

# Synthetic electric and magnetic fields for ultracold neutral atoms

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**Abstract.** We use Raman coupling between magnetic sublevels of a  $^{87}\text{Rb}$  Bose-Einstein condensate (BEC) to create an effective vector gauge field for the neutral atoms. They behave as if they were charged particles in a magnetic vector potential. With appropriate spatial gradients and time derivatives of this vector potential we produce synthetic magnetic and electric fields for the atoms. This paper is a brief summary of the presentation made by the first author at ICAP 2010 in Cairns, Australia. It is not intended as a complete report on the research described, nor does it attempt to be a fully referenced documentation of that research and the relevant literature. We do, however, provide references to the published work where a more complete description and more complete references to related literature may be found.

## 1. Introduction

Ultracold neutral atoms and quantum degenerate neutral atomic gases have proved to be useful in simulating quantum behaviour of a number of models, Hamiltonians, and physical systems. One reason for this is the ability to control the Hamiltonian for the atoms in ways that are difficult for other systems; another is the ability to measure certain quantities, like momentum distributions and correlations thereof, which are often not easily measured in other systems. Bose condensation, Fermi degeneracy, Cooper pairing, BCS/BEC crossover, and the behaviour of quantum particles in periodic potentials are among the areas where cold atoms exhibit behaviour that is hard to observe in analogous condensed matter systems. One of the difficulties facing the simulation of interesting Hamiltonians with neutral atoms is in simulating the response of charged particles to external electromagnetic fields, particularly to magnetic fields. One approach has been to use rotation, where the Coriolis force mimics the Lorentz force. Because of some difficulties with this approach, such as the introduction of a centrifugal force, the challenges associated with adding lattice potentials, as well as various technical imperfections, other techniques have been proposed involving the simulation of a magnetic vector potential.

## 2. Effective vector gauge potential for neutral atoms

The idea behind such an approach is that the Hamiltonian for a charged particle in a magnetic vector potential can be written as  $H = (\mathbf{p} - q\mathbf{A})^2/2m$ , where  $\mathbf{p}$  is the particle's canonical momentum (the quantity canonically conjugate to position),  $m$  is its mass,  $q$  is its charge and  $\mathbf{A}$  is the vector potential.

Evidently, the introduction of a vector potential is equivalent to displacing the origin of the particle's energy-momentum dispersion curve from having its minimum at  $\mathbf{p} = 0$ . A number of theoretical proposals [1-5] have suggested producing such a displacement via 2-photon Raman coupling between different spin states (internal states) and momentum states (external states) within the same electronic ground state manifold. Spatial variation of this Raman coupling can produce a curl of the effective vector potential. Here we outline a specific method [6] for producing an effective vector potential, its experimental realization, as well as the experimental demonstration of synthetic magnetic and electric fields arising from that vector potential. The method is related to an earlier idea [7] involving Raman coupling of spin and momentum states for a different purpose.

In the experimental realization [8] of this method we create an optically trapped Bose-Einstein condensate (BEC) of  $^{87}\text{Rb}$  atoms in the  $F = 1$  hyperfine level of the electronic ground state. The degeneracy of the magnetic levels is lifted by a magnetic field along the  $y$ -direction. We couple the sublevels using a pair of laser beams, counterpropagating along the  $x$ -direction, far-detuned from single-photon resonance with the electronically excited state, but with a frequency difference nearly resonant with the energy difference between the magnetic sublevels. The stimulated Raman transition from one  $m$ -state to another also transfers two units of photon momentum  $\hbar k$ . In a dressed atom picture where the atom's internal (spin) energy, centre-of-mass kinetic energy, and the photon energy are all considered, the Raman coupling produces dressed energy-eigenstates that are superpositions of different  $m$ -states and different centre-of-mass momentum states. For strong enough Raman coupling the lowest of these dressed states has a single minimum as a function of dressed-atomic (canonical) momentum, and with a curvature in  $E(p)$  that is smaller than that of the free-space dispersion curve, implying a larger effective mass than the bare atomic mass. When the Raman detuning for the coupling between  $m$ -states is zero (Raman resonance), the minimum of  $E(p)$  is at  $p = 0$ . For non-zero Raman detuning that minimum is shifted away from  $p = 0$ , resulting in an effective Hamiltonian equivalent to that of a charged particle in a magnetic vector potential. When the magnetic field applied along  $y$  is spatially uniform, the Raman detuning and hence the shift of the minimum of  $E(p)$  are spatially uniform, so the effective vector potential, along  $x$ , is uniform, has no curl, and there is no effective magnetic field.

Reference [8] describes how we load a Bose-Einstein condensate of  $^{87}\text{Rb}$  into the dressed state at the minimum of  $E(p)$  and, using time-of-flight, measure the shift from zero of the minimum of  $E(p)$  and hence measure the vector potential. We emphasize that while the atoms at the minimum have non-zero (canonical) momentum, their mechanical momentum is zero, as is their group velocity, given by  $dE(p)/dp$ .

### 3. Synthetic Magnetic and Electric Fields

To produce synthetic magnetic or electric fields from the effective vector potential arising from the Raman coupling, we must create either a curl of the vector potential (a spatial variation) or a time dependence.

In Ref. [9] we used a spatial dependence of the (real) magnetic field along  $y$  to create a  $y$ -derivative of the Raman detuning and hence of the effective vector potential. A linear gradient along  $y$  of the  $x$ -directed vector potential creates a curl equivalent to a synthetic magnetic field along  $z$ . When our BEC is subjected to a large enough synthetic magnetic field, we find that upon release (trap and Raman coupling turned off), the BEC is seen to contain many vortices, with the number of vortices increasing with the strength of the effective synthetic magnetic field. We also observe that there is a fairly large threshold value of the synthetic field, below which no vortices are seen in the BEC. This threshold behaviour is consistent with the energetic arguments detailed in [10], and in agreement with our own calculations. The vortices do not appear immediately upon the application of an appropriately large synthetic magnetic field, but over a time of some hundreds of milliseconds nucleate at the outside of the atom cloud and migrate to the interior.

To create a uniform synthetic electric field, we need a time derivative of the uniform effective vector potential. The realization of this synthetic electric field is described in [11]. We produce the time derivative by changing the (real) magnetic field from one chosen value to another within a fraction of a millisecond. The resulting change in Raman detuning changes the vector potential, producing a pulse of synthetic electric field that impulsively accelerates the atoms. We turn off the Raman coupling and the trap and observe the velocity of the atoms after time-of-flight finding good agreement with the expected velocity change. We can also deliver a momentum impulse to the atoms, then allow the trapped, Raman-dressed atoms to oscillate rather than releasing them immediately to time-of-flight. We see that the atoms oscillate in the trap with a frequency determined by the effective mass appropriate to their dressed state.

#### 4. Conclusions

We have demonstrated the creation of an effective vector gauge potential, created by Raman coupling between magnetic sublevels of a  $^{87}\text{Rb}$  BEC. An appropriate spatial gradient of this vector potential produces a synthetic magnetic field, leading to a Lorentz-like force on the neutral atoms, as if they were charged particles in a magnetic field. A time variation of the vector potential produces a synthetic electric field that acts on the neutral particles as does a real electric field on charged particles. We hope to use the synthetic magnetic field to study quantum Hall and fractional quantum Hall effects in neutral atom systems.

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