), and $m$ is the atomic mass. In the rotating wave approximation for the frame rotating at $\Delta \omega_L$, $\mathcal{H}_1 / h$ expressed in the state basis of the family $\Psi(\tilde{k}_x)$ is

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Here $\delta = (\Delta \omega_L - \omega_Z)$ is the detuning from Raman resonance, $\Omega_R$ is the resonant Raman Rabi frequency, and $\epsilon$ accounts for a small quadratic Zeeman shift (Fig. 1b). For each $\tilde{k}_x$, diagonalizing $\mathcal{H}_1$ gives three energy eigenvalues $E_j(\tilde{k}_x)$ ($j = 1, 2, 3$). For dressed atoms in state $j$,
$E_j(\tilde{k}_x)$ is the effective dispersion relation, which depends on experimental parameters, $\delta$, $\Omega_R$, and $\epsilon$ (left panels of Fig. 2). For example, the number of energy minima (from one to three) and their positions, $\tilde{k}_{\text{min}}$, are experimentally tunable. Around each $\tilde{k}_{\text{min}}$, the dispersion can be expanded as $E(\tilde{k}_x) \approx \hbar^2 (\tilde{k}_x - \tilde{k}_{\text{min}})^2/2m^*$, where $m^*$ is an effective mass. In this expansion, we identify $\tilde{k}_{\text{min}}$ with the light-induced vector gauge potential, in analogy to the Hamiltonian for a particle of charge $\tilde{q}$ in the usual magnetic vector potential $\vec{A}$: $(\tilde{y} - \tilde{q} \vec{A})^2/2m$. In our experiment, we load a trapped BEC into the lowest energy $j = 1$ dressed state, and measure its quasi-momentum, equal to $\tilde{k}_{\text{min}}$ for adiabatic loading.

Our experiment starts with a 3D $^{87}$Rb BEC in a combined magnetic-quadrupole plus optical trap, as described in Ref. [12]. We transfer the atoms to an all-optical crossed dipole trap, formed by a pair of 1550 nm beams, by ramping the quadrupole field gradient to zero. The trapping beams are aligned along $\hat{x} - \hat{y}$ (horizontal beam) and at $\sim 10^\circ$ from $\hat{z}$ (vertical beam). A uniform bias field along $\hat{y}$ gives a linear Zeeman shift $\omega_{\hat{z}}/2\pi \simeq 3.25$ MHz and a quadratic shift $\epsilon/2\pi = 1.55$ kHz. The optically-trapped condensate typically has $N = 2.5 \times 10^5$ atoms in $|m_F = -1, \tilde{k}_x = 0\rangle$, with measured trap frequencies of $\sim 30$ Hz parallel to, and $\sim 95$ Hz perpendicular to, the horizontal beam.

In order to Raman-couple states differing in $m_F$ by $\pm 1$, the $\lambda = 804.3$ nm Raman beams are linearly polarized along $\hat{y}$ and $\hat{z}$, corresponding to $\pi$ and $\sigma$ relative to the quantization axis $\hat{y}$. The beams have $1/e^2$ radii of 180(20) $\mu$m, much larger than the 20 $\mu$m BEC. These beams give a total scalar light shift up to $60E_r$, where $E_r = \hbar \times 3.55$ kHz, and contribute an additional harmonic potential with frequency up to 50 Hz along $\hat{y}$ and $\hat{z}$. The differential light shift between adjacent $m_F$
states arising from the combination of misalignment and imperfect polarization is estimated to be smaller than 0.2E_r. We determine Ω_R by observing population oscillations driven by the Raman beams and fitting to the expected behavior, as shown in Fig. 1.

We developed a procedure to adiabatically load the |−1, k_x = 0⟩ BEC into the lowest energy, j = 1, Raman-dressed state. For a BEC initially in |0, k_x = 0⟩, this could be achieved simply by slowly turning on the Raman beams at detuning δ = 0, resulting in the j = 1, k_x = 0 dressed state, located at the minimum of E_j=1(k_x). However, our initial state |−1, k_x = 0⟩, for which k_x = k_x + 2k_r, is a member of the family of states Ψ( ˜k_x = −2k_r). This simple loading procedure would therefore result in the j = 1, ˜k_x = −2k_r, dressed state. In order to transfer our ˜k_x = −2k_r BEC to the desired k_x = 0 dressed state, we use an additional rf coupling which mixes families of states with ˜k_x differing by 2k_r. The rf frequency is always equal to the frequency difference between two Raman beams, Δω_L/2π = 3.250 MHz. The loading sequence is as follows: (i) We turn on the rf coupling in 1 ms to a resonant Rabi frequency Ω_r/2π = 12 kHz, with an initial detuning hδ = 15E_r. We then sweep the detuning to resonance in 9 ms (δ is varied by ramping the bias field B_0, leaving Δω_L constant.), loading the atoms into the lowest energy rf-dressed state, a spin superposition still at k_x = 0. (ii) We ramp on the Raman coupling in t_on = 20 ms to a variable Rabi frequency Ω_R, and then turn off the rf in 2 ms. This loads the BEC into the j = 1, ˜k_x = 0 dressed state. In the dressed state, the BEC heats at ~0.3 nK/ms, we believe due to technical noise in B_0 or Δω_L. In addition, we observe unwanted population in the j = 2 dressed state.

Therefore, as part of step (ii), we further evaporatively cool by decreasing the intensity of the horizontal trapping beam by 20% in 20 ms, after which it remains constant. The evaporation typically reduces the BEC number to 7 × 10^4.

In the final step (iii), we transfer the ˜k_x = 0 dressed state into a non-zero ˜k_x state by sweeping the detuning from resonance to a variable δ in t_sw and holding for t_h. As we show below, for t_sw > 20 ms, this process adiabatically loads the atoms into the j = 1 Raman-dressed state at ˜k_x = ˜k_{min}(δ).

We characterize the Raman-dressed state by abruptly turning off the dipole trap and the Raman beams in less than 1 μs, projecting the atomic state onto its individual spin and momentum components. The atoms then expand in a magnetic field gradient applied during time-of-flight (TOF) approximately along ˜y, and the three spin states spatially separate due to the Stern-Gerlach effect. Imaging the atoms after a 20 ms TOF gives the momentum and spin composition of the dressed state (see right panels of Fig. 2). The quasi-momentum ˜k_x of the BEC is given by the shift along ˜x of all three spin components from their positions when ˜k_x = 0. We determine ˜k_x = 0 to within 0.03 k_r by using the loading procedure above, except that in (ii), the Raman frequencies are sufficiently far-detuned that the atoms experience the scalar light shift but are not Raman-coupled; then the rf and Raman fields are snapped off concurrently before TOF.

It is straightforward to adiabatically load into the rf-dressed state in step (i). To ensure the subsequent adiabatic loading from the rf-dressed state into the Raman-dressed state in step (ii), we ramped up the Raman power in a time t_on, then ramped it off in t_sw. For t_on > 2 ms, there is no discernable excitation into other rf-dressed states. We conservatively use t_on = 20 ms as the loading time in step (ii). To determine t_sw in step (iii), we measure ˜k_x as a function of t_sw for negligible t_h. Figure 3 shows ˜k_x versus t_sw at hδ = 0, 1, 2E_r and hΩ_R = 5E_r, for t_h = 0.1 ms. We use t_sw = 20 ms, the time at which ˜k_x has nearly reached its equilibrium value. This adiabatic following is enabled by the external trap, and the time scale is comparable to our typical trapping periods. After t_sw, we add a hold time t_h = 20 ms during which residual excitations damp.

Figure 2 shows spin-resolved TOF images of adiabatically loaded Raman-dressed states at hΩ_R = 4.85(35)E_r for hδ = −2 and 0E_r. The resonance condition, δ = 0, is determined from the symmetry of the rf-dressed state [17], with an uncertainty of h × 1.5 kHz=0.4E_r, limited by the stability of B_0. The quasi-momentum ˜k_x = ˜k_{min}, measured as a function of δ, is shown in Fig. 3a, along with the calculated ˜k_{min}(δ). Each different ˜k_{min} represents a spatially uniform vector gauge potential, analogous to the magnetic vector potential, with ˜k_{min} = qA/h. For such a uniform ˜A, the magnetic field ˜B = ∇ × ˜A would be zero.

For Rabi frequency Ω_R ≤ 4.47E_r/h, E_j=1( ˜k_x) has mul-
In conclusion, we have prepared a Bose-Einstein condensate in a Raman-dressed state with a non-zero quasi-momentum, controlled by the Rabi frequency $\Omega_R$ and the detuning $\delta$. This technique, in conjunction with a spatial gradient of the bias field (therefore the detuning) along $\hat{y}$, gives a spatial gradient of light-induced momentum $\tilde{k}_{\text{min}}(y)x$ and creates an effective magnetic field along $\hat{z}$ [13]. The analog of the magnetic length $l_B = \sqrt{\hbar/(qB)}$ (the classical cyclotron radius of an orbit with one unit of angular momentum $\hbar$) is $(\partial \tilde{k}_{\text{min}}/\partial y)^{-1/2}$, and is about the spacing between vortices in a vortex lattice like that formed in a slowly rotating BEC [5]. For a gradient in $\tilde{k}_{\text{min}}$ of one $k_x$ across a condensate of radius $R$, this gives an analog magnetic length $\approx 1.4 \mu m$ for a $R \approx 10 \mu m$ 3D BEC, and we expect a ~25-vortex lattice to form in the condensate. For dilute 2D systems, this is sufficient to reach the quantum Hall regime.

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[15] Uncertainties reflect the uncorrelated combination of 1-σ statistical and systematic uncertainties.
[16] All the detuning ramps are linear versus time. The Raman beam power, swept by applying a linear ramp to the AOM controlling its power, turns on nearly quadratically.
[17] On resonance the rf-dressed state has equal population in $|−1,k_x = 0⟩$ and $|+1,k_x = 0⟩$, even in the presence of a quadratic Zeeman shift. The resonance condition $δ=0$ determined from the symmetry of the Raman dressing is within $0.25E_r$ of that from the rf-dressed states.