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Light !

An introduction to modern Physics of Light

Programme

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(for the scientific organizing committee)

Programme / Summary:

Light is around us every day, providing energy for life, contrast and beauty in our landscapes and in our art, tools for amazing technological progress, and a fascinating challenge for scientists. In 2014, two Nobel Prizes rewarded scientific achievements related to the usage or production of light: the Nobel Prize in Physics went to the inventors of the blue LED, and the Nobel Prize in Chemistry to those who first succeeded in tracking the few photons emitted by a suitably prepared single molecule. These prizes were not the first, and will not be the last. Light remains the most direct messenger between matter and us, the observers, be it at the smallest or the largest scales in the universe. Its interactions with matter can be exploited in many ways. This Summer School will provide insights into the intriguing double nature of light (electromagnetic wave and particle), and into the ways light can be exploited to explore nature from the tiniest scales to stars and the cosmos. The student will obtain an overview of the interactions between light and matter, and see detailed examples of how the understanding of these interactions helps inventing new technologies or manipulating the radiation itself.

While most lecture topics have been selected for their links to research projects at the Strasbourg and Freiburg institutes, we aim for a significant number of external lecturers (~50%). We have started contacting lecturers. Discussions are ongoing and the programme still evolving. Details of the program may change.

Preliminary School Program

LECTURES [see details on next page]

Introduction: the nature of light [1 day]

(a) A historical perspective

(b) An introduction to quantum optics: from the semi-classical approach to quantized light

(c) Light, horizons, and the geometry of space-time

Interactions between light and matter [1 day]

(a) Light for medecine : photodynamic therapy

(b) The production of *light* by matter – From light bulbs to monolithic blue LEDs (Nobel prize in physics 2014)

(c) Synchrotron light for various applications in material sciences

(d) The production of *matter* by light – pair production in extreme environments

(e) Public evening lecture : atmospheric phenomena

Light as a messenger [1.5 days]

(a) Large scales: stars and the universe

- Spectroscopic diagnostics in astronomy and astrophysics
- The case of the Sun and other stars
- What spectropolarimetry adds
- Collecting light at various wavelengths: a variety of technologies

(b) Small scales: new microscopies (Nobel prize in chemistry 2014)

(c) Small scales: Laser acceleration for particle physics

Manipulating light [0.5 days]

(a) Negative refraction - bending light the wrong way

(b) Getting light to propagate where one thought it wouldn't: plasmonics, strong coupling

(c) Ultra-fast laser spectroscopy: probing matter dynamics on ultra-short time scales

SCIENTIFIC ACTIVITIES

Poster presentations by the participants

Visit to the Kiepenheuer Institute for Solar Physics (Freiburg) and to the Solar Observatory at Schauinsland (near Freiburg)

Visit of experimental laboratories on the Strasbourg scientific campus (Université de Strasbourg and CNRS)

Experiments with an optical telescope at Strasbourg Astronomical Observatory (weather and time permitting)

SOCIAL PROGRAMME

Welcome reception

Evening reception at the Hotel de Ville followed by a trip around town in a “bateau mouche”Lights on the Cathedral (if the event is available)

One excursion to the Vosges, with a walk, a visit of a touristic highlight and a traditional meal of Alsace.

Visit to the European Parliament or the Council of Europe

Lecture summaries

Introduction: the nature of light [1 day]

(a) A historical perspective

School participants are expected to have at least a Bachelor's degree in science, and will know that light can be seen both as a propagating electromagnetic wave and as a flow of massless particles, the photons. Another well-known fact is that the speed of light is fundamental physical constant. The historical perspective will recall how these surprising facts were first suspected, then tested, leading to the modern framework that allows us to investigate ever more subtle interactions between light and matter.

(b) An introduction to quantum optics: from the semi-classical approach to quantized light

This lecture will focus on the most recent developments in our understanding of light. Possible highlights could be entanglement, or optical tweezers, or others, depending on the speaker.

The evidence of quantized exchange between light and matter, which occurs by emission and absorption of light grains that have been called “photons”, laid the foundation of quantum mechanics through the analysis of the blackbody radiation by Planck and the explanation of the photoelectric effect by Einstein. Despite eing so ancient, quantum optics is nowadays among the most fruitful research fields where quantum effects are explored. It is based on the ability to build states with special features that are related to the statistics of their photon numbers, and the way this is addressed. While classical light states are described by a Poisson distribution, novel emitters made of single nano-objects can produce single photon pulses. Nonlinear processes allow us to produce pairs of photons in entangled states. Cavities resonant with Rydberg atoms are used to perform quantum nondemolition measurements (QND), to prepare non-classical light states, and to probe their decoherence. Such studies open new perspectives in the procession of quantum information.

(c) Light, horizons and the geometry of space-time

Light has no mass, and propagates like no other massive particle: it follows the shortest path between two points in space-time, a path that is determined by the local geometry of the universe. This path is bent in the vicinity of mass concentrations, leading to relativistic phenomena such as gravitational lenses that distort our images of remote galaxies. Light propagates at a finite speed. This leads to the existence of fundamental cosmic horizons, beyond which no exploration is possible.

Interactions between light and matter [1 day]

(a) Light for medecine - Photodynamic Therapy

Photodynamic Therapy (PDT) is a technique clinically used in pathologies such as skin or oesophagus cancer, where tumors are destroyed by intense light- induced tissue oxidation. The method relies on the administration of a photosensitizer molecule that is suitable to induce the formation of active species which are powerful oxidizing agent, able to cause necrosis or apoptosis in cancer cells. The fundamental mechanisms by which the oxidation of biomolecules occurs are complex and imply chemical, physical and biological phenomena. This lecture will be an introduction to this complex world.

(b) The production of *light* by matter – From light bulbs to monolithic blue LEDs

After a brief review of the different light sources developed since the introduction of electricity, the lecture will focus on the operating principle of light emitting diodes, the technological barriers to overcome to bring them into industrial operation and the perspective of integrated semiconductor light emitting devices in future electronics. Special interest will be given to blue emitters made of gallium nitride, which are the subject of the 2014 Nobel Prize in physics.

(c) Synchrotron light for various applications in material sciences*Synchrotrons and other accelerators produce beams of bright X-ray light covering a broad range in energy, from infrared to X-rays. These beams are guided in a beamline to interact with the sample of material to be studied, allowing to investigate structural and dynamical properties of matter as well as analytical techniques in many different fields of science like chemistry, physics, materials, biology, medicine, environment, astrophysics, archeology… The lecture will describe the general functioning of modern synchrotron light sources and will give an overview of the various techniques provided by such facilities.*

(d) the production of *matter* by light – pair production in extreme environments *[if time permits]*

At high energies, photons can produce electron-positron pairs or pairs of other light particles. This actually happens! A few natural or man-triggered examples will be described (natural examples: the environments of neutron stars, pair-production supernovae; man-triggered: accelerators).

(e) atmospheric phenomena *[envisaged as a public lecture in the evening]*

Aurorae, halos around the moon and the sun (corona), circum-zenithal arcs, rainbows... many amazing phenomena surprise us when we stare at the sky. What is their origin? What do they tell us?

Light as a messenger [1 day]

(a) Large scales : stars and the universe

- Spectroscopic diagnostics in astronomy and astrophysics

The discrete energy levels of particles lead to preferred wavelengths for the emission or absorption of light: the spectral lines. The relative strengths, the positions, the widths, the shape of spectral lines have taught us much of what we know about the physical nature of stars and interstellar matter. They give us access to gas temperature, density and pressure, and to a measure of the velocities of cosmic objects with respect to Earth. Line profiles are also sensitive to interactions between particles. And by comparing the spectra of nearby and remote objects, we can test whether some of the constants of physics are really constant on cosmic timescales.

- The case of the Sun and other stars. The perspectives of spectropolarimetry

The Sun is only 8-minutes away. It shapes our day, and is our best-studied template for remote objects. Spatially resolved spectroscopy is only possible for the sun. It allows us to study time-dependent phenomena with unique precision. Solar vibrations (helioseismology), like Earth seismology, constrain the interior structure of the sun. Observations in many spectral lines give *insights into the heating of the Corona and the acceleration of particles to outer space. The study of polarized light from the Sun and stars is our best way of testing magnetic fields and their influence.*

- Collecting light at various wavelengths: a variety of technologies *[if time permits]*

The distribution of light across the electromagnetic spectrum gives us precious insights into the mechanisms that rule the lives of stars, the evolution of galaxies, and spectacular phenomena such as supernova explosions or accretion onto black holes. At radio wavelengths, photons are numerous and of low energy, and detection techniques are those of electromagnetic signals: enormous radio telescopes are built, and used jointly to reconstruct images via interferometric techniques. At the other end of the spectrum, astronomical sources emit X-rays and gamma rays – these photons are individually energetic, and are often detected one by one. X-ray "telescopes" are very different from optical ones. And gamma-rays are collected in even more indirect ways, using particle interactions in the Earth atmosphere.

(b) Small scales : new microscopies – going beyond the diffraction limit

These last years, some new techniques have overcome the diffraction limit of spatial resolution in microscopy, which was described by the Abbe's criterion. Some experimental procedures are based on the ability to isolate the emission of a single nano-object, giving rise to very useful methods for the tracking of bio-objects. Some others use very tiny tips to diffract near field into propagating modes. At last, hyper resolution methods like STED or STORM, whose inventions were rewarded by the 2014 Nobel prize in chemistry, use nonlinear response or photo activation of molecule to address single nano-objects. These new microscopy techniques allow us to take optics to the nanometer spatial scale.

(c) Small scales : laser ion acceleration *[if time permits]*

The laser-ion acceleration with ultra-intense and ultra-short laser pulses has opened a new field of accelerator physics over the last decade. Pulses of a duration of a few hundred femtoseconds can now be produced at intensities sufficiently high to induce strong charge separation. This leads to electric fields exceeding the acceleration gradients of conventional devices by 6 orders of magnitude.

Manipulating light, or matter with light [0.5-1 days]

(a) Negative refraction - bending light the wrong way

The concept of negative refraction was coined first in 1966 with Veselago and more recently in 2000 with Pendry. A material with negative refraction would bend light the "wrong" way, but it does not exist in nature. How can we produce metamaterials with such a property? After introducing these concepts, the lecture will move on to experimental demonstrations and discuss possible applications such as the "perfect lens" or the "invisibility cloak"

(b) Getting light to propagate where one thought it wouldn't: plasmonics, strong coupling.

While until recently, the emission and absorption of light were considered intrinsic properties of atoms, molecules, or crystals, the ability to design structures at the micro- and nanometer scale has opened new ways to control the optical properties of materials. Micro cavities or photonics band gaps make it possible to modify the density of electromagnetic modes surrounding the emitters and to change their coupling with that environment. Design of microstructures allows efficient coupling of light with plasmons in metallic materials. A new field of optics is emerging from these perspectives to control light-matter interaction.

(c) Ultra-fast laser spectroscopy: probing matter dynamics on ultra-short time scales

Ultrafast lasers produce light pulses as short as a few femtoseconds. These durations are of the *order or smaller than electron and vibration relaxation times: experiments using a sequence of pulses can thus give valuable information about the dynamics of excited states in a large panel of materials, from atomic to solid-state physics and chemistry. Electrons in semiconductor nanostructures, vibrational states in biomolecules, spins in magnets can be thus tracked over their lifetime. Moreover, the coherence of laser pulses can be exploited: quantum superposition of states can optically be addressed and determined. That gives rise to the possibility of developing new procedures for the optical control and measurement of atoms, molecules, nano-objects...*