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CHAPTER 3

Time-Domain Interferometry with Laser-Cooled Atoms

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Contents

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Abstract A single-state grating echo interferometer offers unique advantages for time-domain studies of light–matter interactions using laser-cooled atoms, including applications that involve precision measurements of atomic recoil, rotation, and gravitational acceleration. To illustrate the underlying physics, we first discuss the output signal of the interferometer in the absence of spontaneous emission. The influence of spontaneous emission, magnetic sublevels, and the spatial profile of excitations beams on matter wave interference in a two-pulse interferometer is described, followed by a discussion of transit time limited experiments using a multipulse technique that offers several advantages. We also examine the enhancement in signal size achieved by a lattice interferometer. The sensitivity of the interferometer to magnetic gradients and gravitational acceleration is discussed along with extensions to frequency-domain studies of atomic recoil and rotation. Applications of coherent transient effects and echo techniques associated with internal state labeled interferometers that utilize magnetic sublevels of a single hyperfine state are considered for precise measurements of magnetic interactions such as atomic g-factor ratios. The article concludes with an overview of the suitability of the traditional two-pulse photon echo technique for measurements of atomic lifetimes and studies of superradiant emission in laser-cooled samples.

1. INTRODUCTION AND DESCRIPTION OF TWO-PULSE STANDING WAVE INTERFEROMETER

1.1 Introduction

Matter wave interference has intrigued scientists since the early days of quantum mechanics. It was not until the late 1980s, however, that the field of atom interferometry was born. There have been a series of beautiful experiments carried out over the past two decades that have probed the fundamental nature of matter wave interference using atom interferometers (Berman, 1997). These include interference of "large" objects and of biomolecules (Hackermüller et al., 2004), interference of independently prepared particles (Andrews et al., 1997), and the origin of quantum mechanical complementarity (Durr et al., 1998). Advances in microfabrication techniques and the development of laser-cooling and trapping for neutral atoms has opened up many new possibilities for constructing atomic interferometers (Keith et al., 1988; Weiss et al., 1993). Besides testing the fundamental nature of matter wave interference, atom interferometers play an essential role in many high-precision measurements of fundamental constants, such as the fine structure constant α and the Newtonian constant of gravity. They offer an independent method for determining these constants that expands our understanding of the fundamental nature of physical laws (Cladé et al., 2006; Fixler et al., 2007; Weiss et al., 1993). Moreover, precise measurements of quantities such as the local gravitational field hold promise for technological advances in navigation and mineral exploration (McGuirk et al., 2002).

This article discusses the physics and various extensions of a particular atom interferometer design developed at New York University (NYU) in the mid-1990s (Cahn et al., 1997). The interferometer involves the interaction of a set of pulsed laser fields with a sample of laser-cooled Rb atoms in a magneto-optical trap. A schematic of the experimental setup of this interferometer is shown in Figure 1. The principle of the NYU interferometer is that the interaction of an off-resonant optical standing-wave pulse (made up of traveling waves with k-vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$) with a two-level atomic system effectively modulates the atomic ground-state energy with a spatial period $2\pi/q$, with $\boldsymbol{q} = \boldsymbol{k}_2 - \boldsymbol{k}_1$. The pulse therefore acts as