The Kapitza-Dirac Effect: Controlling Matter with Light

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In 1927, Clinton Davisson and Lester Germer, in their famous experiment, observed that electrons and other particles can behave like waves in addition to particles and be diffracted by certain periodic materials, such as a crystalline nickel structure. These observations lead Pyotr Kapitza and Paul Adrien Maurice Dirac to theorize that electrons and other particles could be diffracted, and even stopped, by certain periodic, or standing, light wavelengths. However, the rigidly stable and focused properties required of the light used in the apparatus meant that this effect could not, in fact, be observed directly until the development of the laser beam in the 1950s. Today, many types of "optical tweezers" or "optical traps," as they are called, have been and are being developed for a wide range of applications in physics, chemistry, and, especially, biology.

The Kapitza-Dirac effect essentially proposes that a standing wave of light of a certain wavelength can be used to diffract a well-collimated, or aligned, beam of particles, such as electrons (Kapitza and Dirac 1933). The Kapitza-Dirac effect is an implication of wave-particle duality, the fact that particles can behave as waves do and waves can behave as particles do. The beam of particles will behave as a wave does and diffract, which is a property of waves, when the particles pass through the "grating" created by a standing periodic light wave, in this case behaving as a particle grating would for a beam of light normally. This is simply the opposite of the effect observed in the already performed Davisson-Germer experiment, which found that a

particle, such as crystalline nickel, could cause a wave, or a particle behaving as a wave, to diffract (Freimund, Aflatooni, and Batelaan 2001).

The Kapitza-Dirac effect was first observed in 1970 by Arthur Ashkin at Bell Labs (Ashkin 1970). Ashkin used a laser beam to scatter micron sized particles. A laser beam is a stream of photons that have the same wavelength and direction; this makes the laser beam ideal for use in an optical trap, since the laser beam will be able to push the particle predictably. In 1986, Ashkin and his colleagues first used a laser beam to trap a particle and hold that particle in place. This eventually lead to research on using laser beams to cool and trap an object, for which United States Secretary of Energy Steven Chu and others received the 1997 Nobel Prize in Physics. This also lead to the development of what is now referred to as optical tweezers: a focused laser beam capable of trapping and manipulating a particle (Ashkin et al. 1986).

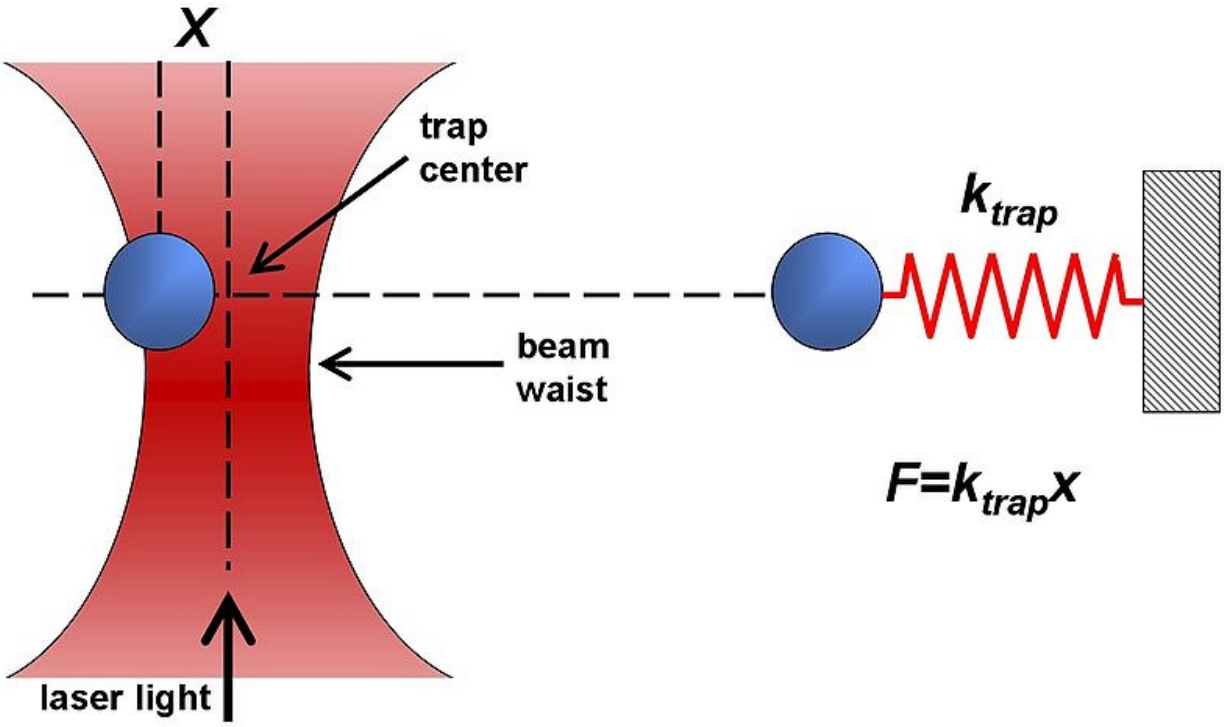

Fig. 1: A particle is trapped in the waist of a focused laser beam.

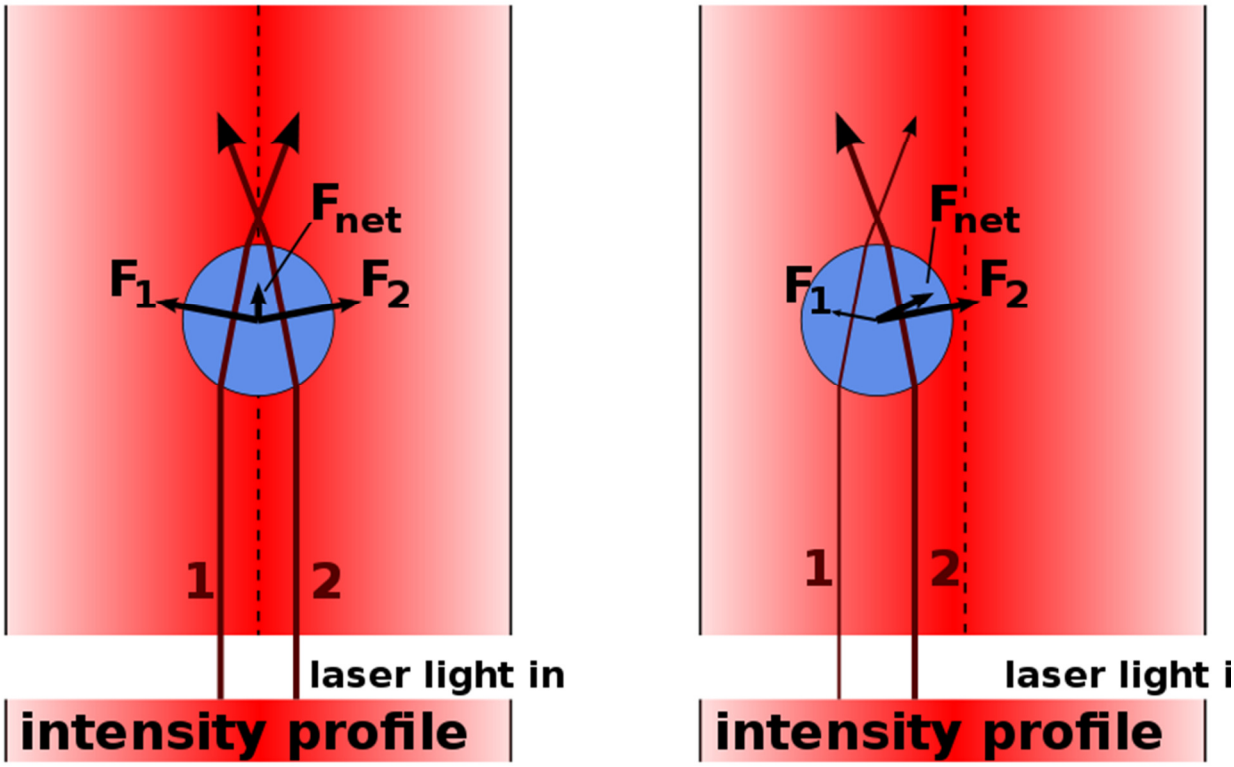

Fig. 2: The particle is forced toward the center by differences in intensity in the laser beam.

The gradient force, meaning that the force will change along the gradient of the laser beam, that holds the particle in place is caused by the difference gradient in intensity between the laser beam light in the center of the beam and the laser beam light toward the edge of the beam (fig 2). The force can be considered as being the same as if the particle were held in place by a simple, harmonically-oscillating spring and is given by the equation

$$F = k_{trap}x$$

where x is the displacement from the center of the laser beam and k_{trap} is a constant unique to the trap, similar to the way a spring constant is for a spring (fig 1).

When the wavelength of the laser beam light is much smaller than the width of the particle, the explanation of the entrapment involves simple kinematics and ray optics. The particle changes the direction of the light beams that hit the particle by refracting them and, thus, since light can be considered as having momentum despite its negligible mass, the particle changes their momentum. Since the momentum of the system is conserved, the change in momentum of the light rays causes a change in momentum of the particle, forcing the particle to move in a direction opposite of the refraction direction (fig 2). This effect can be thought of as the particle being too big to escape the light "grating."

When the particle is much smaller than the wavelength of the laser beam light, however, the particle must be treated differently. In this case, the particle can be treated as an electric dipole at a single point, and the light is treated as an electromagnetic field. The force on the particle in this case is actually a Lorentz force on the particle. The Lorentz force is given by the equation

$$F = \frac{1}{2}\alpha \nabla E^2$$

where α is a constant due to the polarization of the particle, E is the electric field of the laser beam, and ∇ is the gradient of the laser beam. Since the particles in question are much smaller than the wavelength of the laser beam light, this Lorentz force can be approximated with Rayleigh scattering, meaning that the kinetic energy of the system is conserved and the force is given by the new equation

$$F_{scattering}(r) = \frac{k^4 \alpha^2}{6\pi c n^3 \epsilon_o^2} I(r)$$

where k is a constant specific to the trap, α is a constant due to the polarization of the particle, c is the speed of light, n is the index of refraction of the particle, and ε_0 is the permittivity of free space. This means that the gradient force of the laser beam light rays on the particle is proportional to I(r), the intensity of the light as a function of position. This resultant force is to be expected since the farther the particle is from the trap center, the stronger the force pushing the particle back is.

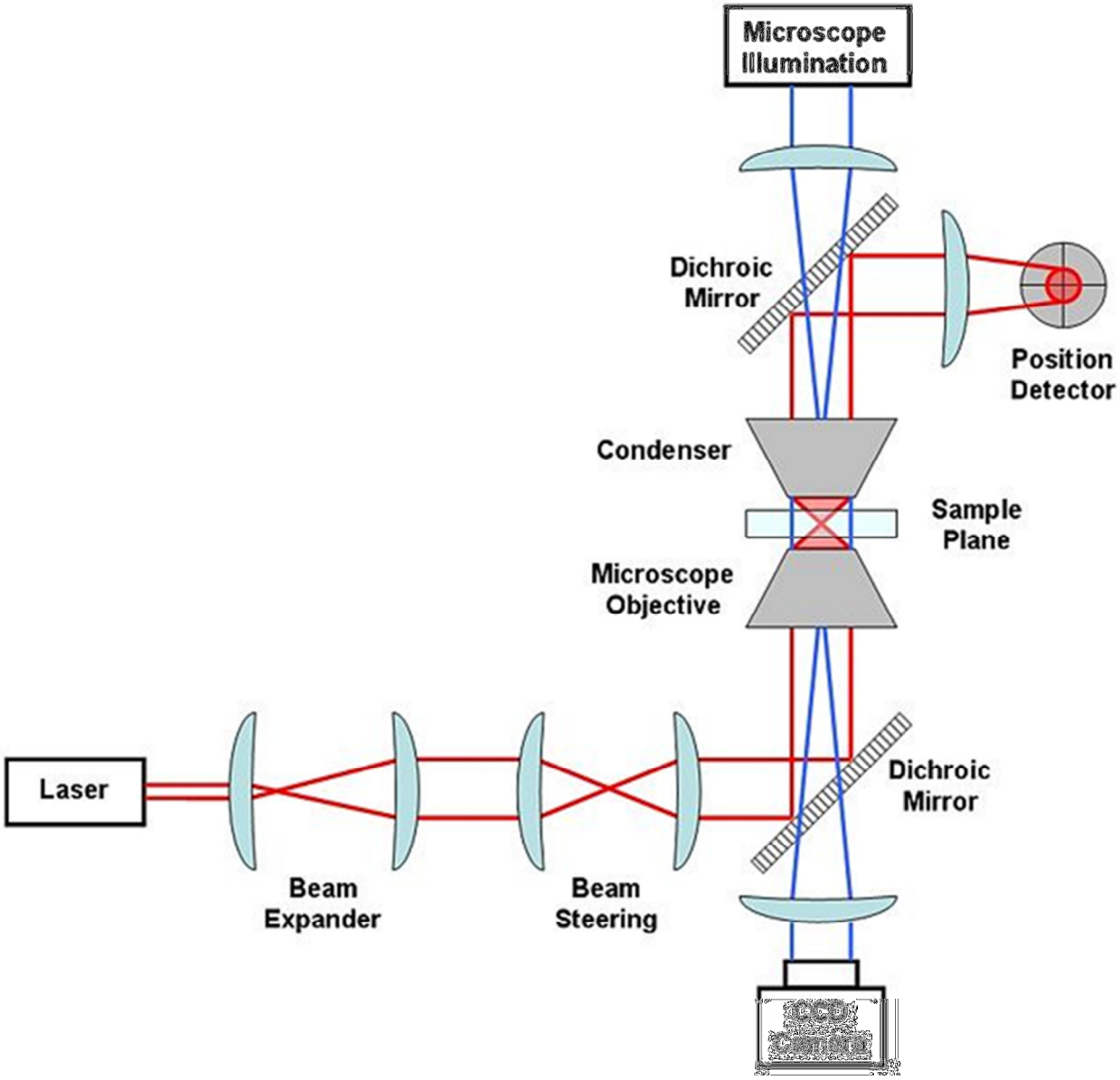

Fig. 3: A very basic design for optical tweezers.

At its most basic design, an "optical tweezers" device involves a laser beam with wavelength specific to the particle to be entrapped, with optical arrangements, such as simple pairs of lenses, for beam expanding and steering, a microscope objective and condenser, a sample plane, a position detector, and a microscope illumination source that is directed at a CCD camera (Fig 3).

The wavelength of laser beam light that is used largely depends on the material being studied, though in some cases the wavelength won't matter that much. For example, many biological materials, such as cells, would require a laser beam of greater wavelength and thus lower energy in order to not damage the cells, while some inorganic materials, such as heavy metals, may need shorter wavelength, higher energy laser beams to be able to penetrate the material effectively, and some materials, such as lighter metalloids, might not need a specific wavelength of laser beam light to be studied. The laser beam must be expanded using a set of lenses to accommodate the size of the particle. The laser beam is also steered using an optical system of lenses so that the laser beam will be in the correct area in the sample plane. The laser beam can also be steered in a way that will move the entrapped particle back and forth laterally in the sample plane.

One of the most important parts of the optical trap is the microscope objective. The objective is what determines the magnitude of the gradient force on the particle. In order to stay in position the net force of the laser beam pushing the particle up must be equal to the force of gravity. This can only be accomplished with certain powers of the apertures of objectives. The

condenser basically allows the objective to function properly by refocusing the light into a readable configuration.

Data generated from the optical trap is collected via a couple methods and used for various things. The microscope illumination source coupled with the CCD Camera is used to track activity in the sample plane, specifically the motion of the particle. The entire plane is illuminated and the particles location is able to be tracked by observing the anomalies in the illumination as recorded with the CCD camera. A CCD camera is a device that can detect light, and even tell what color the light is, that strikes the camera. The position detector is used to determine the orientation of the laser beam and adjust it accordingly. The laser beam can be moved, so knowing where the laser beam is located is crucial to avoiding mistakes.

The laser can be split in a number of ways to allow the entrapment of particles in multiple areas. A laser can simply be focused in a way that allows for multiple focal points for trapping. The laser can also simply be diffracted into multiple lasers with multiple focus points for trapping particles. A single laser can be shared across hundreds of trapping points, or be extended into a single, larger trapping point.

Optical tweezers have a number of already established uses and many more proposed uses. The uses of trapping a single particle are particularly evident when analyzing a very small substance or a very specific sample of a substance. Optical tweezers can also be helpful especially in analyzing particles of an element or alloy, or even a larger substance, such as an entire cell. The optical trap is also used in some methods of laser cooling, as a means of holding the particle in place.

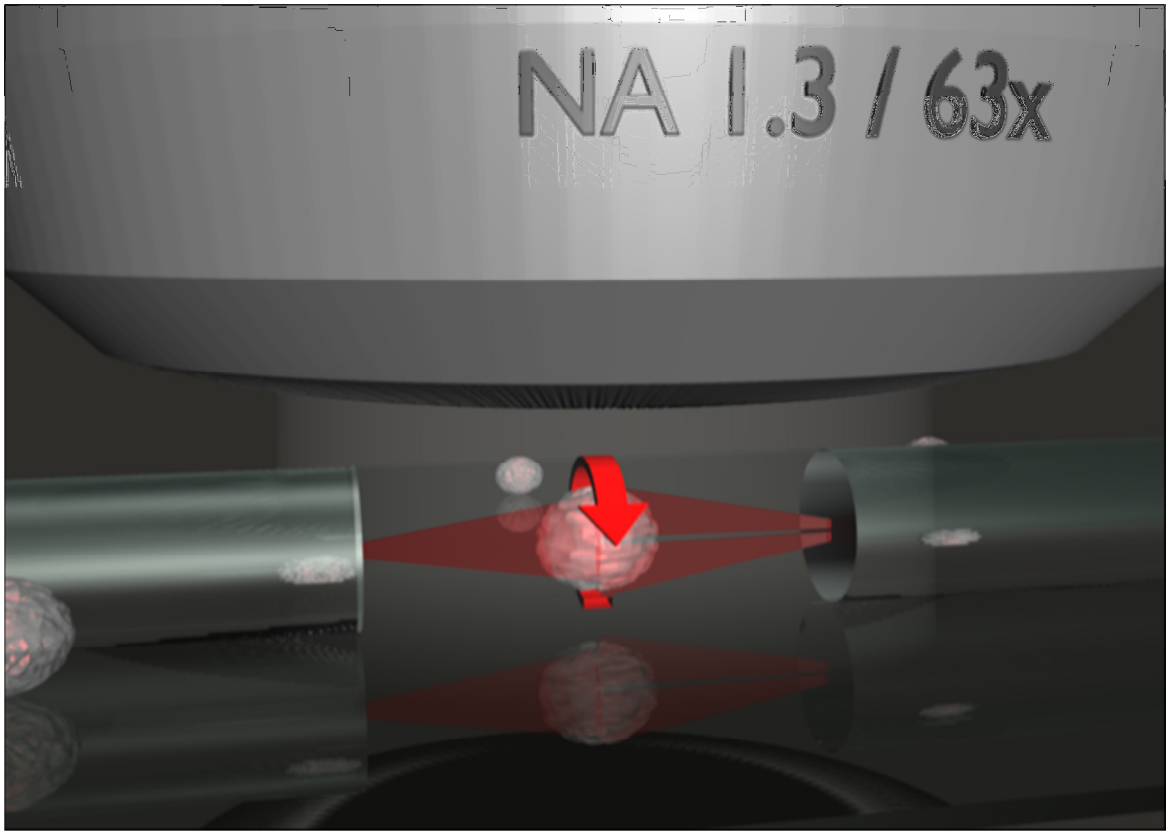

Fig. 4: A computer model of a cell being held and rotated in an optical trap.

One of the most common uses of optical trapping is to sort particles, even larger ones, especially cells and organic micro-tissues. By surrounding a cell with charge, it can be sorted based on its fluorescent properties. When the cell is not surrounded by charge, it can be sorted by its refractive properties. This can be used to sort out a sample of cells based on whether or not they are cancerous, for example, in order to determine the severity of the disease and aid in its treatment.

Another fairly common example of optical entrapment is simply using the device to hold a particle, or multiple particles, in place. With an exceptionally small microscopic particle, it can be difficult to hold it in place. However, an optical trap can hold a particle down to the size of an atom in place, allowing it to be studied more easily.

An optical trapping device can also be used in conjunction with a device that creates a powerful magnetic field to trap a particle further and cool a particle, such as a sample of some low density gases, to near absolute zero temperatures, on the order of micro-Kelvins in some cases. When combined with the electric field of the light in an optical trap, the magnetic field of a magnetic trapping device can hold almost any particle, regardless of charge or other physical properties. This device is referred to as a magneto-optic trap. While the sample of the substance is held in place, it can be bombarded with photons from other lasers. The photons absorb energy, and thus heat, when they collide with the substance if the substance is heading toward the photon. As a result, there is a net loss of energy, and thus temperature, in the substance.

Davisson and Germer's landmark experiment showcasing the dual wave nature of particles with diffraction provided a manner of stepping stone for Kapitza and Dirac. Kapitza and Dirac theorized that a wave, such as a light wave, acting as a particle could also cause diffraction of a particle. With the development of the laser beam, this hypothetical situation was eventually able to be realized as being correct by Arthur Ashkin working at Bell Labs. This theory was also later expanded to include the ability for a wave, such as a laser beam light wave, to be able to influence the physical motion and location of a particle, trapping the particle, in a sense.

An optical trap device has many uses in many areas such as physics, chemistry, and biology, especially with medical applications. Optical tweezers can be used to hold microscopic particles in place, sort particles based on various properties, and also are a part of laser cooling a particle down. In addition there are many uses that are yet undiscovered.

References:

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Fig 1: http://en.wikipedia.org/wiki/Image:Optical_Trap_As_a_Spring.jpg

Fig 2: http://en.wikipedia.org/wiki/File:Optical_trap_unfocused.svg

Fig 3: http://en.wikipedia.org/wiki/File:Generic_Optical_Tweezer_Diagram.jpg

Fig 4: http://en.wikipedia.org/wiki/File:Optical_cell_rotator.png