QUANTUM SCIENCE CONCEPTS IN ENHANCING SENSING AND IMAGING TECHNOLOGIES: APPLICATIONS FOR BIOLOGY – A WORKSHOP

In order to prepare participants for the upcoming workshop, the planning committee has collected the following materials to provide an overview of different fields of science that are relevant to the use of quantum concepts in biological sensing and imaging. The workshop will bring together people from different expertise areas, including experts in both the physical and biological sciences. To encourage a common understanding across the different fields, the following materials provide basic information in both quantum physics and biological imaging and sensing. As you move through the document, you will notice that it starts by outlining some basic ideas in quantum physics, transitions to the applications of quantum physics in biological imaging and sensing, and ends with information on biological imaging and sensing. This document is not meant to be comprehensive, but is an opportunity to start exploring fields of science you might not be familiar with as you prepare for the discussions on this emerging area of research that we will explore during the workshop.

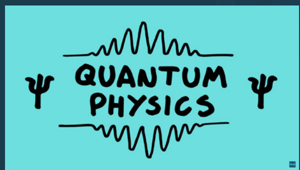
CONTENT LINKS

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

MATERIALS RELATED TO QUANTUM PHYSICS

The National Academies of SCIENCES ENGINEERING MEDICINE

VIDEOS



CLICK TO WATCH

This video gives a very basic explanation of some important concepts in quantum physics, and the background necessary for understanding some of the terminology.

CLICK TO WATCH

This video gives a basic overview of quantum spin and applies this knowledge to understanding quantum entanglement.

LINKS FOR ADDITIONAL READING

Six things everyone should know about quantum physics

Explainer: What is quantum tunneling?

Physicists find coherence and quantum entanglement are two sides of the same coin

TERMINOLOGY

Quantum Physics – Also called quantum mechanics, is the study of the smallest units of matter, such as molecules, atoms, and subatomic particles. At such tiny length scales, the laws that govern matter can be considered counterintuitive.

Correspondence Principle – When looking at the physical properties of large slow-moving objects, quantum mechanics becomes the same as classical physics. This explains why, even though larger objects are governed by quantum mechanics, we do not need to use quantum mechanics to understand the physical properties of many objects in our everyday lives.

Particle-Wave Duality – The idea that electromagnetic radiation, and particles such as electrons, have properties of both waves and particles. Importantly, you can observe either the particle-like properties or the wave-like properties, but you can never observe both simultaneously.

Heisenberg Uncertainty Principle – The mathematical explanation of the fact that there is a limit to how accurately we can know certain pairs of values associated with particles, for example velocity vs position of a particle.

Quantum Numbers – Similar to coordinates on a map, these numbers have values that describe specific properties associated with a quantum system. Electrons, for example, have 4 quantum numbers that describe energy, angular momentum, magnetic moment, and spin.

Spin – A quantum mechanical property (with no classical analogue) that describes how much a quantum object interacts with magnetic fields. Physicists and chemists usually represent a spin with an arrow that can be "down" or "up". These different states correspond to different energy states of such a spin property. Electrons have spin, as well as some atomic nuclei (H, 13C, N).

Tunneling – The ability of a particle (such as an electron) to propagate through a barrier (see "Links for Additional Reading" for a more detailed explanation).

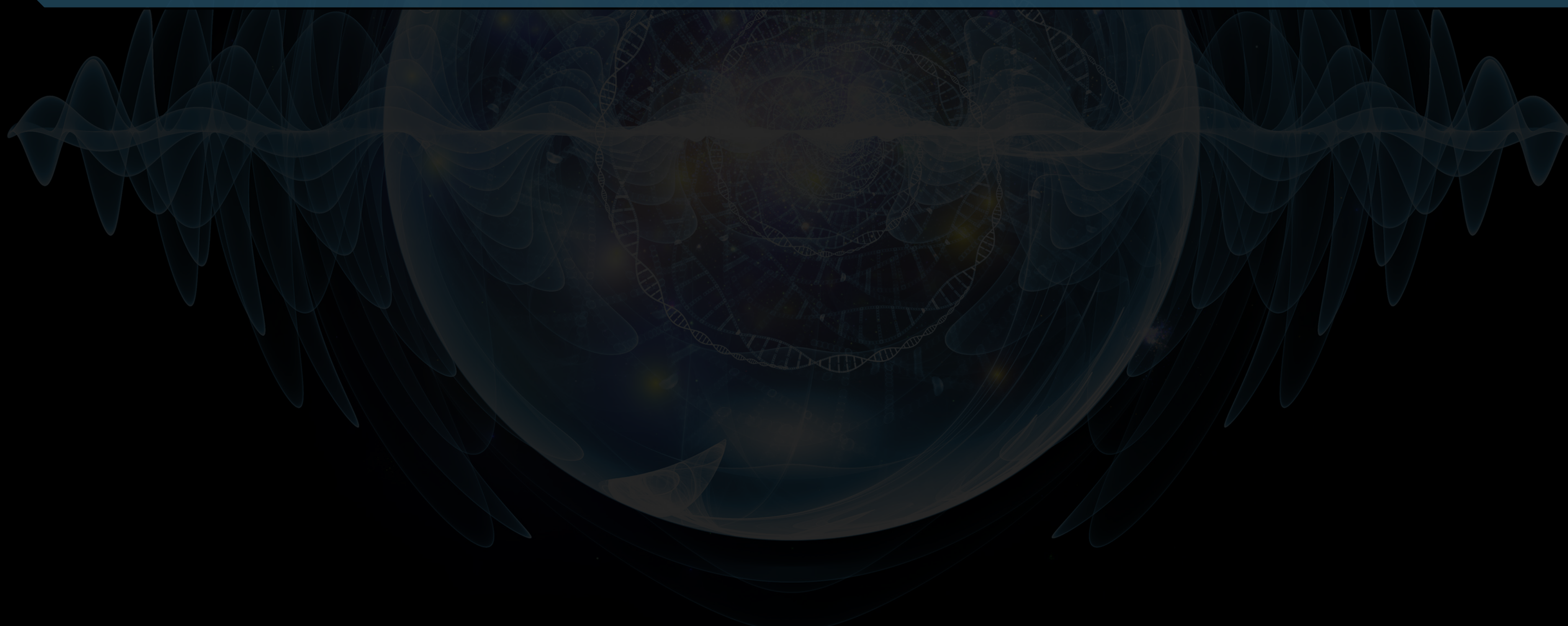
Coherent superposition – Reflects the fact that one single quantum object can be in two different states at the same time. For example, it can be in a coherent superposition of different energy states (see "Links for Additional Reading" for a more detailed explanation).

Spin Coherence – The degree to which a spin-bearing object (e.g., an electron) can maintain itself in a well-behaved superposition of spin states.

Spatial Coherence – Different from spin coherence. In particular, when the wavefunction of an object can interfere (constructively or destructively) with the wavefunction of another object that overlaps in the external spatial degrees of freedom (to be distinguished from spin as an internal property).

Decoherence – Every system that starts quantum dies classical. This fact, that underlies the reason why we live in a classical world, is explained by uncontrolled interactions (ex. thermal) of the quantum system with its "environment", or everything else lying around. These uncontrolled interactions cause the system's quantumness to decrease, and we say that the quantum system experiences decoherence. Decoherence times reflect the typical timescales for this loss of quantumness.

Entanglement – Involves two or more quantum systems. The idea that the quantum properties of different systems are linked, and dependent on each other (see second video for further explanation).



MATERIALS RELATED TO THE INSTRUMENTATION AND MEASURING IN QUANTUM PHYSICS

VIDEOS

CLICK TO WATCH

This video provides an explanation of the theory and instrumentation behind quantum physics work. The content was specifically produced for the Greiner lab at Harvard.

LINKS FOR ADDITIONAL READING

Three tricks physicists use to observe quantum behavior

Quantum Technology is great for Measuring

New Method could lead to more Powerful Quantum Sensors

Quantum Sensors Revolutionize Microscopy

Ultrafast Spectroscopy: timing is everything

TERMINOLOGY

Ultrafast Laser Spectroscopy – Laser pulsing techniques used to study the dynamics of atoms, molecules and materials at a very fast timescale (typically femto- or picosecond).

Qubit (or "Quantum Bit") – The basic block of quantum information, computing, or sensing.

Quantum Sensor – A quantum object that is used as a sensor. There is an extensive body of mathematical arguments proving that, if you use a quantum object to sense quantities, the sensing outcome is improved. In other words, the sensor's "quantumness" enhances the measurement.

Nitrogen-Vacancy Centers – A diamond is generally transparent, but a pair of defects such as a nitrogen atom (N) next to a vacant site (V), creates an NV center that is highly luminescent. The NV center's spin-dependent luminescent properties can be controlled by magnetic fields. An NV center is considered a prototypical quantum sensor.

Coherent Quantum Measurements and Control – Applying tailored electromagnetic radiation onto samples in order to direct and read-out the dynamics of quantum systems within those samples. One example is pulse sequences for nuclear magnetic resonance; such "pulse sequences," are examples of coherent quantum measurements and control.

Open Quantum Systems Formalism – Mathematical tools to describe quantum mechanical systems, such as those typically found in biological systems.

MATERIALS TO INTRODUCE QUANTUM CONCEPTS IN BIOLOGICAL SENSING AND IMAGING

VIDEOS

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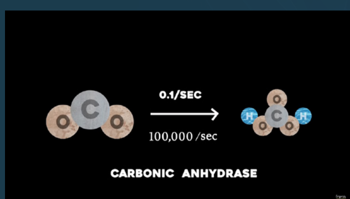
This video provides a basic introduction the field of quantum biology, including some of the goals of the research, and exciting discoveries that propelled the field forward.



CLICK TO WATCH

This video gives a basic introduction to the concept of quantum tunneling used by proteins.

LINKS FOR ADDITIONAL READING

The Future of Quantum Biology

Quantum biology may help solve some of life's greatest mysteries

Magnetoreception in animals

TERMINOLOGY

Fluorescence – A fluorescent molecule can be excited from its ground state to the excited state by absorbing a photon, and it emits a photon when it returns to the ground state. Because the emitted photon (or fluorescent light) is typically red shifted relative to the excitation photon, one can use a color-dependent filter to reject the excitation light and detect only the fluorescent photons. Such nearly background free detection allows ultrasensitive imaging of biological molecules tagged with a fluorescent molecule.

Bioelectromagnetism – Substantial experimental results suggest that quantum effects might underlie biological phenomena, including processes such as magnetic field detection for animal navigation, metabolic regulation in cells, and optimal electron transport in biomolecules. In particular, recent evidence indicates that sensing (both endo- and exogenous) magnetic fields via the quantum property of 'spin' might be more widespread and impactful for physiology than previously assumed. Weak magnetic fields were demonstrated to regulate: the production of reactive oxygen species, mitochondrial respiration, glycolysis rates, and growth in cells related to DNA repair.

In addition, electric fields (for example, related to cellular membrane potentials) have also been demonstrated to regulate different physiological processes, from embryonic development to mitochondrial functioning and optimal electron transport.

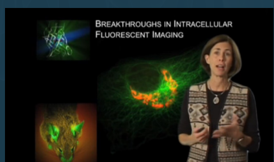
MATERIALS RELATED TO BIOLOGICAL SENSING AND IMAGING

LINKS FOR ADDITIONAL READING

Trends in nano-inspired biosensors for plants

What is Bioimaging?

VIDEOS



CLICK TO WATCH

This video gives an overview of new breakthrough technologies in fluorescence imaging and microscopy

CLICK TO WATCH

This video gives a short introduction to biosensors. While the explanation is health focused, the principles apply to all biosensors

TERMINOLOGY

Biological Sensing – The use of tools and technologies to measure how living organisms interact with their environment in order to accomplish different biological processes. While biological sensing can be broadly defined to encompass the observation of multicellular organisms, for the purposes of this workshop we will focus on interactions at the cellular level, both intracellular and intercellular.

Biological Imaging – A complimentary area to biological sensing that is more focused on gaining a structural understanding of cells, their various components, and surroundings, in order to better understand different biological processes.

Macromolecules – These are cellular molecules that serve a specific function. The basic categories of macromolecules are nucleic acids (DNA and RNA), proteins, lipids, and carbohydrates.

Protein – These are macromolecules within a cell that help maintain cellular structure and perform reactions. They are made up of chains of amino acids. These chains of amino acids are able to fold into precise secondary and tertiary structures which impart ability for the protein to perform specific tasks.

Membrane – Made up of groupings of phospholipids and proteins, they constitute the boundaries of the cell, organelles, and domains within organelles separating the outside from the inside.

Nucleic Acids – DNA and RNA. DNA is the molecule that contains all the instructions for cellular function, growth, and development. RNA, the translation of DNA instructions, is similar in structure, but provides a number of diverse functions, including the coding for protein structure, acting in a structural capacity, performing cellular reactions, and many other capacities.

Central Dogma of Biology – This represents the idea that all life is derived from the process by which DNA is read and used to synthesize RNA (specifically "m" or "messenger" RNA) through a process called transcription. The RNA is then read in a process called translation which produces a chain of amino acids that folds into a protein, also known as an enzyme. These proteins provide the scaffolding and perform the reactions that ensure the proper function of the cell.

Organelle – A discrete component of a cell where different macromolecules (DNA, RNA, proteins, lipids, and carbohydrates) are organized to perform specific cellular functions. Examples of organelles include the nucleus which houses DNA, chloroplasts which convert light into energy in plants and other organisms that use sunlight to produce their own food, and many others.