ZEEMAN COHERENCES AND DARK STATES IN OPTICALLY PUMPED CESIUM FREQUENCY STANDARDS

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Abstract

We develop a model for optically trapped states including Zeeman coherences to show that their number depends only on the change in F (hyperfine state) during the transition and is independent of the polarization or the coordinate system. Using a polarization switching technique, we achieve complete optical pumping even in the small magnetic field used in our primary standard.

Introduction

Modern, optically-pumped, atomic-beam frequency standards use optical state preparation before the microwave interrogation of the clock transition and some form of optical state detection afterward. Incomplete optical pumping in the state preparation region can lead to undesirable background signals at the detector which can significantly degrade the potential short-term stability of the standard. The Orsay group [1] was the first to point out the existence of Zeeman coherences that could lead to trapped population and incomplete optical pumping in a cesium standard. They showed that such coherences evolve with time in a finite magnetic field. If one waits long enough or uses a large enough magnetic field one can achieve essentially complete optical pumping. One of us (JHS, to be published) has developed a complete model for trapped states that deals with all values of F and any linear polarization. We have used this model to find an alternate method to clean out trapped states and achieve complete optical pumping even in the relatively small magnetic field desired inside our frequency standard.

Theory

The simplest examples of optical trapping occur when π-polarized light (optical E-field parallel to magnetic field) is used for optically pumping a ground state F to an excited state F'. In this case $m_F = m_{F'}$. There are no trapped states (all m_F sublevels are pumped) when the light is resonant with $F' = F + 1$. There is one un-pumped or trapped state ($m_F = 0$) when $F' = F$ is driven. There are two trapped states ($m_F = \pm F$) when $F' = F - 1$.

The situation appears significantly more complicated when linear, σ-polarization is used and Zeeman coherences can be established. However, the number of trapped states is the same as when π-polarization is used. In the limit of no magnetic field there is no distinction between π- and σ-polarization and we are free to choose our coordinate system. We choose π as it leads to the simple interpretation given above; that is, we orient our coordinate system along the polarization vector of the light. If now a magnetic field is turned on in the direction parallel to the optical E-field (normal π-polarization) only the phase of the magnetic sublevels changes. But, if the field is turned on in a perpendicular direction (σ-polarization), the magnetic sublevels evolve into coherent superpositions of each other. The trapped states become untrapped by mixing with states that are pumped. But the number of initially trapped states remains the same. In a coordinate system oriented along the magnetic field, the trapped states may appear to be superpositions of the sublevels. But this occurs because of a change of basis, not a change in the trapped state.

The preceding argument predicts that in cesium the $3 \rightarrow 3'$, $4 \rightarrow 3'$ and $4 \rightarrow 4'$ transitions should exhibit trapping while the 3 → 4' should not. These predictions are in accord with the experimental observations reported in [1].

Experimental Solution

In NIST-7, we choose to pump on the 4 → 3' transition to minimize the potential for AC stark shift. We detect on the 4 → 5' cycling transition to maximize the detection signal-to-noise ratio. However, this choice of transitions makes the standard extremely susceptible to optical trapping; population not pumped out of the F = 4 state during optical pumping is fully visible at the detector. This significantly degrades the short-term stability of the standard. Still, linear polarization is necessary to give the desired spectral symmetry.

For *any* chosen reference frame or linear polarization, therefore, some states are trapped. However, the trapped states are defined by the polarization vector of the light; the states that are trapped for one polarization are different from those trapped in another. Hence, if we could change the polarization in either time or space as the atoms traverse the optical pumping region, all of the population could be optically pumped. We achieve this result by optically pumping with a polarization gradient field similar to that used in optical molasses. The optical pumping beam is linear polarized and after traversing the optical pumping region it is retroreflected with its polarization rotated 90°. This creates a zone of complex polarizations which has no net angular momentum.

Results

Typically, our optical pumping beam has a diameter (1/e) of about 3 mm and a power of about 0.1 mW. With this pumping arrangement, we find less than 1×10^{-4} of the initial population remains in the F = 4 level. This degree of optical pumping is not only sufficient to allow atomic, shot-noise-limited performance of the standard, but we have also operated with simultaneous, counter-propagating atomic beams without degradation of stability.

References

[1] G.Théobald, N.Dimarcq, V.Giordano and P.Cérez, "Ground State Zeeman Coherence Effects in an Optically Pumped Cesium Beam," Opt. Comm., Vol. 71, No. 5, pp. 256-262, June 1989.