Unexpected Effects of Magnetic Fields on VSCPT

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The application of magnetic fields $\vec{B}$ enhances the richness of laser manipulation of the motion of multi-level atoms. Some of the earliest such experiments discovered that weak $\vec{B}$-fields ($\omega_Z \equiv \mu_B g|\vec{B}|/\hbar \ll \gamma_p$ where γ_p is the optical excitation rate) could induce sub-Doppler cooling in Rb if $\vec{B}$ were not along the $\hat{z}$-axis determined by the light field [1]. Velocity selective resonance (vsr) experiments in stronger fields ($\omega_Z > \gamma_p$) showed cooling of Rb toward a non-zero, tunable velocity $v_{vsr} = \omega_Z/k$ or $\omega_Z/2k$, depending on the polarization arrangement [2]. The opposite Doppler shifts for atoms traveling at v_{vsr} in a standing wave maintain the Raman resonance between the ground state sublevels that have been Zeeman shifted. At v_{vsr} atoms traverse one cycle of the optical standing wave ($\lambda/2$) in one period of the Larmor precession (π/ω_Z or $2\pi/\omega_Z$). Although the cooling force of Ref. [2] can be calculated [3], its mechanical origin remains a mystery, unlike the sub-Doppler Sisyphus cooling force (for a review, see [4]).

Moreover, later experiments in Ne suggested that the cooling to finite velocity v_{vsr} was not only sub-Doppler, but that the rms width δv of the velocity distribution $N(v)$ was actually below the recoil limit $v_r \equiv \hbar k/M$ [5]. Our recent measurements in metastable 2^3S_1 He (He*) on the $\lambda = 1083$ nm transition clearly show cooling to v_{vsr} with δv as low as $\sim 0.6 v_r$ [6]. Optical cooling processes, even Sisyphus cooling, are limited to steady state $N(v)$ with δv at least as large as a few v_r because of the randomness associated with the spontaneous emission necessary for phase space compression [4]. Thus our observed narrowness of $N(v)$ in He* must arise from some kind of magnetically induced quantum interference whose nature is still unknown.

Clearly, phenomena related to VSCPT would produce such a state, but the interference is of the excitation of two different momentum states, so $N(v)$ would have the characteristic two-peaked shape, separated by $2v_r$. With $\sigma^+ - \sigma^-$ light and $B = 0$ we observe the usual two-peaked VSCPT over a modest range of laser parameters. As we vary $\vec{B} = B_z$ ($\hat{z}$ is along the optical $\vec{k}$-vectors) the center of the two-peaked $N(v)$ shifts along the v_z axis according to $v_{vsr} = \omega_Z/k$ as discussed above. As we vary the laser parameters with fixed interaction time T, $N(v)$ evolves from the two-peaked VSCPT signal to a single peak (blue detuning) or dip (red) as in [7] when $\gamma_p T < \sim 5$. The peak (dip) has $\delta v < v_r$ and is centered at $v = v_{vsr}$ (0 for $B = 0$).

Furthermore, our He* data on the $J = 1 \rightarrow 1$ transition using other $\vec{B}$-field and polarization configurations also show single peaks or dips with $\delta v < v_r$ centered at $v = \pm v_{vsr}$. For example, $\vec{B} = B_x$ always gives a single peak or dip at each of the two velocities $v = \pm v_{vsr}$, and each with $\delta v < v_r$. In this case the selection rules of VSCPT are compromised by B_x, and there is no truly trapped dark state. There are "leaky dark states" or "weakly coupled states" $|WC\rangle$

[7] that are similar to VSCPT states. We say the lifetime of atoms in $|WC\rangle$ is limited by such leaks, and attribute these single peaks to the same cause as those that appear with shorter T.

A simple classical picture of these experiments yields very appealing models. For ordinary VSCPT the $\sigma^+ - \sigma^-$ optical field forms a standing wave helix of linearly polarized light $\vec{\mathcal{E}}$ of period $\lambda/2$. The atomic wave function is composed of similar waves because its components have $M_J = \pm 1$ and these components are moving at velocity $\pm v_r$ so they also form a standing helix of deBroglie waves of period $\lambda/2$. When the relative spatial phase of these superposed waves has the electric dipole moment of the atom $\vec{D}$ everywhere orthogonal to $\vec{\mathcal{E}}$, the transition amplitude vanishes and the state is dark. An applied $\vec{B} = B_z$ simply causes Larmor precession of the atomic wave function about $\hat{z}$, and the dark state condition requires that the atom move at v_{vsr} to maintain $\vec{D} \perp \vec{\mathcal{E}}$. For $\vec{B}$ perpendicular to $\hat{z}$, say $\vec{B} = B_x$, the precession is about $\hat{x}$ but a similar condition still obtains. Where $\vec{\mathcal{E}} = \mathcal{E}_x$, $\vec{D} = D_y$ and where $\vec{\mathcal{E}} = \mathcal{E}_y$, $\vec{D} = D_z$. Orthogonality is not preserved all along the trajectory, but the spatial average of $\vec{\mathcal{E}} \cdot \vec{D}$ vanishes.

A quantum mechanical description of our experiments begins with a Hamiltonian that includes the atomic kinetic energy as well as the internal energy and the optical interaction [7]. Numerical calculations with this model have produced an $N(v)$ with the characteristic two-peaked VSCPT signal at large T, but indeed a single-peak of δv below v_r centered at $v = 0$ for $\gamma_p T < \sim 10$. This model reproduces the features of VSCPT as usually described [8], but also shows the relevance of the detuning and of the experimental interaction time. One of the key features of Ref. [7] is that short interaction times produce $\delta v < v_r$ but whose underlying physical processes result from interferences in excitation amplitudes, just as in VSCPT.

To describe our experiments, we have added the Zeeman energies to the Hamiltonian of Ref. [7]. For $\vec{B} = B_z$ so that these are on the diagonal, we have found the same eigenvalues and eigenvectors, however, with $N(v)$ not centered at zero, but shifted to $v = v_{vsr}$. When $\vec{B} = B_x$, however, we expect and find different phenomena. By choosing the quantization axis along $\vec{B} = B_x$ the light field can induce σ^+, π, and σ^- transitions. Thus the selection rules are compromised and the relevant states are analogous to $|WC\rangle$. In particular, because of the leak out of $|WC\rangle$ at rate Γ, $N(v)$ has a single peak with $\delta v < v_r$, similar to the $N(v)$ associated with in a short interaction time $T = 1/\Gamma$.

Acknowledgments: Work supported by the U. S. O.N.R. and A.R.O.

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