Doppleron-catalyzed Bragg resonances in atom optics

Scott Glasgow, Pierre Meystre, and Martin Wilkens

Optical Sciences Center and Program in Applied Mathematics, University of Arizona, Tucson, Arizona 85721

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A novel scheme to achieve large-angle atomic diffraction by standing-wave fields is proposed. It uses a high-order Doppleron resonance as a catalyst to speed up a high-order Bragg resonance by orders of magnitude. This effect occurs when the atom–field frequency detuning is such that the Bragg resonance and the Doppleron resonance become degenerate.

Of central importance to atom interferometry[1–4] is the construction of effective atomic beam splitters that provide large scattering angles. In beam splitters based on the near-resonant interaction between atoms and standing-wave fields,[5–9] the splitting of the atomic wave function results from the fact that each absorption or emission process is accompanied by a change of the atomic center-of-mass momentum by $\hbar k$, with k being the wave number of the field. The most common realization of such a beam splitter relies on first-order Bragg scattering, which generates a splitting of the atomic wave function in momentum space by $2\hbar k$. For typical atomic beams, with velocities in the 100-m/s range, this produces extremely small scattering angles that not only complicate the detection of the splitting but, more importantly, limit one's ability to affect the two partial wave functions differentially. Higher-order Bragg scattering would of course improve the situation and has been numerically demonstrated.[10] However, its practicality is questionable, owing to the need for atom–field interaction times that scale exponentially with the scattering order.

Attempts at solving this problem include the use of three-level transition schemes[11] and the application of velocity-tuned or Doppleron resonances.[12–14] In this Letter we outline a novel scheme that uses a high-order Doppleron resonance as a catalyst to speed up a Bragg resonance by orders of magnitude. A similar scheme involving a first-order Bragg resonance that is accelerated by a zeroth-order Doppleron resonance has been discussed by Pritchard and Gould.[15] In general, the acceleration of a Bragg resonance occurs when the atom–field frequency detuning is such that the Bragg resonance and the Doppleron resonance become degenerate.

For concreteness, we assume that the momentum of the atom in the direction perpendicular to the standing-wave field is large enough to be treated classically and that the field couples only two atomic electronic levels $|e\rangle$ and $|g\rangle$. The electrotranslational states of the atom are then completely defined by two quantum numbers i and n, where $i = e$ or g and n describes the transverse center of mass momentum of the atom, in units of $\hbar k$.

In the band theoretical description,[16] Bragg resonances occur at the center and the edges of the first Brillouin zone. They correspond to the avoided crossing between two electrotranslational states that correspond to the same electronic state and opposite transverse momenta. Under ideal conditions, they couple only two states of transverse momenta $r\hbar k$ and $-r\hbar k$, where r is an integer, through a virtual transition between the two electronic states. For incident atoms in their lower state $|g\rangle$, we have then

$$|g, r\rangle \rightarrow |g, -r\rangle. \tag{1}$$

In contrast, Doppleron resonances involve real transitions between the ground and excited electronic states and the transfer of $(2s + 1)\hbar k$ of transverse momentum, for instance,

$$|g, r\rangle \rightarrow |e, r + 2s + 1\rangle. \tag{2}$$

They correspond to the avoided crossing between two electrotranslational states of opposite electronic states and with translational momenta differing by an odd number of $\hbar k$. These anticrossings can take place anywhere in the first Brillouin zone,[16] but the catalytic reaction considered here requires that they occur at either its center or its boundary.

Considering for the sake of concreteness incident atoms in the state $|g, n + 2m + 1\rangle$, we discuss how the Bragg transition to the final state $|g, -(n + 2m + 1)\rangle$ can be accelerated by orders of magnitude, provided that it is degenerate with the Doppleron resonance between this same initial state and an intermediate state $|e, n\rangle$ (see Fig. 1).

In the absence of interaction, the detuning $\Delta = \omega - \Omega$ between the laser frequency Ω and the atomic transition frequency ω required to achieve this degeneracy is readily found by energy conservation to be

$$\Delta + n^2 = (n + 2m + 1)^2 \tag{3}$$

or

$$\Delta = (2m + 1)(2n + 2m + 1), \tag{4}$$

where frequencies are expressed in terms of the recoil frequency $\omega_r = \hbar k^2/2M$, with M being the atomic mass, and n and m must be integers.

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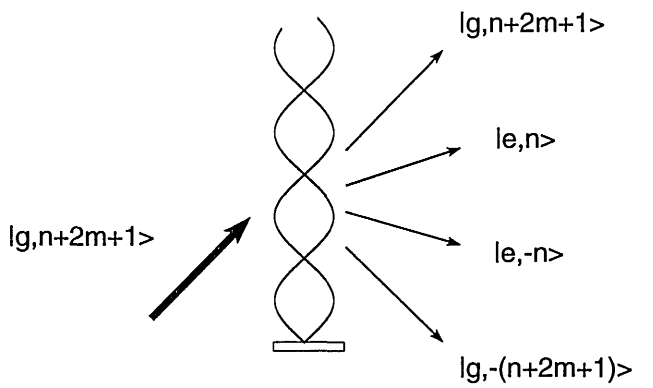

Fig. 1. Geometry of the Doppleron-catalyzed Bragg scattering arrangement.

The introduction of the dipole coupling between the atom and the standing-wave transforms the crossing between the four relevant electrotranslational states $|g, n + 2m + 1\rangle$, $|g, -(n + 2m + 1)\rangle$, $|e, n\rangle$, and $|e, -n\rangle$ into avoided crossings. It also alters the resonance condition (4), owing to the dressing of the bare electrotranslational states by the laser field.[17] If the corrected detuning is chosen appropriately, the relevant eigenstates become, in the limit of weak laser field strengths and for $m > n$,

$$|\psi_{+g}\rangle = 2^{-1/2}[|g, n + 2m + 1\rangle + |g, -(n + 2m + 1)\rangle], \tag{5}$$

$$|\psi_{-g}\rangle = 2^{-1/2}[|g, n + 2m + 1\rangle - |g, -(n + 2m + 1)\rangle], \tag{6}$$

$$|\psi_{+e}\rangle = 2^{-1/2}(|e, n\rangle + |e, -n\rangle), \tag{7}$$

$$|\psi_{-e}\rangle = 2^{-1/2}(|e, n\rangle - |e, -n\rangle). \tag{8}$$

To lowest order in the field strength, the upper and lower electronic states therefore do not mix. This is of course the same as in conventional Bragg scattering with large atom–field detuning. The difference between the normal case and the present situation is merely in the degree to which the degeneracy between the eigenenergies of the symmetric (ψ_{+g}) and antisymmetric (ψ_{-g}) eigenstates is lifted. A lengthy but straightforward analysis shows that in normal Bragg scattering, the splitting of the eigenenergies E_{+g} and E_{-g} scales as the field strength to the $2(2m + 1 + n)$th power.[17] In Doppleron-catalyzed Bragg scattering, in contrast, we find that it scales as the field strength to the $2(2m + 1 - n)$th power only. As the period of Bragg oscillations (Pendellösung oscillations) scales as the inverse of this splitting, we see that the degeneracy between the Bragg and Doppleron resonances leads to a considerable acceleration of the population transfer between the states of transverse momenta $(n + 2m + 1)\hbar k$ and $-(n + 2m + 1)\hbar k$.

To illustrate this discussion, Fig. 2 summarizes numerical results obtained by solving the time-dependent Schrödinger equation for the (interaction picture) Hamiltonian

$$H = \frac{\hat{p}_x^{\,2}}{2M} + \hbar\Delta|e\rangle\langle e| + \hbar\mathcal{R}\cos k\hat{x}(|e\rangle\langle g| + \text{h.c.}), \tag{9}$$

where $\mathcal{R}$ is the standing-wave Rabi frequency. In this example, we have $n = m = 3$, so that we use a Doppleron resonance between the states of transverse momenta $10\hbar k$ and $3\hbar k$ to accelerate Bragg diffraction between the states of transverse momenta $10\hbar k$ and $-10\hbar k$. The Rabi frequency is chosen as $\mathcal{R} = 30$, so that the detuning Δ leading to a degeneracy of the Bragg and Doppleron resonances is $\Delta = 80$, which is approximately 10% off the value $\Delta = 91$ that follows from the zero-field resonance condition (4). (All frequencies are in units of the recoil frequency ω_r, and time is in units of $1/\omega_r$.) Figure 2 shows the probabilities for the atom to have transverse momentum $10\hbar k$ and $-10\hbar k$, respectively. We note that after an interaction time $t \simeq 360$, the probabilities of finding the atom in these states are both approximately 42%. At this time, the system acts as an almost perfect beam splitter. The essential point here is that this time is approximately 860 times shorter than the time that would be required to achieve the same result by using normal 10th-order Bragg scattering with $\mathcal{R} = 30$ and $\Delta = 91$, i.e., without the catalytic influence of the Doppleron degeneracy.

We have shown in a recent paper that in contrast to Bragg resonances, Doppleron resonances are extremely sensitive to spontaneous emission.[17] This is because for atoms initially in their ground state and large enough detuning, the population of the excited electronic state remains negligible in the first case, while Doppleron resonances necessarily involve real transitions between $|e\rangle$ and $|g\rangle$. Since the present process involves Doppleron resonances as a catalyst, it is therefore important to determine if the excited state $|e\rangle$ ever becomes populated. The states of odd transverse momentum are particularly significant, as they correspond to an atom in its upper electronic state. Figure 2 also shows the time dependence of the levels $|e, 3\rangle$ and $|e, -3\rangle$. Together

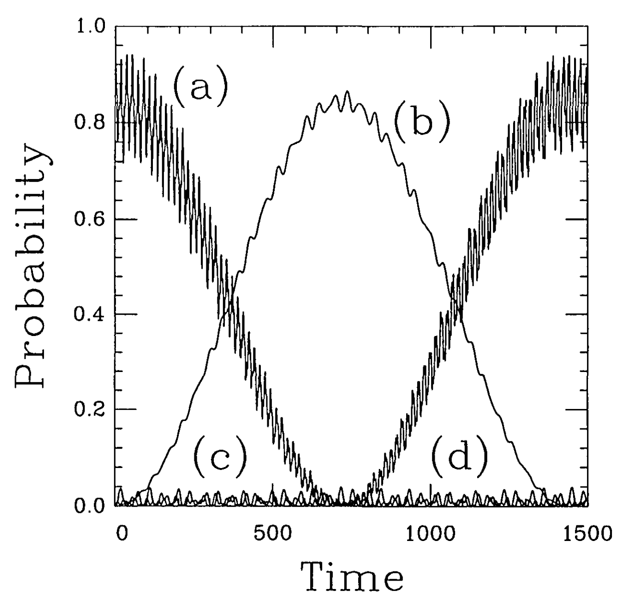

Fig. 2. Populations of the states $|g, 10\rangle$ [curve (a)], $|g, -10\rangle$ [curve (b)], $|e, 3\rangle$ [curve (c)], and $|e, -3\rangle$ [curve (d)] as functions of time. Here $\Delta = 80\omega_r$, $\mathcal{R} = 30\omega_r$, and the time is in units of $1/\omega_r$.

with the levels $|e, \pm 9\rangle$ and $|e, \pm 11\rangle$, they are the only states that become significantly populated. We see that although small, the populations of these states are by no means negligible. Hence, spontaneous emission may prove devastating if it occurs on a scale small compared to the population transfer time between the $10\hbar k$ and $-10\hbar k$ momentum states. Yet, these populations remain sufficiently small (1% on average) that an appropriate choice of long-lived transitions with a natural lifetime of the order of the inverse recoil frequency should lead to an experimental demonstration of our scheme. We can obtain an upper bound for the spontaneous emission rate by noting that the transfer time is of the order of $360/\omega_r$ for the example of Fig. 1. For an average upper electronic-state population of 10^{-2}, spontaneous emission will be negligible provided that $\gamma \ll 3/\omega_r$. Considering as an example the intercombination transition $^3P_1$–$^1S_0$ of ^{40}Ca, with a transition wavelength $\lambda = 657.46$ nm, a lifetime $\tau \sim 0.4$ ms, and a recoil frequency $\omega_r/2\pi \simeq 10^4\ s^{-1}$,[18] we find that this condition is well satisfied.

In summary, we have shown that by choosing an appropriate atom–field detuning, such that a Doppleron and a Bragg resonance become degenerate, one can achieve a catalytic enhancement leading to an orders-of-magnitude increase in the speed of Bragg population transfer. This technique offers a promising alternative to achieve large-angle atomic diffraction by standing waves. A detailed description of this theory, including a full assessment of the effects of spontaneous emission, is the subject of our continuing research.

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