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# The Optical Tweezers and the Nobel Prize in Physics

Celso Luis Levada, Huemerson Maceti, Miriam Magalhães O.Levada, Ivan José Lautenschleguer

Science Teaching Group of the Herminio Ometto Foundation – Brazil
celsolevada@yahoo.com.br

***Abstract***— *The Royal Swedish Academy of Sciences awarded the Nobel Prize in Physics in 2018 to three scientists, Arthur Ashkin of Bell Laboratories, Holmdel, USA, Gérard Mourou of the École Polytechnique, Palaiseau, France, and University of Michigan, Ann Arbor, USA, and Donna Strickland of the University of Waterloo, Canada. Inventions that were distinguished with the award revolutionized laser physics. Extremely small objects and incredibly fast processes are now being seen by the incidence of light. These advanced and accurate instruments are opening up areas of research yet to be explored and can be used in many industrial and medical applications.*
***Keywords***— ***Nobel in Physics, Laser, Arthur Ashkin, Gérard Mourou, Donna Strickland.***

## I. INTRODUCTION

The Nobel Prize in Physics is an award distributed annually by the Royal Academy of Sciences of Sweden to scientists from various fields of physics. It consists of one of five Prizes established by Alfred Nobel in 1895, revering notable contributions in physics. According to Alfred Nobel's aspiration, the award is administered by the Nobel Foundation and the laureates are chosen by a council of five members elected by the Royal Swedish Academy of Sciences. The awards usually take place in Stockholm on 10 December, the anniversary of Alfred Nobel's death.

In 2018, Arthur Ashkin, Gérard Mourou and Donna Strickland were the three researchers awarded the Nobel Prize in Physics for contributions made in the field of Lasers Physics. These works, although related to Physics, are multidisciplinary and have practical applications in many other branches of knowledge, including Chemistry, Biology and Medicine. A brief biographical and curricular summary will be made of each of the laureates, with the help of information obtained on the web.

Arthur Ashkin(1) was born in Brooklyn, New York, in 1922, into a family of Ukrainian Jewish origin. His parents were Isadore and Anna Ashkin. Ashkin met his wife, Aline, at Cornell University, and then they got married and had three children and five grandchildren. Ashkin graduated from the James Madison School of Brooklyn in 1940. He attended Columbia University and was a Columbia Radiation Laboratory technician responsible for building magnetrons for US military radar systems. Ashkin earned his Bachelor of Physics degree from Columbia University in 1947, received his Ph.D. from Cornell University in 1952, and then went to work for Bell Labs at the request and recommendation of Sidney Millman, who was Ashkin's supervisor at Columbia University.

Gérard Mourou(2) was born in 1944 in Albertville, France. Mourou graduated from the University of Grenoble, where he obtained his Master degree in Physics in 1967, and graduated in 1970 at the University of Paris with a specialization in optics. In 1973, he obtained a PhD in Sciences from Paris University, currently University of the Sorbonne, working with short-pulse lasers. He performed postdoctoral research at San Diego State University, USA. From 1979, he worked at the University of Rochester, New York and, in 1988, joined the University of Michigan. Mourou also served as Director of the Laboratory of Applied Optics at the École Polytechnique, where he set up a research group on ultrafast lasers, concomitant with his academic career in the United States from 1977 to 2005.

Donna Theo Strickland(3) is a physicist specialized in laser and academic who was born in Guelph, Canada, on May 27, 1959. Strickland is married to Douglas R. Dykaar, a consultant in Optics and Electronics. The couple has two kids. She graduated in Physics Engineering in 1981 from McMaster University. She then obtained a doctorate in optics, with the thesis based on the development of an ultra-fast laser with application in multi-photon ionization, where she was overseen by Mourou. From 1988 to 1991, Strickland was a researcher at the National Research Council of Canada. In 1992, she worked as a physicist in the laser division of Lawrence Livermore National Laboratory. She has worked in the ultra-fast laser division of Lawrence Livermore National Laboratory and has also been a member of the technical team at Princeton's Center for Advanced Technology for Photonics and Optical-Electronic Materials. In 1997, she

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joined the University of Waterloo as a teacher, where she currently works and leads a study group in high-intensity laser for optical investigations.

## II. INFORMATION ABOUT OPTICAL TWEEZERS

According to DWIVEDI(4), the great development of biotechnology in the 1980s provided the arising of techniques capable of manipulating and extracting nanometric scale information from biological systems. Among them, it is possible to highlight the optical tweezers, which represent a tool that uses a beam of light to capture and move small particles. By exerting forces of the order of piconewtons on the captured particles, its main application is of interest microscopic, especially in the study of cells and biomolecules. The term "optical tweezers" was used by Arthur Ashkin in his article in the journal Science No. 235 in the year 1987.

This new tool meant the achievement of an ancient science fiction dream of using the radiation pressure of light to move physical objects. According to GOLLNICK(8), the German physicist Johannes Kepler (1571-1630) was the first to suspect that light had strength, and it was even able to push some objects. For him, the pressure of the sun's rays acted on the tail of the comets, sweeping them away, and always in the opposite direction of the Sun. Two centuries later, the Scottish physicist James Clerk Maxwell mathematically demonstrated that Kepler was right. The Kepler idea is confirmed, in 1873, by the Scot James Maxwell who creates the theory by which light is made of electricity and calculates the exact strength of the light rays. But light rays are usually rarefied and therefore very weak.

## III. OPTICAL TWEEZERS

It is important to note that in the optical trap, (Figure 1), the capture occurs in a way in which the entrapped particle does not remain fixed, but oscillates around a position of equilibrium, that is, it behaves like a Hooke's spring(7), governed by the equation $F = kx$, generating forces on an object proportional to its displacement from the center of the trap. It is as if there is a spring connecting the center of the particle to the focus of the laser (figure 2), so that when the laser is moved, the particle accompanies its movement three-dimensional. According to ASHKIN(7), for force measurements, the trap of the particles is approximated by a harmonic well, whose force can be determined by Hooke's law. This requires a method to measure the displacements of the trapped object relative to the center of the trap during the interaction. For this, one can use the aid of another optical trap acting as a disturbing force. In various experimental situations, it is desired to measure the force in the radial dimension or in the axial dimension. The interaction between light and matter can be understood as a collision that occurs when the incident photon has its trajectory deflected by a particle, causing a retreat in the object that deviated it and several forces arise as a result of the photons clashing with the particle to be captured.

Briefly, one can say that the optical traps involve the equilibrium of two types of optical forces, the radiation pressure force in the dispersion form and the gradient force. The first force pushes the object along the direction of light propagation while the gradient force pulls the object along the spatial gradient of light intensity. According to ASHKIN(7), when the gradient force is greater than the radiation pressure force, the object is attracted by the point of greatest intensity formed by the focused light and so it can be entrapped. However, if the gradient force is less than the radiation pressure, the direction of the resulting force tends to push the center of the particle away from the laser focus, ejecting it rather than imprisoning it. The balance occurs when the two forces equal each other. The gradient force is proportional to the polarizability of the particle as well as to the gradient of the field, while the radiation pressure force is due to the transfer of momentum from the light to the particle. These two forces are applied by a beam of intensity I on a dielectric particle of radius r.

According to ASHKIN and DZIEDZIC(11), the gradient force is given by:

$$\vec{F}_{grad} = 2\pi \frac{n}{c} \alpha \nabla I \qquad (1)$$

In this equation, the term $\alpha$ represents the effective polarization of the spherical particle in the medium, $\nabla I$ symbolizes the luminous intensity gradient, c is the speed of light and n is the refractive index of the medium. On the other hand, the force due to the radiation pressure, according to ASHKIN and DZIEDZIC(11), is given by the following relation:

$$\overrightarrow{F_{pr}} = \frac{c}{n} P_{pr} \vec{u} \qquad (2),$$

where $\overrightarrow{F_{pr}}$ represents the force due to the radiation pressure, c is the speed of light in the middle, n is the refractive index of the medium, $\vec{u}$ is a unitary vector in the direction of light propagation and $P_{pr}$ symbolizes the diffusion power of light.

The radiation force is the result of the reflection of the photons in the object, causing a separation force of the particle in relation to the light source. The force due to the gradient originates from the refraction of light through the sphere. For a spherical object, these forces are in equilibrium, causing the sphere to be positioned at the focal point of the laser beam. The problem of optical tweezers related to a microsphere of arbitrary radius is

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quite complicated. In view of this there are many works with limit theories, valid for microspheres representing the particle, very small or very large compared to the wavelength of the laser light used.

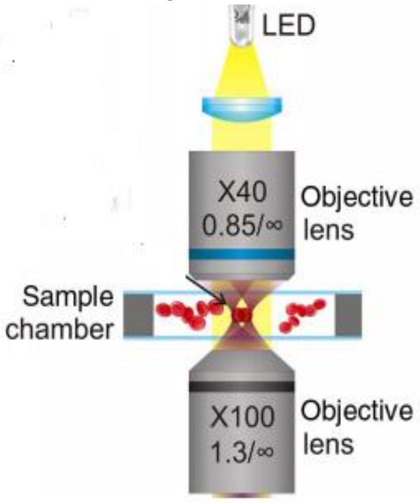


*Fig 1- Optical trap / Source Lee et al., Journal of Biomedical Optics 21(3), 035001 (March 2016)*

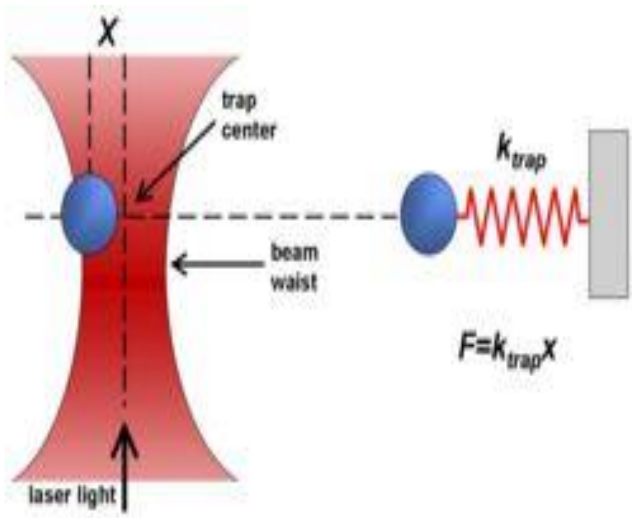


*Fig. 2 Dielectric objects are attracted to the center of the beam obey Hooke law*

Source: http://image.sciencenet.cn/olddata/kexue.com.cn/upload/blog/file/2010/4/201041414574052820 5.pdf

## IV. PRACTICAL APPLICATIONS

Several aspects of the optical tweezers make it a very important tool in the life sciences, such as its non-destructive remote handling and measurement capable since it uses light only in real time. The optical tweezers have been used in two ways, direct manipulation of microorganisms and measures of mechanical properties. According to BUICAN[5], the acceleration of the particles by short and high intensity laser pulses has a great potential of use in medicine, as in the treatment of tumors, allowing a high precision and a higher repetition rate of pulses. These laser pulses are widely used in optical correction surgeries, since they are associated to energies that may not be as high.

The technique of optical tweezers allows, for example, studying biological systems, especially the DNA molecule and its interaction with some important drugs in medicine, widely used in the treatment of human diseases. According to GREULICH[6], optical tweezers are applied in several studies such as the research of interactions between proteins and DNA, involved in the organization, replication, transcription and repair of DNA, as well as the study of protein energy field and kinetics of molecular motor.

Regarding ultra-fast laser pulses, it can be said that the processing techniques can be used in the direct recording by photo-resistance laser and other transparent media, in the creation of three-dimensional photonic crystals, as well as micro-optical components, grids, tissue engineering structures and optical waveguides. These structures are useful for enabling telecommunications and bioengineering applications that rely on the creation of increasingly sophisticated miniature parts. The precision, the speed of manufacture and the versatility of the ultrafast laser processing make it well accredited to become an important industrial tool.

## V. FINAL CONSIDERATIONS

According to EISBERG[9], the invention of the laser in the 1960s allowed access to a coherent source of light and was the beginning of many investigations into the properties of light and its interactions with matter. Laser has made it possible to exploit optical forces related to optical traps. Originally an acronym for Light Amplification by Stimulated Emission of Radiation. The way a laser works is by oscillating the electrons between two allowed states, causing them to emit a photon of a very particular energy when they fall from higher energy state to the lower. These oscillations cause the emission of light.

Since it was invented for the first time, there were other opportunities for scientists to develop techniques to make the laser better, more powerful and more efficient. When the laser was created, its beams were of low power because any attempt to amplify the light even more would destroy the device. However, using an ingenious approach, these nobelists were able to create ultra-short high intensity laser pulses without destroying the amplification material. Gérard Mourou and Donna Strickland paved the way for shorter and more intense laser pulses. Strickland is the third woman in history to win the Nobel Prize in Physics and the first in 55 years.

According to FIGUEIRA[10], until recently it was not possible simultaneously to create short and powerful pulses, since concentrating energy in a short time would imply creating distorted pulses or damaging the laser components. This inconvenience led us to believe that there would be no further innovations in the area and that laser research would have entered a process of stagnation. However, Mourou and Strickland were the first to recognize that the CPA technique, that is, Chirped Pulse Amplification, applied to the radars, could be used in optics. In the application of the CPA technique, it starts with a short laser pulse increasing its duration, and then amplifying this elongated pulse and, in the end, reduces the duration back to the original. Thus, the pulse is prevented from being short during the phase in which problems may occur. This type of laser produces extreme optical powers: very high energies concentrated in incredibly short durations, which today reach the thousandths of billionths of a second. These laser pulses characterize the shortest-lived phenomenon produced by mankind and consequently allow the study of other phenomena in incredibly short time and distance scales. These ultra-short lasers have numerous applications, including countless corrective eye surgeries that are performed every year. In addition to its practical applications, the method may open a new frontier of research in particle physics. On the other hand, scientists are already beginning to apply the technique to accelerate subatomic particles, which may in the future replace large accelerators such as the LHC.

## REFERENCES

[1] ASHKIN, A. https://en.wikipedia.org/wiki/Arthur_Ashkin, access in 03/10/2018

[2] MOUROU, G. https://en.wikipedia.org/wiki/Gérard_Mourou, access in 03/10/2018

[3] STRICKLAND, D. https://pt.wikipedia.org/wiki/Donna_Strickland access in 03/10/2018

[4] DWIVEDI, G. et al 2014 J. Phys.: Conf. Ser. 534 01205, available in http://iopscience.iop.org/article/10.1088/1742-6596/534/1/012059/pdf

[5] BUICAN, T.N. (1993) Optical Trapping: Instrumentation and Biological Applications. In: Jacquemin-Sablon A. (eds) Flow Cytometry. NATO ASI Series (Series H: Cell Biology), vol 67. Springer, Berlin, Heidelberg.

[6] GREULICH, K., Micromanipulation by Light in Biology and Medicine, available in https://books.google.com.br/books?isbn=1461241103, access in 05/10/2018

[7] ASHKIN, A. History of optical trapping and manipulation of small-neutral particle, atoms, and molecules. *Journal On Selected Topics in Quantum Electronics*. 6: 841-856. DOI: 10.1109/2944.902132

[8] GOLLNICK, B. Optical and Magnetic Tweezers: a Brief Historical Perspective, text available in https://www.linkedin.com/pulse/optical-magnetic-tweezers-brief-historical-benjamin-gollnick-ph-d-, access in 02/10/2018

[9] EISBERG, R. M. "Fundamentals of Modern Physics", John Wiley & Sons, Inc., 1961

[10] FIGUEIRA, G. "Como um ovo de Colombo deu um Nobel brilhante", text available in https://www.publico.pt/2018/10/12/ciencia/comentario/, access in 10/10/2018

[11] ASHKIN, A.; DZIEDZIC, J. M..: Optical Trapping and Manipulation of Viruses and Bacteria, Science 235:1517-1520 (1987)

[12] NEUMAN, K C. AND BLOCK, S M.; Review of Scientific Instruments 75, 2787 (2004), available in https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1523313/, access in 08/10/2018.