ELECTRON MATTER OPTICS AND THE KAPITZA-DIRAC EFFECT

by

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ELECTRON MATTER OPTICS AND THE KAPITZA-DIRAC EFFECT

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University of Nebraska, 2003

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The diffraction of electrons by a standing wave of light was first proposed by Kapitza and Dirac in 1933. We observed this effect for the first time in September 2001 by showing separate electron diffraction peaks. It was first observed for a focused laser beam, where the standing wave of light serves as a thin light crystal. Later, the effect was also observed with an unfocused laser beam, where the standing wave serves as a thick light crystal, where scattering can only occur at the Bragg angle.

The theory behind the effect has been formulated within both atomic optics and electron optics communities. It involves the ponderomotive potential that an electron experiences within the electromagnetic field of two counter-propagating laser beams. The derivations of the differential equations given by both communities have identical results with their own benefits when making numerical calculations. These theoretical calculations fit well to our data, which falls between the limits of the diffraction and Bragg regimes.

To analyze the data collected in these experiments, the statistical behavior of the arrival of electrons, governed by the Poisson distribution, was taken into account. The Gaussian nature of the laser beam and its consequences on focusing needed to be addressed, along with how far from diffraction limited the laser beam actually was.

There may be a possibility of new effects arising from the interaction of electrons and light. The effect is like KDE, but modified to include two counter-propagating lasers

of different frequency, the consequence of the longitudinal velocity of the electrons, and the role that the polarization of the laser light plays.

Preface

Chapter 3 is in preparation to be submitted to Physical Review A.

Chapter 4 is published in Nature[1] for the diffraction regime, and in Physical Review Letters[2] for the Bragg regime.

Chapter 5 is preliminary work that we plan to publish.

Chapter 6 is scheduled for release in Laser Physics.

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Chapter 1, Introduction

1.1, History of Wave-Particle Duality

Learning the true nature of matter and light has been a goal of physicists for centuries. Newton believed that light was composed of corpuscles to explain its reflection, refraction, and rectilinear motion through space. His beliefs held for almost two centuries until in 1804, Young[3] proposed an experiment to show the interfering nature of light, now known as his famous double-slit experiment. This established the wave nature of light. About a century later, in 1905, Einstein's work on the photoelectric effect[4] showed that light also had a particle nature by carrying energy in quanta known as photons, a word coined in 1926 by G. N. Lewis[5]. In 1923, Compton[6] showed that light, in his case x-rays, also carried and transferred momentum via the photon. These established the particle nature of light. That same year, de Broglie[7] proposed the theory that matter, which was believed to be purely a particle in nature, also possessed a wave nature. In 1927, Davisson and Germer[8], and separately Thomson and Reid[9], verified de Broglie's theory by diffracting a free beam of electrons by solid crystal structures, for which Davisson and Thomson shared the 1935 Nobel Prize in Physics. The notion that light and matter possess the properties of waves *and* particles is known as wave-particle duality. Some go as far as to call an entity possessing this quality a wavicle, even though visualizing such a characteristic is next to impossible. This characteristic is now accepted and its benefits are being utilized in grocery stores, hospitals, manufacturing plants, CD players, and many other ways.

1.2, History of the Kapitza-Dirac Effect

In 1933, Kapitza and Dirac[10] theorized the Bragg scattering of electrons by a standing wave of light, now known as the Kapitza-Dirac effect (KDE). This use of light as a diffraction grating for the electrons reverses the traditional roles of light and matter in a beautiful display of wave-particle duality. During Kapitza and Dirac's time, the most intense light source was a mercury arc lamp; with the intensities that those could achieve, the probability of scattering an electron was one out of every 10^{14} electrons. This was due to both the lack of intensity and the wide bandwidth of the light source. Higher intensities and narrower bandwidths became available with the advent of the laser[11] in 1960.

Soon after, attempts were made to show this effect. Two experimental groups reported an effect: Bartell's group[12] and Schwarz's group[13]. Two other groups did not report an effect[14,15]. Explanations were offered[16,17,18,19,20] to account for the controversy of the early experiments. Bartell's group, upon further analysis of the data of both claims, believe that they had observed effects caused by a lack of electron beam resolution and laser induced noise. Schwarz's group claims that their parameters placed the effect strong enough to scatter out of and back into the main beam. Regardless of this older controversy of whether they observed a laser's affect on an electron beam, no diffraction peaks were observed, and recent reviews[19,21] state that KDE had not been observed for electrons in any of the earliest cases.

1.3, KDE and Atom Optics

Free electrons interact weakly with photons, preferring the force of a constant

electric field over the oscillating field associated with a photon. Electrons bound to the nucleus of an atom interact strongly with photons that have energies that match energy level transitions. At these resonant energies, an atom will absorb a photon, not only acquiring its energy but its momentum as well. After this process, the atom wants to lose this energy. If a photon of the same energy is present, it will easily emit a photon with the same energy as it absorbed, a process known as stimulated emission. As before, the atom will also release momentum to the photon and recoil in the appropriate manner. When applying these principles to KDE, it is found that far less intense laser light is needed to diffract atoms than it is for free electrons due to this resonant enhancement. This was shown by a group at M.I.T. [22] They also showed that Bragg scattering, a process that will be explained in a later chapter, was possible with atoms and a standing wave of light[23]. These examples of *atomic* KDE stimulated much work in the field of atom optics.

1.4, Successful Experiments Using KDE with Electrons

Bucksbaum *et al.*[24] showed that electrons, produced by multiphoton ionization of atoms, could be deflected by light into two incoherent peaks. This high-intensity Kapitza-Dirac effect did not show individually resolved, coherent diffraction peaks. In September 2001, we demonstrated the diffraction of a free beam of electrons into separate, coherent beams using a standing wave of light[1]. Later, we experimentally confirmed the prediction of the original 1933 paper by Bragg scattering electrons with KDE.

1.5, Motivation

One of the main properties of wave-particle duality concerns the wavelength of matter. This wavelength can be much shorter than that of optical light. When it comes to measuring a distance, the wavelength of the 'measuring tool' is the limiting factor. For instance, in an optical microscope, the wavelength of optical light limits the detectable size of an object under the lens, making higher resolving power impossible. Another example is that of interferometers. The difference in the arm lengths of an interferometer is measured to a minimum of half a wavelength. For optical light, this is down to the order of 10^{-7} meters. In comparison, electrons with an energy of about 1 keV have a wavelength on the order of 10^{-9} meters, which can be made smaller by using higher velocity electrons. With sensitivity to displacements on that order, not only can images of smaller object be resolved, but the effect of weak forces can be observed as well.

Electron microscopes are already in abundance for imaging the very small, and electron biprisms use electric fields to coherently split-up and recombined an electron beam to make interferometers. What advantage does using the Kapitza-Dirac effect give? Two things that electrons have that photons do not are charge and rest mass. These two properties make is possible to probe both the electromagnetic and the gravitational forces in unique ways. In order to probe these forces, the electrons must have enough time to act on other particles. The electron beams of electron biprisms have energies in the tens of keV. However, electrons used in KDE have energies much lower than that, around 100 eV, making them slower and giving the forces time to act. This is of immense importance for the gravitational force, which is much weaker than the electromagnetic force.

The charge of the electron can also be a problem at slow velocities due to image charge. If an electron passes close to a conductor, an equal and opposite image of the charge forms in the conductor as a reaction to the electron moving the free electrons in the conductor. This would arise if one used a metallic diffraction grating on the electrons. If someone wishes to probe effects due to very small forces, this image charge would be a source of 'noise' that one would have to deal with. This is not an issue when using a grating composed of a standing wave of light.

In addition, when using a material grating, the periodicity of the grating is set until another grating it put into place. Theoretically, if tunable lasers could produce the intensities needed for KDE, the periodicity can be used to control the diffraction angle, or just to see if any new effects arise. Different configurations of lasers could also be tried. For instance, different polarizations, combinations of different wavelengths of light, and modulation of the light could all produce new effects, parameters not possessed by material gratings.

A use of diffraction by KDE could be to diffract the electron beam three times to produce a Mach-Zehnder interferometer. This kind of interferometer would have unique control characteristics that could be used to increase the efficiency of an interferometer or to produce configurations capable of testing new parameters. The wavelength, charge, and mass of an electron give the possibility for creating a very sensitive interferometer that could be used to test phenomenon like, for example, the Casimir force[25] and the Aharonov-Bohm effect[26].

1.6, Summary of the Chapters

Chapter 2 will cover the theory behind KDE: the derivation of the ponderomotive potential from the Coulomb and Lorentz forces on a n electron in a standing wave of light, the quantum mechanic approach that produces coupled differential equations, and the differences in the Bragg and diffraction regimes. Chapter 3 will cover the general experimental setup, including a description of the vacuum system, the optics, the magnetic shielding, the electronics, and the data collection. A form of this chapter is in preparation to be submitted to Physical Review A. Chapter 4 will discuss the experimental procedures, the data collected for the experiments, and the numerical solution to the Schrödinger equation used to fit curves to the data in both the diffraction regime, published in Nature[1], and the Bragg regime, published in Physical Review Letters[27]. Chapter 5 discusses the theoretical work for finding higher order effects, which include position-dependent forces generated when two lasers with different wavelengths are counter-propagated and electron longitudinal velocity effects. This is preliminary work that we plan to publish. Chapter 6 discusses the theoretical possibility of spin polarizing a free electron beam with two wavelengths of laser light by taking into account the conservation of angular momentum. This chapter is scheduled for release in Laser Physics. Chapter 7 is the conclusion, which discusses the results, explains why the earliest experiments were inconclusive, and gives possible future uses for this research.

Appendix 1 shows how the Heisenberg Uncertainty Principle is related to Gaussian optics and a laser's M^2 value. Appendix 2 is the FORTRAN 90 program used to find the numerical solutions for the quantum mechanical equations of motion due to the Kapitza-Dirac effect. Appendix 3 is the FORTRAN 90 program used for the

numerical solutions for the classical equations of motion due to two counter-propagating lasers with different wavelengths.

Chapter 2, Theory

2.1, Classical Photon Fields

Let us consider an electron interacting with light. The classical equation of motion of an electron is given by

$$m\ddot{\vec{r}} = -e\left(\vec{E} + \dot{\vec{r}} \times \vec{B}\right), \tag{1}$$

where m is the mass of an electron, $\ddot{\vec{r}}$ is the electron's acceleration, $\dot{\vec{r}}$ is the electron's velocity, e is the charge of an electron, $\vec{E}$ is the electric field, and $\vec{B}$ is the magnetic induction. Eq. (1) is derived from the Coulomb force and the Lorentz force. The E and B fields come from the laser light.

First, what happens to an electron when it interacts with a single traveling wave? It is known that the electron experiences a quiver motion due to the oscillating E-field and the Coulomb force. This motion crossed with the B-field produces a Lorentz force that makes the electron perform a figure-8 motion while in the laser[28]. There is no net time averaged potential present, which means the electron returns to its original state before the laser was on.

Now, what happens in an electron when it interacts with two counter-propagating lasers with the same wavelength? This is represented by a vector potential formed from two counter-propagating wave. For now, let us use the waves traveling along the x-axis and linearly polarized in the z direction,

$$\vec{A} = \frac{1}{\omega}\sqrt{\frac{I}{\varepsilon_o c}}\left(\sin(kx - \omega t) + \sin(-kx - \omega t)\right)\hat{z} = -\frac{2}{\omega}\sqrt{\frac{I}{\varepsilon_o c}}\cos(kx)\sin(\omega t)\hat{z}, \tag{2}$$

where k is the light wavevector, ω is laser light angular frequency, ε_o is the permittivity of