FACULTY OF SCIENCE

RESEARCH AT THE RACAH INSTITUTE OF PHYSICS

UPDATED AUG 2020

ASTROPHYSICS AND RELATIVITY

ABOUT

Recent discoveries — gravitational waves, extrasolar planetary systems, ultra high energy cosmic rays and neutrinos, distant galaxies and black holes, fast radio bursts, and more — have placed Astrophysics at the center of research in the physical sciences. The field addresses some of the biggest open questions in science today. What is the origin of dark energy and dark matter? How and where can we search for extraterrestrial life? What is the origin of the heaviest elements in the universe? How do black holes and neutron stars pair up, emit gravitational waves and merge?

While most of the research is theoretical we also carry out observations (mostly in radio astronomy). The group runs a computer cluster of several thousand cores that carries out advanced numerical computations. Recently, a relatively large (0.5 meter) optical telescope was installed on the top of Ross Building; its main use is for educational purposes.

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UPDATED AUG 2020

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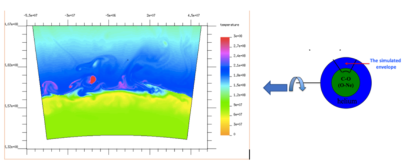

Color map of the temperature fluctuations in the accreted convective helium envelope. Snapshot at the moment of ignition of the detonation (red region).

Novae eruptions are usually found because of their spectacular and sudden optical brightening, which occurs over a matter of days. There are about 50 or so nova eruptions per year in the Milky Way. Some nearby ones — about a quarter of the way to the Milky Way's center or closer — are bright enough to see with the naked eye. The novae in nearby galaxies are also bright enough to be observable. After peak intensity, the nova typically takes weeks or months to dim by a factor of 10. Spectroscopic observations show that matter is ejected from novae at velocities ranging from about 300 km/s to almost 10,000 km/s.

The standard model for classical novae consists of a thermonuclear runaway (TNR) of a degenerate hydrogen rich envelope accreted on top of the core of a white dwarf in a close binary system. As long as the accretion process continues, the degenerate matter accumulated at the base of the hydrogen rich envelope is compressed and heated. Under the prevailing degenerate conditions, the heated matter is burning without hydrodynamic regulation by expansion. Therefore, explosive runaway occurs once the relevant timescale for heat release by hydrogen burning in the degenerate envelope becomes shorter than any of the available cooling mechanisms.

Lately, the discovery of GeV γ-rays from classical novae has led to a reassessment of this variety of explosions, and highlighted their importance for understanding radiative shocks, particle acceleration, and dust formation in more exotic, distant transients. Recent collaboration between observers and theorists has revealed that shocks in novae are energetically important, and can even dominate their bolometric luminosity. Shocks may also explain long-standing mysteries in novae such as dust production, super-Eddington luminosities, and “flares” in optical light curves.

I am exploring the physical mechanisms related to the novae eruptions mainly by numerical simulations. The main topics are:

1. Convective reactive flow and mixing mechanisms at the boundary between the white dwarf core and the accreted envelope.

2. Nucleosynthesis in nova. The contribution of novae to the chemical composition of the galaxy.

3. The expanding envelope and its interaction with the surrounding matter.

4. The dynamics of accreted helium envelopes. Mainly, the mechanisms for ignition of helium detonations in sub Chandrasekhar SNIa explosions.

ASTROPHYSICS AND
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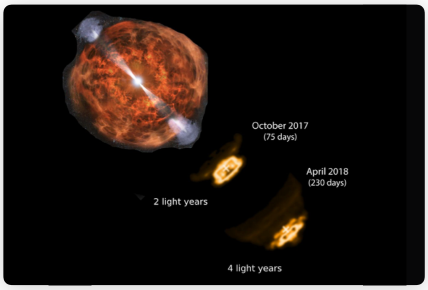
(a)

An illustration of a supernova explosion.

(b)

An illustration of a star tidally disrupted by a supermassive black hole.



(c)

An illustration of mildly relativistic outflow ejected from the first gravitational wave event ever discovered of a neutron star merger (based on results from our joint research).

The Explosive and Transient Universe

Time-domain astronomy has experienced a renaissance during this recent decade. This field encompasses explosive transients, variable sources, and moving objects. Thanks to the advent of synoptic optical facilities, the field of time domain astronomy is undergoing fantastic growth. The main goal of our observational research group at HUJI is the observational study of many types of cosmic explosions. While we study them in various wavelengths (including optical and Xray) our focus is on exploring them in radio waves (since radio observations provide unique diagnostics as they trace high-energy particles and magnetic fields), using several large telescopes around the world.

The richness of cosmic explosions and thus of our research topics is large: **1. Supernovae** - These are the explosive deaths of massive stars (see figure [a] for illustration). In our supernova study, we aim at characterizing some of the physical processes taking place at the explosion (such as shockwave properties) and link them to the properties of the progenitor star prior to the explosion. By doing so, we are building an empirical understanding of the last stages of stellar evolution leading to stellar death. **2. Tidal disruption events** - When a star passes too close to a supermassive black hole, it might be torn apart by tidal forces (see figure [b] for illustration). This phenomenon is still not well understood but leads to a flash of light when it occurs. In our observations of this transient phenomenon we address several key open questions in this field, such as, are relativistic jets launched and why? And what happens to the stellar debris? In parallel, this phenomenon allows us to probe the environment in the close proximity around black holes, a capability which is currently not possible in any other way. **3. New types of explosions** - In our research we observe, characterize and study new types of cosmic explosions, such as fast luminous optical transients. So far, with respect to this and other new and rare transient phenomena, we only found the tip of the iceberg, and working towards unveiling their nature. **4. New frontiers** - The discovery of **gravitational wave events** and of an electromagnetic counterpart associated with one of the events (our group was part of the discovery team; see an illustration of the moving outflow based on our research in figure [c]), has opened a new era of multi-messenger astronomy. Moreover, the radio astronomy field has seen tremendous developments over the last decade with the inauguration of new radio facilities which enables advanced and novel scientific research. Our group at HUJI is involved in several key scientific research programs centered on these new fields.

Students (both graduate and undergraduate) are welcome to apply for research student positions in our group. In addition to performing their own research, students in the group will have the opportunity to gain experience in working with several major telescopes worldwide and will also participate in top international collaborations in astrophysics.

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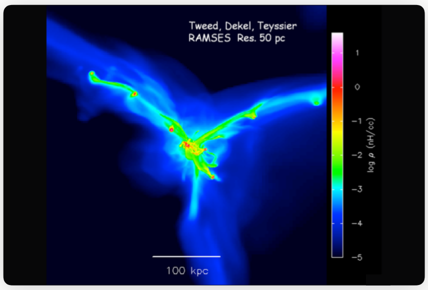
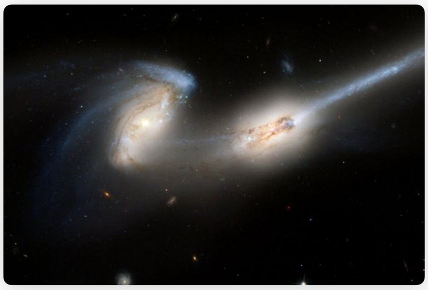


(a)



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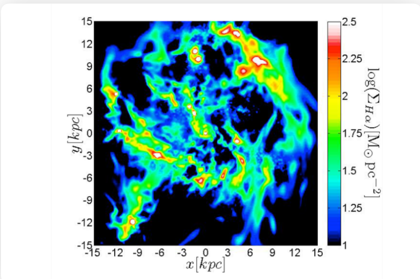

(c)

Research projects are available in the cosmology group led by Prof. Avishai Dekel and Dr. Nir Mandelker on a variety of topics in the cutting edge of cosmology and the theory of the formation and dynamics of galaxies and the large-scale structure in the universe. These projects can be offered to good students, for Ph.D., M.Sc., or undergraduate projects. The type of work ranges from analytic work, through numerical analysis, to developing and running challenging hydro-cosmological simulations. The projects could be theoretical, possibly involving cosmological simulations, or related to observational data. In particular, our analysis can involve advanced machine-learning methods for the comparison of theory and observations.

The current projects focus on open issues concerning the most active phase of galaxy formation, during the first few billion years of cosmological evolution, which is one of the most active fields of modern astrophysical research. The research program is part of an international team work aimed at developing a new theoretical understanding of the origin of galaxies and the large-scale structure in the universe.

Specific topics in the cosmology group research include the big-bang cosmological model and the big questions of dark matter and dark energy. The focus is on galaxy formation at its peak epoch, ten billion years ago. In particular, we explore the feeding of galaxies in the early universe by cold streams from the cosmic web **(Figure a)**, including galaxy mergers **(Figure b)**, through the hot gas in the dark-matter halos that host the galaxies at their centers. We study the formation of disk and ring galaxies on one hand **(Figure c)**, and the development of elliptical galaxies and dwarf galaxies, each presenting challenging open questions. A question of special interest is the interplay between the galaxies and the super-massive black holes at their centers. Very interesting challenges involve the mechanisms of star formation in galaxies, and the dramatic effects of feedback from supernova explosions and from the central black holes on the suppression of star formation and the ejection of gas from the galaxies.

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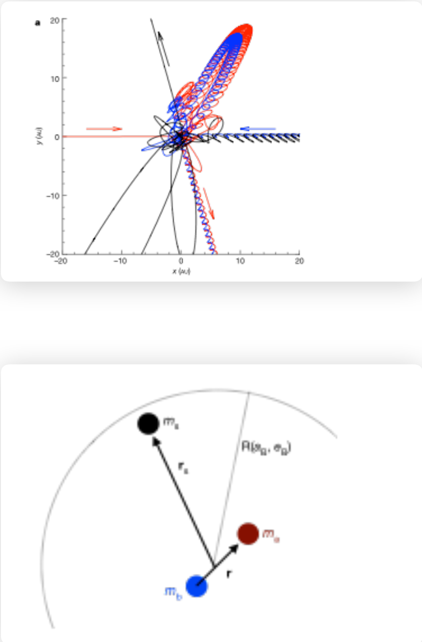

(a)

(b)

Fig. 1 | Non-hierarchical three-body scatterings.

a, Two-dimensional projection of an equal-mass resonant scattering encounter, where an interloper star (red) encounters a binary (blue and black). The resonant interaction unfolds over several dynamical times before the system disintegrates in a partner swap. **b**, Schematic illustration of the metastable triple at the moment of disintegration.

Our research group studies a wide range of questions in (mostly theoretical) astrophysics, using both analytical and numerical tools. Three key areas are listed below:

1. Supermassive black holes: most galaxies host a single one of these objects, which mass between one million and ten billion times the mass of the Sun. Despite the key roles that supermassive black holes play in galaxy growth and high energy astrophysics, surprisingly little is known about their formation and evolution. We study different mechanisms for forming the seeds of supermassive black holes, build models for "tidal disruption events" (luminous flares produced when unlucky stars are torn apart by a black hole's tidal field), and use observational data to make inferences about black hole demographics (distributions of masses and spins).

2. Gravitational waves: the LIGO and Virgo experiments have opened a new window on the Universe by detecting gravitational waves from merging (stellar-mass) black hole binaries, enabling new and powerful tests of general relativity. However, gravitational radiation is quite inefficient at extracting orbital energy from binary systems, and it is surprisingly difficult to get two black holes so close that they will inspiral in less than the age of the Universe. A zeroth-order astrophysical question remains unanswered: what astrophysical process is responsible for producing the majority of the observed gravitational wave signals, and what astrophysical environment is it happening in? There are currently half a dozen competing theoretical explanations, several of which we are modeling and investigating. We also make predictions for low-frequency gravitational waves emitted by supermassive black holes, which will be detected by the future space-based LISA interferometer.

3. Gravitational dynamics: the deceptive simplicity of Newtonian gravity leads to a beautiful diversity of self-gravitating systems, from the super-integrable Keplerian 2-body problem, to intrinsically chaotic few-body systems, all the way up to star clusters composed of millions of constituents, and galaxies composed of billions. We study the long-term behavior of large-N systems (e.g. galaxies) using the tools of non-equilibrium statistical mechanics. Small-N systems can more easily be investigated in a deterministic way, which we use to study exoplanetary systems and hierarchical triples. A notable recent success we are investigating further is our statistical solution to the generic three-body problem.

Suitable projects in these areas can be found for the interested student, especially one with a strong background in analytical mechanics, statistical mechanics, fluid dynamics, or general relativity.

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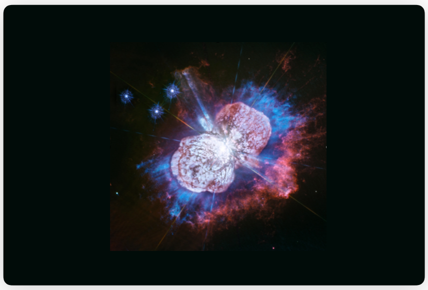

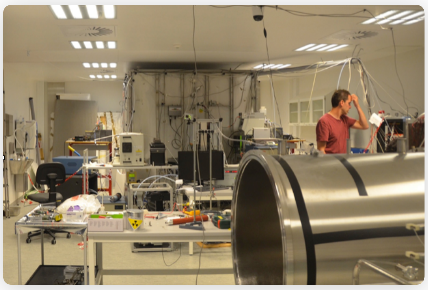

My interests cover two main themes. The first is the study of extremely luminous objects that surpass the so called Eddington luminosity "limit", the luminosity for which the radiation pressure is larger than the gravitational pull. Systems approaching this luminosity become unstable and the porous atmosphere that develops allows for a much larger radiative flux to escape. Massive stars, high rate accretion disks and supernova precursors are example of such objects which require appropriate modeling. Projects here range from analytic calculations to numerical simulations of various complexity. The image on the left is the envelope ejected by η Carinae during the 20 years it was super-Eddington.

The second theme is that of cosmic rays, which ranges from the modeling of cosmic ray diffusion in the dynamic galaxy to the study of their effects on earth's climate, on time scales ranging from days to billions of years. Projects here range from the analytical and numerical modeling of cosmic ray diffusion in the Milky Way, to modeling and measuring their effects on climate. Data and methods used are extremely diverse as well, ranging from astronomical and meteoritic data, to paleoclimatic and modern climate data. The methods are also diverse, and include even laboratory measurements in an on going experiment in Denmark.

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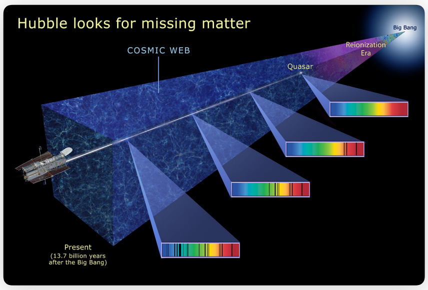

NASA, ESA, and and A. Feild (STScI).

Photo demonstrates how COS uses absorption of light from a distant source to probe the plasma along the line-of-sight.

Interstellar and Intergalactic Plasma

Most of the baryonic mass in the local Universe resides not in stars or planets, but rather in diffuse distributions of interstellar and intergalactic Plasma. In fact, as a result of baryonic processes of various scales - from stellar winds to intergalactic shocks - more than 90% of the baryons today exist in the form of diffuse ionized plasma. The study of ionized plasma thus plays a central role in modern astrophysics.

This field is driven by high-quality data obtained using the unparalleled sensitivity of the Cosmic Origins Spectrograph (COS) onboard the Hubble Space Telescope (HST), as well as other observational facilities. However, theoretical interpretation is often challenging: The dynamical and radiative processes through which stars and galaxies form and evolve drive the plasma far from equilibrium, and cause mixing and interaction between different phases. Through the hot galactic coronae cold accretion filaments flow, hot outflows burst, and neutral satellites zoom-past. Inside galaxies supernovae explode, and the hot bubbles that they blow push against the cooler phases, again causing mixing and interaction. These phase-mixing processes are all important ingredients of structure formation: they are related to star formation and demise and are coupled to the gas accretion rate, metal enrichment, and the extent and composition of galactic outflows.

Crucially, these mixing processes produce distinct UV and X-ray signatures. Interpreting existing observational signatures can thus provide unique clues regarding the formation and evolution mechanisms at play. My group's research helps provide the theoretical framework required in order to use UV absorption-line observation of gas in and around galaxies to gain a robust physical understanding of the physical processes affecting the gas.

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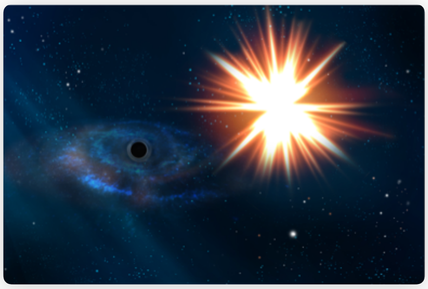

I am a theoretical astrophysicist, and my most of my research includes projects which involve extensive numerical simulations. Some of the topics I have focused on recently are supernovae, dynamics of stars close to supermassive black holes, and the physics of radiative shocks.

ASTROPHYSICS AND
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A star disrupted by a black hole
(numerical simulations)

A binary neutron star merger
(artist view)

A gamma-ray burst
(artist view)

Gravitational waves, black holes, neutrons star as well as single protons that have kinetic energy equals to a bullet, are some of the phenomena that I work on within the field of “relativistic astrophysics”. Extreme gravitational fields, the strongest magnetic fields and densities exceeding nuclear densities arise in these systems and enables us to explore physics that cannot be explored on Earth. Remarkably technological developments, such as the construction of gravitational wave detectors or new satellites and ground (and even underground) observatories that have been constructed recently enable us to explore these phenomena. While my research is theoretical it is closely linked to these observations, some of which have been predicted by my research while others have been interpreted using my results.

Currently my work focuses on three specific phenomena:

1. The mergers of binary neutron stars and black holes and the resulting gravitational waves and accompanying electromagnetic emission. Interestingly, these mergers are also the foundries where gold and other heavy elements are produced and my research encompasses this aspect as well.

2. Tidal disruptions of stars by supermassive black holes that exist in galactic centers.

3. Gamma-Rays, the brightest explosions in the Universe that arise when a massive star collapses to form a black hole. The collapsing matter produces (in a yet unknown process) a highly relativistic jets just before it falls into the black hole and these jets emit short bursts of gamma-ray bursts, producing for a brief moment the brightest objects in the Universe.

My research has been supported by two successive grants ERC grants, by the US National Science Foundation (NSF), by the Israeli Science Foundation and by the Israel Space Agency.

ASTROPHYSICS AND
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I study several hydrodynamics problems related to galaxy formation.

For example, alongside my group, I study the conditions in gaseous galactic halos, and how they relate to their environment in the cosmic web, and to the galaxy at their center. Observationally, the halo, or circumgalactic medium (CGM), can be observed by absorption in spectra that are emitted from quasars and penetrate through halos before being observed by telescopes on earth or in space. The observations indicate that gas in the halo is separated into multiple phases, with varying densities, temperatures and kinematic properties. Theoretically, we expect halos to be turbulent, magnetized and metal enriched, as a result from winds generated from the galaxies, and an external virial shock at the outer edge of the halos.

As gas flows along the cosmic web, filaments of gas penetrate galactic halos and interacts with them. This causes gravitational instabilities, Kelvin-Helmholtz instabilities and cooling instabilities. The survivability of these streams is key to understanding how gas is fed into galaxies.

These problems and more are studied using analytic techniques, numerical simulations and observational data.

ASTROPHYSICS AND
RELATIVITY

QUANTUM SCIENCE AND TECHNOLOGY

ABOUT

Physicists in the field are continuously developing novel optical methods to address, control and measure a wide range of quantum objects, including natural particles like photons and atoms, quasi particles which are quantum superposition of photons and matter, and even artificial atom-like objects such as quantum dots and superconducting circuits. Today we are at the stage where using these quantum objects, we can experimentally realize and study phenomena such as non-local entanglement and teleportation, which up to few decades ago were considered to be thought (Gedanken) experiments. Such experiments elucidate fundamental principles of quantum mechanics in real world settings, opening the door for next-generation technologies like quantum computation, quantum communication and quantum sensing.

The quantum science and technologhy team at the Hebrew University covers a rich set of topics. On the experimental side, research activities include quantum information processing and weak measurements with photons, development of single and entangled photon sources, quantum coherence of superconducting circuits, and quantum sensing with NV centers. On the theoretical side, novel theoretical methods to control and probe quantum coherence are being developed and lay the foundations for future quantum technologies.

The team members are also affiliated with the Quantum Information Science center, which fosters close collaborations between its members.

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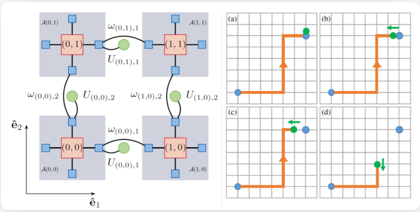

Sources: left - Emonts, Banuls, Cirac and Zohar, arXiv:2008.00882 (2020);
right - Zohar, Phys. Rev. D101, 034518 (2020)

My research focuses on developing and applying quantum information based methods for quantum many body physics; in particular, quantum field theories, of interest both in particle and condensed matter physics.

These are very complicated models to study, since they involve a number of degrees of freedom, described by exponentially large Hilbert spaces, that do not enable exact analytical or numerical treatment. In many relevant physical cases the interactions and correlations are very strong, and thus conventional approximation methods (perturbation theory or mean field, for example) are not valid either.

Along the way towards a quantum computer, which is a long, still ongoing challenge, two important milestones have been achieved: first, the understanding of quantum entanglement, special type of quantum correlations that govern a lot of phenomena in many body physics. It can be analyzed and exploited, and allows us to construct special types of quantum states that are physically relevant but easy to handle, and using them reduces the complexity of the problems: tensor network states. We study them analytically and numerically, generalize them to further classes of physical states (for example, gauge theories) and apply them to the study of nonperturbative problems.

Second, nowadays several experimental platforms, studied as quantum computer candidates, offer complete control in the lab and allow us to perform quantum simulation: the mapping of an unknown physical model to such a well controllable platform - a quantum simulator, serving as an "analog quantum computer" for a specially tailored task, enabling the direct observation and analysis of previously inaccessible physics. We study, analyze and design (theoretically or in collaboration with experimentalists) quantum simulators aiming at nonperturbative open problems of many body physics and quantum field theory.

The models of interest are very broad, and so far have included tensor network studies and quantum simulation, using cold atoms in optical lattices, of lattice gauge theories, aiming at new methods for dealing with bottlenecks in the study of nonperturbative gauge theories; in particular, Quantum Chromodynamics (QCD), the theory of the strong nuclear force. Besides that, of interest are fermionic models, and ways to represent them in non-fermionic terms. Other applications may include any many-body or field theory, either from the condensed matter or the particle physics disciplines.

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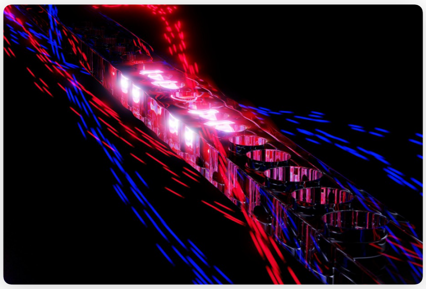

Artist's concept of a phononic crystal, with interacting vibrational and optical modes (credit: Simon Hönl, IBM Research Europe).

Quantum phenomena are routinely observed in microscopic objects of various kinds: photons, atoms, molecules, and currents in superconductors. But quantum mechanics applies to objects at all scales - or at least that's what we believe! In the last few years, it became possible to observe signatures of quantum behavior at the macroscopic scale, i.e. with fabricated systems up to nanogram mass. Understanding quantum phenomena better at this scale will shed light on the processes of quantum measurement and decoherence, and will expand the toolset available for new quantum technologies, such as sensing of extremely weak signals or processing quantum information. In the future, it may even allow exploring the connection between quantum mechanics and gravity.

I am interested in exploring and developing techniques to engineer quantum states in macroscopic objects - for example superposition states (à la Schrödinger's cat) or entangled states - and measure their dynamics. My research involves ultra-high-quality mechanical oscillators, such as high-stress membranes, phononic crystals, and others, that are sufficiently isolated from their environment, and at the same time can be strongly coupled to laser fields. These fields can be used to manipulate the mechanical state, e.g. to cool its motion (as in atomic systems), as well as to obtain information on the state. One challenge is to measure the quantum state in a non-destructive way, which translates to being able to resolve features finer than the quantum zero-point fluctuations.

Another research interest is novel quantum information processing paradigms. Unlike traditional qubits, which operate in a two-dimensional Hilbert space, harmonic oscillators operate in much higher dimensional (in principle, infinite) space, making it possible to encode quantum information in very robust ways. This can greatly reduce the requirements for quantum error correction and provide a breakthrough in the scalability of quantum computers. One of the ways this might be done is using the motional states of single trapped atoms.

Research in the lab combines different experimental disciplines, such as optics, nanofabrication, and cryogenics. I don't have a web page yet, but please see my Google Scholar for some relevant publications.

QUANTUM SCIENCE AND TECHNOLOGY

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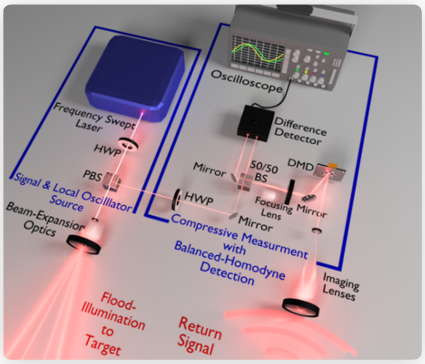

Professor Howell's research interests lie in the fields of classical and quantum optics.

His efforts have included ultra-precision measurements, fundamental tests of quantum mechanics, hot and cold atomic physics, quantum cryptography, quantum information processing, digital signal processing, slow light, low-light level nonlinear optics, quantum cloning, optical cloaking and laser radar.

His current interests include precision gravimetry, quantum gravity, ultra-precision measurements of Doppler shifts, Doppler mapping, weak values and precision inertial rotations.

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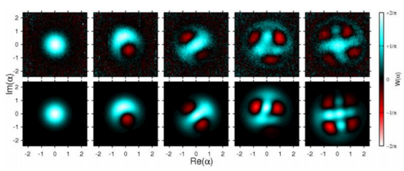

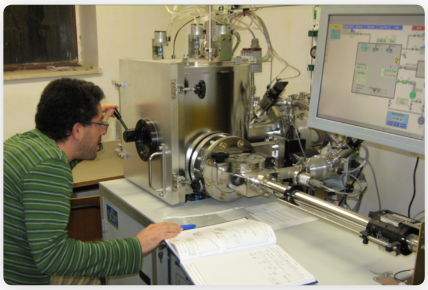

The purpose of the Quantum Coherence Lab (QCL) at HUJI is to explore the phenomena of macroscopic quantum coherence and decoherence. We study superconducting Josephson circuits, in which macroscopic physical quantities such as magnetic flux behave quantum mechanically. We also study implementations of macroscopic quantum coherence in slow and stored light in atomic ensembles, manipulating and storing non-trivial patterns of light and subsequently retrieving them.

The study of decoherence, in addition to showcasing fundamental physics, is crucial in overcoming the main bottleneck in the field of quantum computation and quantum information processing.

Excellent students interested in working on challenging projects are welcome to contact us!

QUANTUM SCIENCE AND TECHNOLOGY

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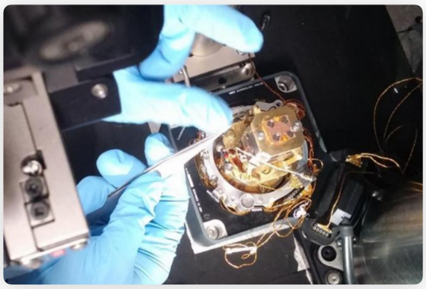

Quantum Science and Applications with Diamond

My research aims to create a new platform for both fundamental studies in quantum science and interdisciplinary applications. Specifically, I am researching the nitrogen-vacancy (NV) color center in diamond, which can serve as a building block for quantum information processing, quantum simulation and quantum sensing. My research program focuses on these three aspects of the diamond-NV platform:

Quantum information building blocks: NV centers have excellent quantum coherence properties, as well as remarkable optical and microwave control. We are extending the current state-of-the-art in this context, e.g. through optimized, advanced control sequences, reaching record coherence times. We aim at reaching the regime of fast coherent interactions in an NV ensemble, which would allow the creation of highly entangled states, including spin-squeezed states, with potential for significant impact on various quantum technologies, such as quantum memories and quantum metrology.
We are extending the concepts of quantum information science into quantum thermodynamics, considering the coupling of the NV to its environment, e.g. with the NV acting as an atomic-scale refrigerator. This approach could have significant impact on varied real-world applications of such quantum technologies, e.g. as a method for hyper-polarizing contrast agents for advanced MRI diagnostics (part of the FET-Flagship on quantum technologies).

Scalable quantum simulators in diamond: We are developing quantum spin networks with a large number of individually addressed spins (optically), coupled through superconducting structures (funded by the EU ERC Starting Grant). This work could lead to scalable, universal quantum simulation and quantum computing, addressing open research questions such as frustrated spin systems, surface codes, dissipative quantum dynamics of many-body spin systems and effects of disorder on quantum and topological phases.

Diamond devices as quantum sensors: Diamond based magnetic microscopy can be applied to various fields of science, including physics, biology and earth sciences. For example, we are studying magnetic signatures of minerals (in collaboration with Prof. Ron Shaar from the Institute for Earth Sciences), to gain insight into the physics of the underlying magnetization process, and to extract otherwise unavailable climatic data over a large timespan (tens of thousands of years). We are also studying novel condensed matter systems, such as newly discovered 2D van-der-Waals magnets (in collaboration with **Prof. Hadar Steinberg**). We are advancing toward incorporating super-resolution microscopy to magnetic sensing and to correlation microscopy, to enable measurements that are unachievable with other techniques. In terms of applications, we are developing a nanoscale MRI (Magnetic Resonance Imaging) device, to provide a cheap, portable and yet sensitive alternative, relevant for a variety of medical scenarios, and for situations in which traditional MRI machines are not available.

QUANTUM SCIENCE AND TECHNOLOGY

EXPERIMENTALIST

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One of the most important challenges in my field today is achieving feasible quantum applications and technologies based upon quantum mechanical principles. My research group will focus on understanding fundamental quantum systems along with advancing quantum control over integrated nanophotonic quantum systems.

Our vision is realizing quantum information processing (the basis components of quantum computing), novel linear and nonlinear quantum materials and quantum applications, such as quantum networks. This will be done in specific laboratory conditions we will enable here at HUJI.

In this path we combine experimental techniques of quantum control, low temperature, optics, nanophotonics, material science, along with theoretical and computational tools of quantum optics and quantum information. Our group is for students who love physics and want the opportunity to push science and technology to the next stage in a state-of-the-art lab.

QUANTUM SCIENCE AND
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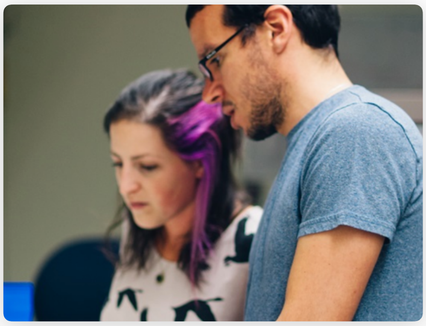

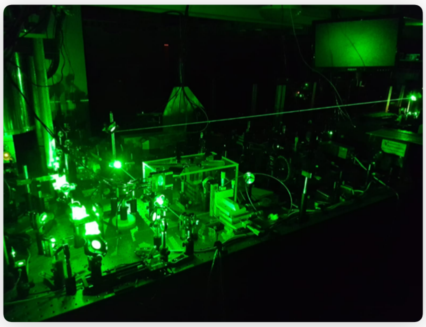

Nanophotonics of Quantum Structures Lab

Quantum physics reveals its most surprising and puzzling aspects on microscopically small systems. Some of the most astonishing phenomena occurs when many identical quantum particles “dance” together in a collective manner, and exotic effects like superfluidity, superconductivity, quantum Bose-Einstein condensation, and massive quantum entanglement suddenly appear. Atoms are the most natural objects to observe quantum effects, but atoms are heavy and therefore their collective quantum behavior can only be seen at extremely low temperatures.

In our lab we engineer tiny, nanometric-sized solid quantum structures where we can excite, using just light, “ultralight artificial atoms” made of dancing energetic electrons. These quasi-particles, called “excitons”, are the building blocks for exploring new exotic collective quantum phases of matter, like super-solids, hybrid light-matter particles, and quantum liquids, and for designing new quantum-photonic devices, such as single photon sources and photon quantum gates for quantum information technologies.

Here are some examples of what we scratch are heads on:

Harvesting quantum light: how does light and nano-matter interact on the quantum level, and can we use it for making ultrafast, ultra-pure single photon sources and nano-optical devices for quantum cryptography and quantum computing?

Light-induced ultra-cold quantum condensates on a chip: how can we turn light (photons) into an artificial quantum matter (a quantum condensate) inside nano-structures?

Mixing light and matter for future quantum opto-electronics: photons in vacuum do not interact. How to make new quasi-particles which are half-light half-mater and use them to make photons that interact strongly with each other? This is a basis for photonic quantum gates.

Two dimensional artificial atoms in flatland: How can we use combinations of two dimensional layered materials to create tiny devices with engineered artificial atoms?

Students who join our group experience state-of-the-art experimental tools and quantum many-body models, as well as advanced simulations of system dynamics, and of course lots of black coffee.

QUANTUM SCIENCE AND
TECHNOLOGY

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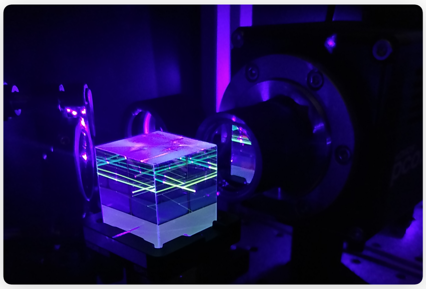

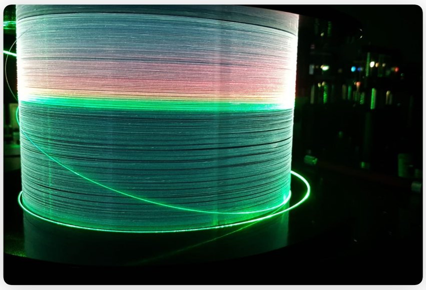

Complex Photonics Lab

We study experimentally how light interacts with complex photonic systems, such as scattering media, disordered multimode fibers, aperiodic photonic crystals and more. Such systems are composed of a large number of spatial, spectral, and polarization degrees of freedom, which are strongly coupled due to disorder. Our curiosity driven research focuses on understanding the fascinating physical phenomena that emerge in these systems, which exhibit both the quantum (particle-like) and classical (wave-like) nature of light.

Specific research interests:

Quantum optics: Entanglement is one of the most counterintuitive phenomena in quantum physics. We study the physics of highly entangled photons in complex systems and explore how they can be harnessed for novel quantum technologies.

Fiber optics: Optical fibers are an attractive solution for meeting the ever-growing demand for high-bandwidth, low-loss, reliable technology. They are at the heart of many day-to-day technologies, such as data transfer and medical endoscopes. Studying the physics of such systems is key for overcoming the inherent challenges they present.

Light in random media: Thick random samples like human skin, white paint or clouds, are opaque, as most of the light that illuminates them is backscattered. We develop methods to cancel the effect of scattering for imaging and communication applications.

Nonlinear optics: The interplay between nonlinearity, disorder and interference exhibits fascinating and rich physics. Multimode optical fibers are a perfect testbed for studying such phenomena, as they exhibit strong nonlinearity and random mode mixing. We launch into the fiber ultrashort optical pulses and explore the role of mode-mixing in nonlinear processes such as white light generation, spontaneous four-wave mixing and self-phase modulation.

QUANTUM SCIENCE AND
TECHNOLOGY

BIOPHYSICS

ABOUT

Physicists' methodology of studying Nature has unravelled various phenomena that were traditionally labelled as belonging to Chemistry, Engineering, etc..., and thereafter became an inherent part of Physics. Biology is the challenge of the new century. It is notoriously complex and a coherent theoretical description of biological system is lacking. However we are witnessing a revolution in the ability to study biological systems quantitatively. Furthermore new methods are developed yielding huge amounts of data. Still interpretation of such data hinges upon discovering the general principles governing biological complexity.

The goal of the Biological Physics group at the Racah Institute is to uncover the general principles governing various biological systems using a combination of experimental tools (microfluidics, high resolution microscopy, automated systems, whole genome sequencing), theoretical approaches taken from the study of physical systems (statistical mechanics, non-linear dynamics), and cutting edge analysis tools developed for biological systems (neural networks, big data analysis, deep learning).

These approaches have led to new insights on the way biological systems operate from the single molecule to the organ level, as well as medically relevant findings.

MEMBERS

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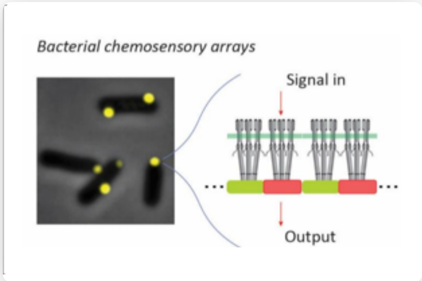

Biophysics: sensory signaling in bacteria

Bacterial cells continually sense external signals and accordingly execute adaptive responses. We study the bacterial chemotaxis system that serves as a highly tractable model system for exploring principles of sensory signaling at the molecular, cellular, and population level. The chemotaxis system allows the bacteria to track chemical gradients and thereby influences their distribution in the environment, including the process of host invasion.

Notably, the chemosensory apparatus is a large, membrane-bound, array of sensory molecules. To study how signals are perceived and processed by these molecular arrays we use various microscopy techniques that allows real-time detection of the physical and biochemical responses of the sensory molecules to external stimuli. The corresponding behavioral responses of the bacteria to environmental challenges are also studied by using microscopy, combined with channel-based devices.

BIOPHYSICS

THEORETICIAN

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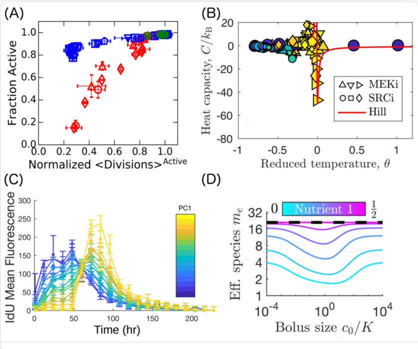

My research interests lie in the physics of living systems. I am fascinated by how effective physics is at reducing the material world to compact equations. When it comes to living systems, their huge complexity seemingly poses a barrier towards finding unifying principles. Yet I believe it is possible to strip down this complexity to its essential elements to understand biological systems with the same depth and rigor physics has brought to our understanding of non-living matter.

My aim it to discover general principles that govern living systems using theoretical tools, while remaining close to experimental data; I find it exciting to be a real partner to experimentalists in these pursuits. Currently, I am focused on the physics of the immune system and of the microbiome; both these systems are essential to our health, sustain quantitative experiments, and yet their theory is in its infancy.

I borrow techniques from statistical physics, nonlinear and stochastic dynamics, numerical simulations, big data analysis and machine learning.

BIOPHYSICS

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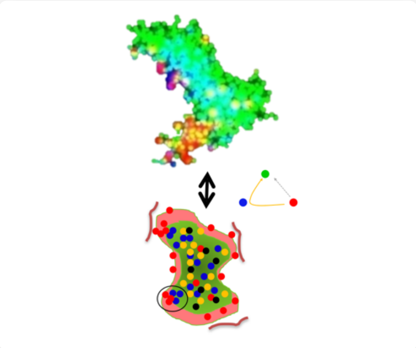

Nanostructure and cooperativity of protein complexes

ES et al, Nat Comm 2016
ES et al, Immunity 2011

The Sherman lab for Biophysics

The cell is the smallest unit of life. In the laboratory for Biophysics at the Racah Institute of Physics, we are interested in understanding the cell as a complex, out-of-equilibrium system where stochastic processes such as reaction-diffusion give rise to emergent, and often concerted processes that allow cell function and 'decision-making'. Such processes include molecular self-assembly, signal transduction, information processing, and cell activation.

Importantly, the stochasticity of cellular processes gives rise to inherent heterogeneity and asynchrony in cellular processes, which are averaged out by current research techniques. To gain a fundamental understanding of such processes, we develop and employ enabling spectroscopic methods and super-resolution light microscopy to resolve single molecules and molecular interactions in intact (fixed and live) cells. To interpret our data, we develop and apply statistical analyses of point processes, models from non-equilibrium statistical physics and simulations of complex systems. We then apply these methods to study the biophysics of emergent and critical, yet poorly understood, processes in the cells, as detailed below.

Our description of these processes in single molecules detail allows us to shed new light on the interplay between stochasticity and nanoscale organization and their role in cell function.

Specific topics of interest include:

1. Developing techniques for super-resolution microscopy in live cells, esp. at the single molecule level.
2. Resolving the cooperativity and structure of protein complexes, and their role in cell signaling and activation in health and disease - e.g. in immune cells and in cancer.
3. Studying the mechanical properties and work of living cells.
4. Molecular random walks and underlying mechanisms of protein sub-diffusion and self-assembly.

BIOPHYSICS

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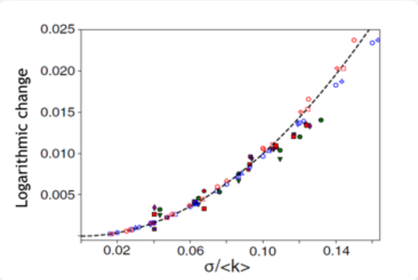
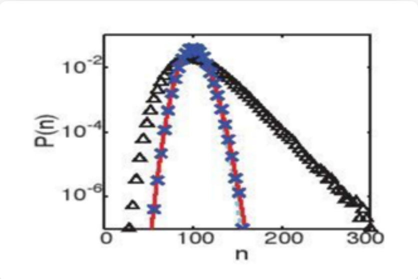


Logarithmic increase in the frequency of large deviations as network heterogeneity increases



Extrinsic noise greatly affects probability distribution function of copy numbers

Research interests

I am interested in non-equilibrium statistical mechanics, large deviation theory, gene regulatory networks, statistical physics on networks, and stochastic animal movement.

We use methods from statistical and quantum mechanics to study stochastic populations residing on degree-heterogeneous networks with nontrivial topology.

We also study stochastic gene regulation and genetic switches, focusing on the interplay between intrinsic and extrinsic noise. Finally, we study the role of noise in evolving reaction-diffusion ecosystems and animal movement.

BIOPHYSICS

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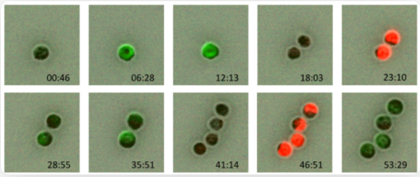

Automated analysis of cancer cells division reveals a chaotic process in the cell-cycle (Nature, 2015)

The goal of Biological Physics is to reach an understanding of biological processes that is based on a mathematical description that is quantitative and predictive. In Einstein's words, we would like to describe biological systems with equations that are "as simple as possible, but not simpler".

The key biological process at the heart of Biology is the process of self-replication. The amazing process that allows a cell to make an (almost) perfect copy of itself, is what defines Biology.

The Balaban lab combines theory and experiments to reach that goal. The theoretical ideas are based on principles of non-linear dynamics used in Physics and the study of high dimensional networks using deep learning. Theoretical ideas then drive the way quantitative experiments on single cells are performed, which in then trigger the development of new theoretical approaches.

The projects in the lab can be anywhere from 100% theory to 100% experiments. For example, we develop new experimental tools to study single bacteria under the microscope (microfluidics chips, automated image analysis software development, automated microscopy...), extract quantitative information of single bacteria and analyze them in the framework of a model that can predict their behavior under a large range of conditions. Applications stemming from this research may impact the way bacterial infections and cancer are treated.

BIOPHYSICS

THEORETICIAN

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I am interested in physics of motion out of thermal equilibrium, quantitative description of social influence using financial market data, evolution of information assessment and light matter interaction.

1. Out of thermal equilibrium, an environment imposes effective mechanical forces on nano-fabricated devices as well as on microscopic chemical or biological systems.

One can ask the question how to calculate these forces together with the response of the system from first principles.

2. Observations of animal contests pose a question whether the decision to quit the fight depends on the own state of the player (self-assessment) or on a state of the opponent (mutual assessment). I am trying to address this problem using evolutionary game theory and neural network techniques.

BIOPHYSICS

THEORETICIAN

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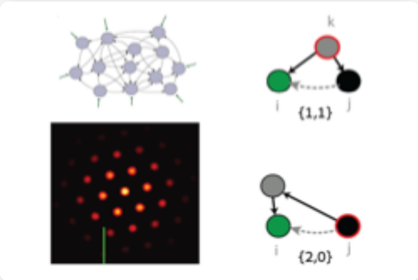

Yoram Burak's research group investigates how neural circuits in the brain perform biologically relevant computations, such as: maintenance of short term memory, sensory inference, spatial computation, and generation of sequential neural activity.

Lab members apply diverse theoretical and computational tools borrowed from statistical physics, the theory of nonlinear dynamics, information theory, and machine learning to approach, in a principled way, questions on design principles and mechanisms that underlie computation in the brain. We are also interested in the relationship between organization and function in other biological systems, and in the statistical physics of soft matter.

BIOPHYSICS

CONDENSED MATTER PHYSICS

ABOUT

Condensed matter physics is concerned with elucidating and exploring properties of many-particle systems that emerge from the interactions between their constituents. It covers an enormous range of phenomena and length scales, all the way from atoms to exotic quantum effects in macroscopic objects. Consequently, it is responsible for much of our basic understanding of the world we experience, while offering avenues for various technological applications.

The condensed-matter group at the Racah Institute is involved in a broad spectrum of research activities. On the experimental side these span topics such as superconductivity, light-matter interaction, physics on the nano scale, electronic glasses and solid-state devices, using a host of experimental tools from transport measurements to optical techniques and a number of surface probes. In parallel, the group has access to advanced fabrication and characterization facilities at the Nano Research Center.

The theoretical group studies strongly correlated electronic systems, superconductivity and topological phases of matter using a variety of advanced analytical and numerical techniques. The research is done while keeping in close contact with experimental groups, and involves interfaces with other disciplines such as high-energy physics and computer science.

MEMBERS

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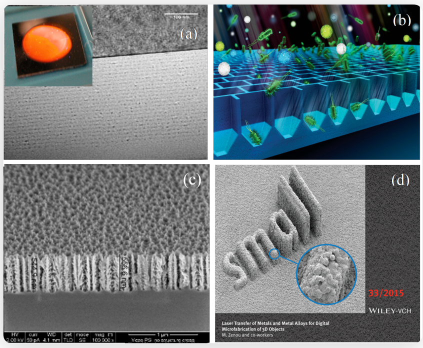

Our research is aimed at developing semiconductor-based nano-structures, investigating their fundamental properties and developing a variety of electronic, optoelectronic and photonic devices that are based on these nanostructures. To this end, we have developed techniques to create silicon-based nanostructures (such as porous silicon) see **Fig. (c)**, silicon nanocrystals **Fig. (a)** and silicon photonic crystals see **Fig. (b)**. We have conducted an extensive research to reveal the underlying physical mechanism responsible to the unique optical properties of these nanostructures, particularly the strong, room-temperature luminescence across the visible and the near infrared range of the optical spectrum from most type of silicon nanostructures; see, inset to **Fig. (a)**.

In addition, we have performed an extensive research for exploring transport and conduction phenomena in these nanostructures. On the application side, we have developed a laser-based method for direct digital printing of metals and semiconductors structures based on silicon (in a close collaboration with our industrial partners - PrintLogic Ltd.). The printing method, called "LIFT" (laser induced forward transfer), is capable of printing complex structures of metals and semiconductors in three-dimensions (3D) with a fairly high spatial resolution; see **Fig. (d)**. More applied research projects include the development of photovoltaic solar cells made of thin films of silicon and organic-inorganic perovskite nanostructures **Fig. (c)**; developing thin films of MOS-like transistors and light emitting devices (such as lasers); developing biosensors based on silicon photonic crystals including sensors for the sensing of viruses (such as the Corona virus.

CONDENSED MATTER
PHYSICS

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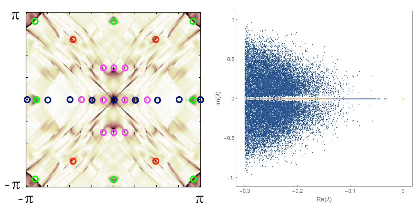

Richard Feynman noted that discovering the fundamental laws of physics is like trying to learn the laws of chess by observing chess games. I am interested in the opposite question: **How do exceedingly complicated physical behaviors, akin to chess games, emerge from a set of simple basic rules**. In particular, I investigate quantum systems where collective non-trivial phenomena emerge from the strong interactions between many particles. Examples include high-temperature superconductivity, the quantum Hall effect and spin liquids. The research involves studying phenomenological models in order to explain various experimental signatures, as well as more microscopic models that allow to identify the underlying mechanisms. The left figure is an example of the former, and depicts the expected signal from scanning tunneling microscopy of an exotic superconducting phase called a pair-density wave.

More recently, I have been interested in studying open quantum systems out of equilibrium with the specific goal of identifying universal features in their dynamics, such as the way they approach their steady states. To this end, I have employed ideas from random matrix theory to study the spectral properties of the Liouvillian, which is the generator of the dissipative time evolution. Together with my collaborators we have found that beyond a critical strength of the coupling between the system and its environment the decay to the steady state progresses through a series of isolated and universal decay channels. This is related to the appearance of isolated real eigenvalues of the Liouvillian, as depicted in the right figure.

CONDENSED MATTER
PHYSICS

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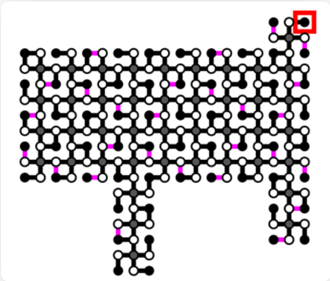

TemplereyPatchTree

I do research in the field of mathematical physics with applications in condensed matter physics. To explane some of the most interesting phenomena in nature one must, in many cases, not only invoke physical principles but also rather intricate mathematical structures. It is surprising that wave structure of shallow water, the conduction at low temperatures or the properties of molecular chains, to name but a few examples, may have something to do with the Riemann Hilbert problem, the inverse scattering method or group theory, but it so happens to be the case.

My research focuses in elucidating such connections in a way that allows to practically describe physical systems through exact analytical computations.

CONDENSED MATTER PHYSICS

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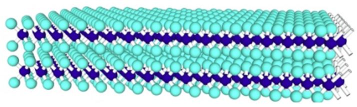

Each layer consists of 3 atoms, and is 0.6 nm thick.

Many new discoveries in solid state physics emerge from the study of new materials. Even more interesting is the combination of different materials, and the study of how they interact with each other. Our dream is to design and build material systems, assembling new structures from basic elements.

Developments in the past 2 decades bring us close to this dream. In my lab we study layered materials, which peal easily – by using sticky tape. A trained student in my lab can peal a chunk of material down to a single atomic layer – just like selecting a card from a deck.

Example. There is a whole family of layered materials that share the structure on this right:

Each layer consists of 3 atoms, and is 0.6 nm thick.
When we peal them, this is what we get. The material is this image is a semiconductor. The darker parts are thinnest. They are 2 layers (1.2 nm) thick.

Now we can get to work. Our next step is to stack these materials – layer by layer, atom by atom. Here we see a stack of two materials. One is a superconductor (MoS2), and the other is a semiconductor (NbSe2). This stack already has electronic contacts, which we build in our nanofabrication center. Together, we get a device where electrons can tunnel through the semiconductor, and reach the superconductor. Such a tunneling device is a sensitive spectrometer. Using the device on the right we learned that the superconductor actually has two types of carriers. We can tell that by the two peaks in the spectrum on the left.

What else can we learn from such devices? Something very interesting happens if the semiconductor is defective. If a single atom is missing, we get a “stepping stone”, which allows discrete electronic transport through an otherwise opaque barrier. Such a defect is called a quantum dot. We found, that such quantum dots can actually become superconducting, if they reside very close to a superconductor. We can also use the dot as a very local spectrometer, and as a sensor of electrical field.

CONDENSED MATTER
PHYSICS

THEORETICIAN

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Amusia, Miron Ya., Emeritus professor, born 18.11.1934, D.Sc. in theoretical and mathematical physics, APS fellow, Humboldt research award recipient etc., author/ co-author of 18 books, and more than 530 refereed papers, and 500 conference talks. Scientific adviser to 25 PhD students, 14 of whom are full professors.

Main direction of scientific activity is investigating manifestations of interparticle interaction in the behavior of many-particle systems.
A simple approach to understand the behavior of such a system is to present it as a model system of weakly interacting quasi-particles that move in a common field. The simplest but very productive approach to quasi-particle system is to entirely neglect the interaction between them that leads to so-called independent particle approximation (IPA). It permits to make an important step in describing nuclei, atoms, molecules, clusters (including fullerenes and endohedrals), as well as condensed matter objects. But in a number of processes, e.g. in photoionization, IPA is insufficient. So, it is necessary to take into account the so-called residual interaction that results in strong collective effects, which are prominent in all above-mentioned objects. The collective effects lead to complexity of all these objects. Amusia's primary aim today is studying complexity of endohedrals and manifestations of fermionic condensate in fermion liquids and solids at low temperatures.

Entirely, The current research interests of M. Amusia are :

1. Properties of fullerenes and endohedral as building blocks of materials,
2. Fermion condensation as a new state of matter,
3. Photoabsorption and photoemission by multi-particle systems,
4. Many-body effects in endohedral, fullerenes, atomic and nucleonic collisions.

Most important resent results

1. It is demonstrated that the photoionization cross-section of an endohedral is qualitatively modified due to action of the fullerenes shell upon the photoelectron. It is predicted that outer shell endohedral photoionization cross-section exhibits a giant endohedral resonance.
2. It is demonstrated that Fermion condensation leads in numerous objects to the universal behavior that permits to introduce a notion of a new state of matter that exists in condense matter and a number of solids.

CONDENSED MATTER
PHYSICS

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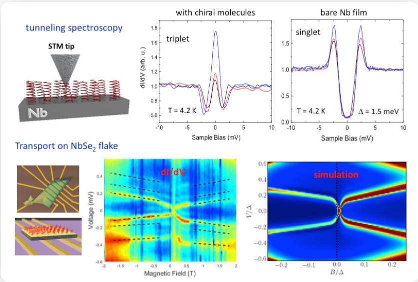

We combine various scanning local-probe methods, Scanning Tunneling Spectroscopy (STS) and Atomic Force Microscopy (AFM) with global transport and photo-transport measurements and theoretical simulations in studies of nanostructured and hybrid superconductor and semiconductor systems. Presently we focus on:

Unconventional superconductivity: Emergence of and control over triplet-pairing superconductivity in superconductor/ferromagnetic and superconductor/chiral-molecules hybrid systems. We also study proximity effects at superconductor/graphene interfaces, finding evidence for (unconventional) p-wave order-parameter and effects of chiral-induced magnetic states and spin-orbit coupling.

Cu (In,Ga) Se2 and perovskites solar-cell materials: Here we aim at understanding the origin of the high conversion efficiency of solar-cells comprising these materials. Our studies are at the basic science experimental-simulations level, focusing on the complex photo-conduction processes in these materials.

Electrical properties of individual colloidal semiconductor nanocrystals: Using low-temperature STS we measure the electronic level structure and map the wavefunctions of quantum-confined states of various systems - spherical quantum-dots, nanorods, nanocrystal molecules made of two merged nanocrystals.

CONDENSED MATTER
PHYSICS

UPDATED AUG 2020

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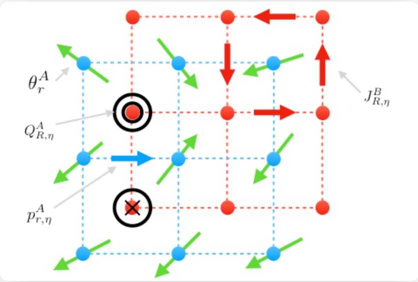

I am a condensed matter theorist, and my main research interest concerns unraveling collective phenomena that arise when a large number of microscopic constituents are strongly interacting. I am particularly interested in "inherently quantum" states of matter exhibiting intricate patterns of entanglement, which do not have a direct classical analogous counterpart. Notable examples are superconductors, which conduct electrical current without dissipation and spin-liquids that defy freezing even at absolute zero temperature. These exotic quantum states are expected to serve as the basic building blocks of future quantum-based technologies.

The exponential scaling of quantum many-body problems poses a challenging computational task and making headway must rely on a profound understanding of the physical problem. Obstructions to simulating quantum systems using a classical computer with finite resources draw the line between the quantum and classical world. I am very actively involved in devising new numerical methodologies that push this boundary and applying them in various strongly correlated quantum systems.

CONDENSED MATTER
PHYSICS

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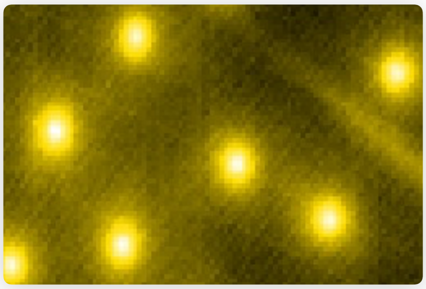

My broad research goal is to discover and characterise novel electronic order in strongly correlated materials. In other words, we try to understand why sometime an electronic state is superconducting and sometime ferromagnetic.

I study these phases using a novel scanning SQUID microscope with single electron spin sensitivity and thermal sensitivity better than one millionth of a degree. The SQUID is located on the apex of a nanometric pipette and has ~50 nm resolution.

One example of images acquired in our lab is shown here.
t is superconducting vortices in a 10 nm thick superconductor.
The scale of this image is 5 x 15 micrometer.

CONDENSED MATTER
PHYSICS

THEORETICIAN

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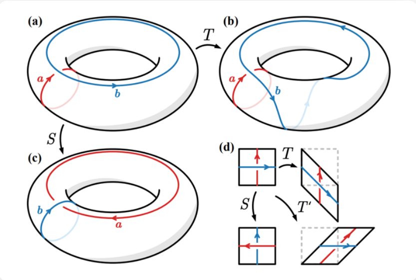

Broadly speaking I'm interested in the analytical and numerical study of emergent phenomena especially in cases where this emergent phenomenon carries a computational value. An emergent phenomena is one where a collective of particles/components behaves very differently than the sum of its parts. An emergent phenomena with a computational value is one which is either hard to simulate or one which, if we could control, would give us some practical computational advantage.

In terms of more concrete lines of research I study quantum field theory in conjugation with topological quantum computation. I work on a theory of deep learning based on certain correspondences between deep learning and statistical field theory. I study the computational limitations of Quantum Monte-Carlo algorithms and other algorithms for studying quantum systems, and I work on applications of information theory in complex interacting systems. Common to all these lines of research is the potential to better understand as well as advance our current computational forefront.

CONDENSED MATTER
PHYSICS

HIGH ENERGY PHYSICS

ABOUT

In high energy physics, we are after the fundamental building blocks and laws of Nature. Research in high energy physics at the Racah Institute spans a broad range of fields, including quantum field theory, quantum gravity, the Standard Model of particle physics and beyond, and early universe cosmology. The fundamental laws of nature are currently described by the Standard Model of particle physics (a quantum field theory) and by Einstein's theory of general relativity. Research in high energy physics aims to understand these theories, go beyond them, and merge them into one.

The Standard Model provides a beautiful description of the quantum world, unifying the strong, weak and electromagnetic forces, and giving the basic constituents of matter. It has withstood nearly five decades of experimental scrutiny with unprecedented success. However, there is experimental evidence and theoretical indications that the theory is not the final answer of Nature. Research in particle physics goes beyond the Standard Model, addressing its unanswered questions. Topics includes the hierarchy between the weak force and the strength of gravity, the identity of dark matter, why the world is made of matter and not antimatter, the origin of neutrino masses, collider physics, cosmology of the early universe, particle astrophysics, and the interplay of all the above.

Fundamental physics is described by beautiful mathematical structures. Understanding the formalisms, answering the most basic questions of Nature about quantum mechanics, developing calculational tools, and ultimately embedding gravity into a quantum theory, drives significant research. Topics include quantum field theory, supersymmetry and supersymmetry breaking; String theory, including branes and extra dimensions; Scattering amplitudes, new concepts and methods for gauge theories and gravity; Einstein's gravity, including the Effective Field Theory approach to General Relativity and in particular to the post-Newtonian limit of the gravitational two body problem; Black holes; and Quantum Information

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The main focus of my research is on problems in string theory -- a consistent quantum theory of gravity (and the other forces). My research activities include black holes in string theory, in particular, the physics near the horizon, the fate of the interior, and especially the way the singularity is resolved.

Moreover, I am interested in the interplay between the dynamics of branes in string theory and Quantum Field Theory. These motivate candidates for natural extensions Beyond the Standard Model of the electro-weak and strong forces.

HIGH ENERGY
PHYSICS

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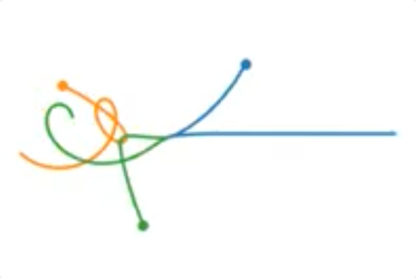

Barak Kol studies theoretical physics and the fundamental laws of nature, mostly Quantum Field Theory and Einstein's Gravity.

As of summer 2020 he is involved in two main topics fitting for 3rd year projects and M.Sc. research:

The three-body problem:
The gravitational three-body problem is a rich and long-standing open problem in physics. Its chaotic nature makes a deterministic prediction impossible, and instead, it was suggested to seek a statistical prediction. Recent research by Kol presents an exact reduction of the problem and is believed to be an essential step towards this statistical theory. A key innovation is the use of the flux of phase-space volume.

A new method to evaluate Feynman diagrams:
Feynman diagrams are the computational core of Quantum Field Theory, the language of the theory of fundamental interaction and particles. However, despite over 70 years of extensive study, we are still lacking a general theory for the evaluation of the associated integrals. In 2015 Kol introduced a new method for this purpose which reveals an underlying geometry and has already enabled novel diagram evaluations.

HIGH ENERGY
PHYSICS

UPDATED AUG 2020

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My research endeavours are focused on various aspects of theoretical high energy physics. These include such fundamental realms as Quantum Field Theory, General Relativity and a somewhat elusive essence of synergy between the two. In recent years I am particularly interested in applications of Quantum Information techniques towards unravelling the structure of gravity and quantum field theory.

HIGH ENERGY
PHYSICS

THEORETICIANS

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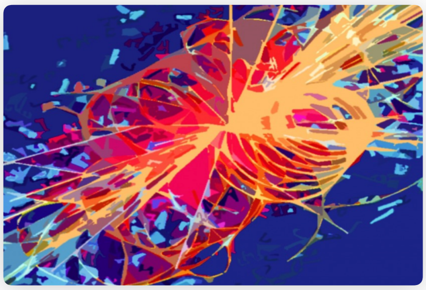

We are theoretical particle physicists, sometimes called high energy phenomenologists. Phenomenology means theoretical work that is in close contact with experiment. As phenomenologists, we address fundamental questions left unanswered by the Standard Model of particle physics: What are the dark matter particles of the Universe? Why does our world consist almost entirely of matter and not of anti-matter? Why is the mass of the weak force carriers so much smaller than the scale of gravity? These are several of many indications that there has to be new physics beyond the Standard Model. The Large Hadron Collider (LHC), operating at record-breaking energies, together with a host of astroparticle observatories, will teach us much in this regard.

Our research focuses on the phenomenology of such new particles and interactions, with particular emphasis on novel theoretical ideas, experimental signals and their interplay. We perform machine learning data searches for the LHC. We propose new theories of the particle identity of dark matter and novel experimental avenues to detect dark matter on earth. We work in close contact with experimentalists to bring these ideas to life. We work on novel solutions to the hierarchy problem, including the use of early universe dynamics. With a fresh take on the old puzzles of the field, we think about the interface of particle physics with other aspects of physics, towards the goal of identifying the fundamental constituents of Nature.

We currently have research projects on all these topics, appropriate for excellent undergraduate and graduate students.

HIGH ENERGY
PHYSICS

NONLINEAR, STATISTICAL AND SOFT MATTER PHYSICS

ABOUT

The research in the nonlinear physics group at the Racah Institute of Physics spans a wide range of complex systems whose behavior originates from nonlinearities and noise. Such systems appear in very wide contexts: from biological to inanimate, from deterministic to stochastic, and from fluid to solid.

Working in close contact, the theoretical and experimental groups constantly contribute to each other in the ever-lasting cycle of theory-motivated experiments and vice versa.

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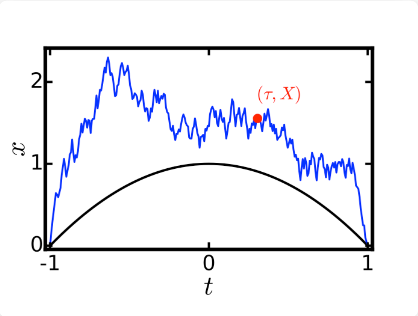

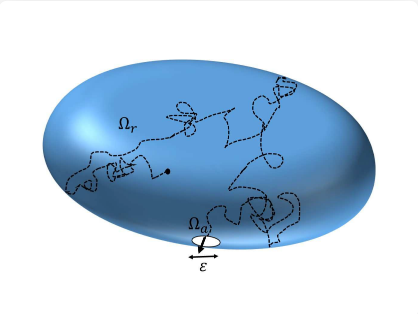

My research area is non-equilibrium statistical mechanics. I study atypically large fluctuations in different non-equilibrium stochastic systems. Rare large fluctuations are of importance in a large variety of situations: from a sudden extinction event in a long-lived population of animals to a rare large peak in the height of a growing surface, and to the trajectory of the first among myriads of sperm cells, competing with each other for reaching the oocyte.

One subject, suitable for a M.Sc. student or an excellent 3rd year student, deals with a highly efficient description of a whole class of stochastic processes with the help of an approximation method akin to geometrical optics.

NONLINEAR
PHYSICS

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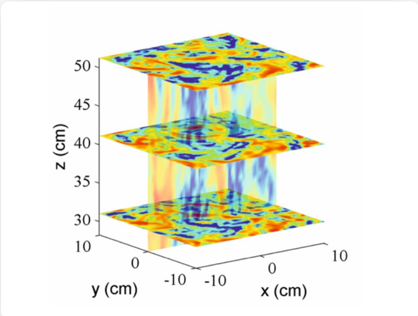
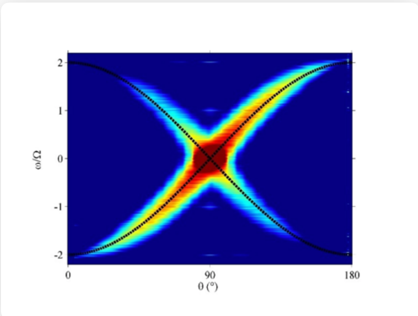


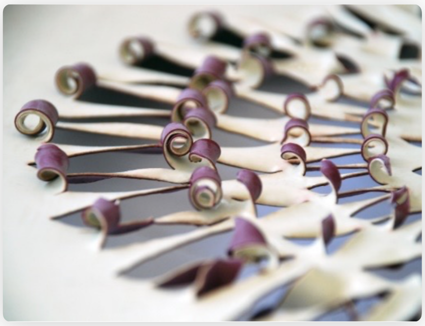
(a)

3D flow field
The flow field in 3D rotating turbulence with vertical tornado-like structures.



(b)

Energy Spectrum
Energy spectrum of the flow in (A) – all the energy is concentrated around the dispersion relation of inertial waves (dashed line).



(c)

"Frustrated materials" 2018
Examples of frustrated latex prepared in collaboration with designers (Arielle Blonder, Shira Shoval)

I work in the field of **nonlinear physics**, conducting experimental study in two main topics.

The first is the study of **"non-Euclidean solids"**, which was invented by my group. Here, we study and design thin sheets with exotic geometrical and mechanical performance, by manipulating their internal geometrical degrees of freedom. We compute and design the structures using a formalism developed in the group (by students who did theoretical work), which uses differential geometry as a language to describe solids. The experimental work and the context of the research cover a wide range of fields and scales. They include macroscopic active matter sheets, nano-scale self-assembled macromolecules, leaf growth and novel composite materials. We collaborate with theoreticians, mathematicians, botanists, chemists and recently with designers and architects. Students build their own experimental systems and they are typically involved in developing new theoretical ideas.

The other topic we study is **turbulence in rotating systems**.
These types of flows are characteristic of geophysical and planetary systems. Turbulence is the extreme nonlinear state, in which all the degrees of freedom of a system strongly interact. As such, it is disordered and multi-scale, described by its statistical properties. Strong rotation dramatically affects hydrodynamic turbulence, by flipping the direction of energy flow between scales (towards large scales) and by introducing a strange, Coriolis-driven, type of bulk waves, known as "inertial waves". These effects lead to the buildup of large, powerful structures, such as hurricanes that persist within the turbulence. We study such flows using a large rotating water tank, equipped with advanced visualization systems that allows measuring the flow in three dimensions. We discovered that the flow can be described as **wave-turbulence.** This discovery opens the way for new advanced experimental and theoretical studies. Students first learn how to operate the system and then design and perform their experiments.

NONLINEAR
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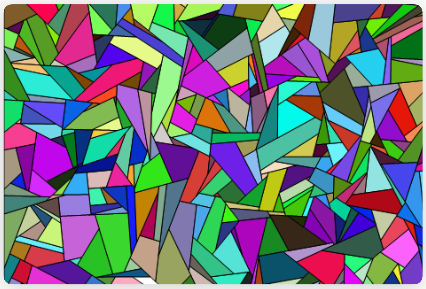

I am a nonlinear statistical physicist. My group works on a broad spectrum of theoretical problems in these fields, using analytical and numerical methods. Among other things we work on:

1. Packing problems
2. Statistical mechanics of and on random networks
3. Elasticity: fracture, fragmentation, friction...
4. Nonperturbative techniques in statistical field theory
5. Out-of-equilibrium statistical mechanics
6. Superoscillations

These items are sometimes surprisingly connected, and if you wonder how you are invited to contact me with this or any other question.

NONLINEAR
PHYSICS

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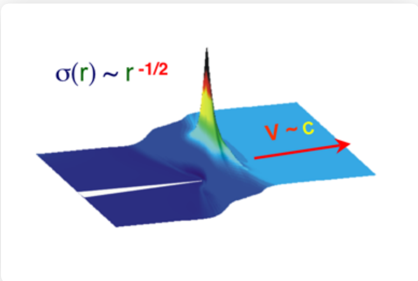

Currently my group is studying the fundamental physics of fracture ("How Things Break") and friction ("How Things Slide"). These questions are closely related to the fundamental physics of earthquake dynamics as well as to how materials fail.

These highly important questions are interdisciplinary with significant ramifications in different fields of Science that range from Material Science and Physics to Earthquake Dynamics and Engineering.

NONLINEAR
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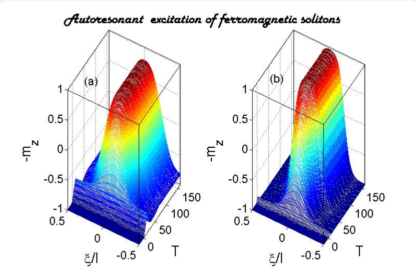

My main research effort of recent years involved studies of autoresonant pattern formation in dynamical and extended systems. The autoresonance is a fascinating physical phenomenon where a nonlinear system phase-locks (synchronizes) with oscillating driving perturbations and remains synchronized even when the frequency of the drive is chirped, i.e. varies in time and/or space.

Due to this phase-locking the system performs an excursion in its solution space frequently reaching very nontrivial and unexpected coherent sates.

We have pioneered many exciting new applications of autoresonance in various fields of physics including nonlinear dynamics, nonlinear waves, fluids, atomic and molecular physics, plasmas and planetary dynamics. Most recent examples are excitation of solitons in ferromagnetic nanowires, formation of giant plasma waves for manipulation of intense laser beams, and transition from the classical to quantum mechanics in chirped, laser driven atomic and molecular systems.

NONLINEAR
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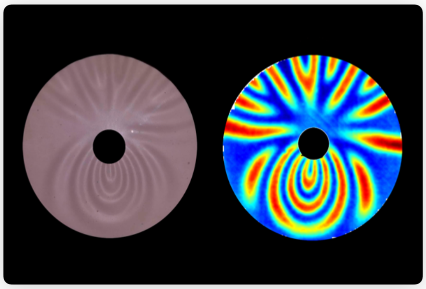

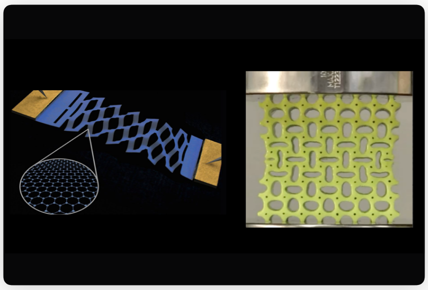

Soft-matter physics spans a broad spectrum of systems that constantly challenge the classical theories of solids and fluids. Examples of such systems include biological and inanimate cellular tissue, mechanical meta-materials, active responsive matter, wrinkles and fracture in thin sheets, and granular matter. Understanding these exotic mechanical systems is likely to promote existing theoretical frameworks towards a unified theory of solids and fluids.

With this motivation the research in our group focuses on the development and application of geometric and analytical tools to model and solve problems in soft-matter physics. In particular, we develop generalisations of the classical theories of solids and fluids to describe the physics of cellular tissue and mechanical metamaterials in the language of Riemannian geometry, and correspondingly develop mathematical methods for solving the complex mechanical problems within these generalised theories.

Among the achievements of our group are the Riemannian description of topological defects in solids, the development of new methods for solving nonlinear problems in theories of mechanical metamaterials and fracture, and the development of generalised mechanics of biological tissue.

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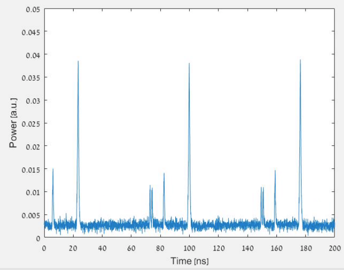

I am a theorist working in the field of nonlinear physics, studying complexity in two classes of physical systems.

The first is the dynamics of coherent optical waveforms in nonlinear resonators and lasers. High intensity light affects the properties of the medium, for example by changing its index of refraction, giving rise to nonlinear optics. The optical nonlinearities can then make the waveform evolve spontaneously into coherent waveforms, such as ultrashort pulses which duration is smaller than a picosecond, and which are tremendously useful in science and engineering. From a theoretical standpoint it is interesting to view the light pulses as atom-like units that can interact with each other and form molecule-like bunches, and other, more intricate configurations. In the accompanying figure you can see an experimental snapshot of a laser operating in the exotic 'soliton rain' regime, where dozens or more pulses co-propagate in the laser cavity, while continuously being created from noise - and annihilated in a closely packed condensate of pulses. Mathematically these systems are often described by nonlinear partial differential equations with noise sources, and this research is done in close collaboration with experimentalists.

The second project investigates the topological invariants of wave systems depending on parameters. This subject first came to the forefront with the discovery of topological insulators, where the waves are quantum wave functions in a periodic medium, and the parameters are the components of the lattice momentum. Systems with different topological invariants are in many ways similar to different phases of matter, in the sense that they have different macroscopic behavior, and a change of topology is tantamount to a phase transition. This idea has been extended to classical elastic, electromagnetic, and other waves. Our goal is to understand the topology of complex wave systems, such as systems with disorder or chaos, which may be the only way to realize some of the more complex topological phases in experiments. In such systems it is not practical to calculate the topological invariants for individual systems; instead, they are studied probabilistically, in the spirit of statistical physics. For this purpose we develop statistical models for complex wave systems, and attempt to calculate the probability distribution of their topological invariants.

NONLINEAR
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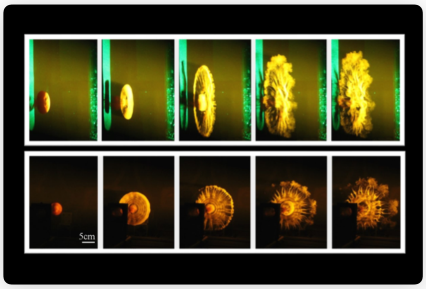

Climate, turbulence and earthquakes, aging, disease, failure, and death are some of the big phenomena that rattle our daily lives. They all concern far from equilibrium systems that entail a cataclysmic change. They occur only once and are entirely irreversible, the problems involved are colossal and highly complex. Nucleating sometime in the 70's, distinct fields developed in parallel to confront the challenge of complex systems: soft matter physics, nonlinear dynamics, chaos, pattern formation, out-of-equilibrium and jammed systems, and modern turbulence. In all these fields, researches sought simple behavior and structure in the immanent complexity. However, they often followed the traditional approach of equilibrium physics. This approach is inherently limited and may not fully capture the depth and beauty that arise from the interplay between distant scales. A new approach is called for. One that does not give up on reaching a simple description of nature but where the path to a minimalistic description of the fundamental laws of nature begins by an all-inclusive experimental study leading to the development of a complex quantitative phenomenological model. Fortunately, a plethora of breakthroughs in experimental capabilities are available to address these issues. These include advanced imaging technologies with higher speeds and better resolution, reliable and realistic computer simulations, tools to handle vast amounts of data and AI. This makes it an exciting time to systematically and intentionally address big questions.

My research combines soft condensed matter physics with solid and fluid mechanics and aims to elucidate dynamic processes that are highly nonlinear, are far from steady-state, and are intrinsically irreversible. To accomplish this, my lab develops experimental tools that lead to breakthroughs in understanding of important and complex multi-scale systems and processes, specifically, violent flow, failure, aging, deterioration and damage. Some examples of interest include disintegration of a smoke ring; crushing of a beer can; splashing of a drop on surfaces; crumpling, fracturing and fatigue of soft (and rigid) matter; frictional slip on a tectonic fault (or a banana peel). Common to all these phenomena is that they are ethereal, complex, and irreversible events. To probe such transient processes, we develop innovative experiments and tools that enable their observation on relevant timescales. Importantly, we try to keep our model systems approachable but real, as this gives a better chance of discovering something cool and new. Specifically, our tools capture precision, high-speed, multi-scale and multi-dimensional data. In collaboration with theoretical and computational scientists we are combining our experimental expertise with numerical simulation and machine learning tools to capture the full phenomenon in all its complexity.

NONLINEAR
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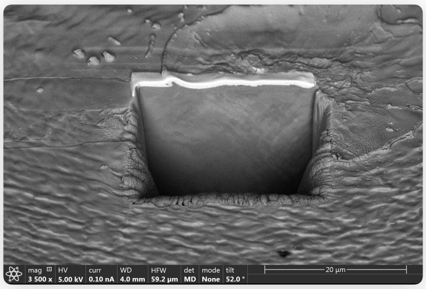

SEM of the plastically deformed region below the surface of a copper electrode which underwent a BD.

I am an applied theoretician and part-time experimentalist working on material dynamics far from equilibrium. Materials under real-life conditions are driven to respond to external constraints, be it stresses, irradiation, or high voltages. Our group applies various theoretical methods to explore possible origins of observed properties and processes under such conditions.

The main tool we employ is molecular dynamics simulations, but other specific mean-field and MC calculations are used as well. In addition to simulations, we explore various observable effects using dedicated experimental scenarios: ranging from acoustic emission and light emission from electrodes exposed to extreme fields, as well as microscopy forensics of these electrodes. Experimental work is mostly done within the context of the CLIC collaboration in CERN.

Current projects include:

1. Origins of breakdown under intense electric fields.

In this project, we are trying to understand the underlying mechanism controlling the breakdown of vacuum in systems where metallic electrodes are exposed to extreme fields. This is one of the main limiting factors for devising new applications and specifically particle accelerators. The work is done as part of an international effort led in CERN. We explore both mean-field and local models and compare model results to dedicated experiments aimed at exposing pre-breakdown behavior. Projects include deriving theoretical predictions for measurements done in CERN and devising new methods for calculating expected signals. In addition, TEM and FIB assisted SEM microscopy is done to explore processes using post-exposure analysis.

2. Local response function to external loads.

Hard metals subjected to external stresses and strains demonstrate a nonuniform elastoplastic response. Even the most simple metals contain a wide variety of defects, grain boundaries, and precipitates. Molecular dynamics simulations are widely used to explore the response of metals at such conditions. We are developing new methods to employ MD deriving local properties and response function in situ during simulations of out of equilibrium processes. These capabilities could be used to describe mechanisms controlling yield and mixing in complex hard metal systems. Projects include numerical application of new algorithms and techniques to explore metallic alloys under external stresses such as found in severe plastic deformation.

NONLINEAR
PHYSICS

NUCLEAR AND HADRONIC PHYSICS

ABOUT

The atomic nucleus forms a unique laboratory where different interactions (strong, weak, and electromagnetic) and particles meet. The relevant degrees of freedom depend on the energy and distance scales, and range from collective coordinates and A-body systems of protons and neutrons at low energies, Hadrons (Baryons and Mesons) at intermediate energies, to quarks and gluons at high energies. The diversity of phenomena and simple patterns observed in nuclei, in spite of their apparent complexity, is the result of the fundamental interactions acting between the constituents, their internal and in-medium properties and the underlying symmetries that govern their behavior.

The study of nuclei and their constituents is a challenge.
It exemplifies a strongly correlated finite quantum system at work, a test ground for new phenomena awaiting to be explored by a variety of probes and, most importantly, incorporates a fruitful exchange between experiment and theory. The research carried out at the Racah Institute embraces a wide range of topics, from the single-nucleon to an ensemble of nucleons.

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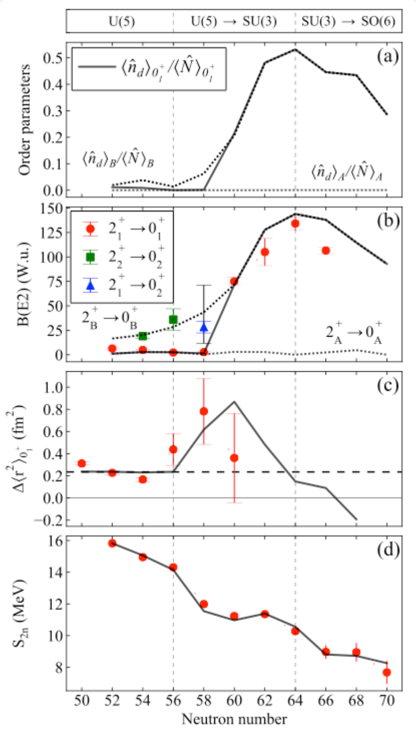
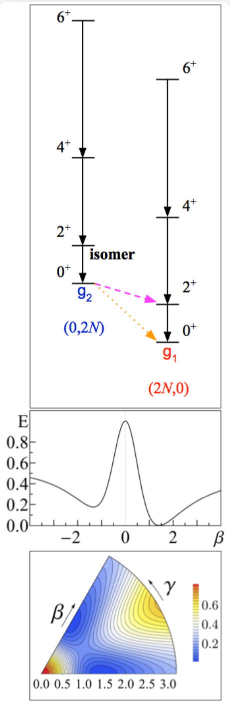


QPTs in the Zr chain of isotopes



PDS and shape-coexistence in nuclei

NUCLEAR AND
HADRONIC PHYSICS

The structure of atomic nuclei is determined by the combined strong, electromagnetic and weak interactions acting among, up to, hundreds of nucleons (protons and neutrons). Given this environment, one might have expected an extremely chaotic and complex situation, but in fact, nuclei often display extremely regular excitation patterns. These simple patterns range from the regular sequences of single particle levels (resulting in shell structure and magic numbers), to variety of nuclear shapes and collective modes like vibrations and rotations and phase transitional behavior. A key question in this context is

What is the origin of the simple patterns in complex nuclei?

This profound problem of “simplicity out of complexity” is confronted in the research categories described below.

1. Partial dynamical symmetries in nuclei

Often, simple patterns reflect underlying symmetries. Algebraic models form a convenient framework to examine symmetries in many-body systems. In such models, the Hamiltonian is expanded in elements of a Lie algebra (G_0), called the spectrum generating algebra. A dynamical symmetry (DS) occurs if the Hamiltonian can be written in terms of the Casimir operators of a chain of nested sub-algebras of G_0. In such circumstances, the entire spectrum is analytically solvable and the states are classified by quantum numbers related to the algebras in the chain. DSs provide clarifying insights into complex dynamics. However, in most realistic systems, the predictions of an exact DS are rarely fulfilled and one is compelled to break it. To address such generic situations, we develop the notion of partial dynamical symmetry (PDS), for which the symmetry is obeyed by only a subset of states, and investigate its implications for nuclear spectroscopy, including band structure and shape-coexistence.

2. Quantum phase transitions in nuclei

Quantum phase transitions (QPTs) are structural changes in a system that occur as a function of coupling constants in its quantum Hamiltonian. As one varies the control parameter ξ in the Hamiltonian, H(ξ) = (1 - ξ) H1 + ξ H2, the symmetry and equilibrium shape of the system change from H1 to those of H2. A different type of phase transitions occurs when two (or more) configurations coexist. In this case, the change in the control parameters can result in a crossing of configurations. In the present research category, we explore the role and empirical manifestations of both types of QPTs in nuclei.

The basic tools of research are algebraic methods employing models based on spectrum generating algebras and geometric methods employing coherent states. The theoretical- analytic aspects involve the extensive use of symmetries and group theory. The numerical-computational aspects involve detailed comparisons with empirical data.

THEORETICIAN

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When the properties of a physical system are insensitive to the details of the microscopic interaction between its constituents, the system is said to be universal. A very rich and important case is a system governed by the low energy scattering parameters. To some extent, this is the situation, for example, in nuclear physics, in helium clusters, and in ultracold atoms near a Feshbach resonance. Although the energy scales of these systems differ by many orders of magnitudes and the microscopic interparticle physics is completely different, they share similar characteristics and dynamics.

To be specific, let's briefly mention two interesting examples: First, the Efimov effect, which is the emergence of an infinite number of three-body bound states, identical up to a constant scaling factor, when the two-body subsystem binding energy approaches zero.
Another example is the Tan's relations, connecting several characters of the system to the so-called contact, which measure the probability of two particles to be in close vicinity.

To study these systems we are developing novel computational techniques and computer codes, including machine-learning techniques and parallel computation.

NUCLEAR AND
HADRONIC PHYSICS

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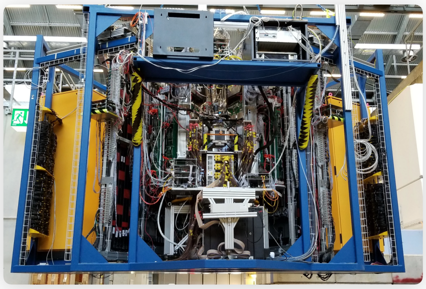

We are the Fundamental Interactions group at the Hebrew University of Jerusalem's Racah Institute of Physics. We are part of the nuclear and hadronic physics group but have close ties to the optics and non-linear groups operating at the institute.

Our group studies two of the fundamental forces of nature, the ElectroWeak force and the Strong Nuclear Force, by conducting experiments on systems which are affected by these forces. Among the questions we are currently trying to answer are:

Is there physics beyond the Standard Model? How does one see the effects of such possible physics on low energy processes like nuclear beta decay?

How well do we know the structure of the proton and neutron? Are the charge and magnetization distributions in them different from each other? And what are the charge and magnetization radii of the nucleons?

Is a nucleon inside a nucleus still a nucleon? Do it's properties change in a measurable way?

How can we use the anti-matter partner of the electron (the positron) to study material systems?

How do the nuclear reactions inside stars change the chemical evolution of the galaxy?

NUCLEAR AND
HADRONIC PHYSICS

EXPERIMENTALIST

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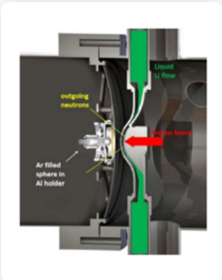
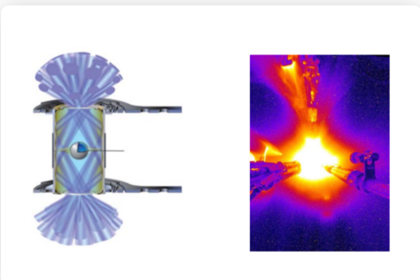


36,38 Ar (n,g)
Phys. Rev Lett. 121, 112701 (2018)
Laboratory source of stellar-energy neutrons

60Fe: Nature 532, 69 (2016)
244Pu: Nature Commun. 6,5956 (2015)
244Pu: Nature Phys. 11,1042 (2015)
Deep seafloor crust stores deposited interstellar dust



National Ignition Facility Discovery Program:
Approved Proposal 2021-2022
Laser-induced fusion produces stellar neutron density

Synthesis of heavy elements in stars

The large majority of heavy elements in Nature, say above iron, are synthesized in stars via capture of neutrons. We investigate in the laboratory some of these neutron capture reactions and also detect traces of rare atoms produced in the Galaxy over the last few million years.

Capture of neutrons proceed along two paths, the slow(s-) and rapid (r-) process, depending on the neutron density of the stellar site.

At low neutron density, the s-captures occur one-by-one and the relevant reactions can be studied in the laboratory. We lead a world effort in this direction based on a neutron source at the SARAF facility of Soreq Nuclear Research Center (Israel), the most intense laboratory source of neutrons at stellar energy.

In a research program initiated at Racah Institute and pursued now at Australian National University, we detect rare atoms in the actinide region produced in stellar events via the r-process and deposited on Earth as interstellar dust.

The implosion induced by the 192 lasers (1 MJ - 400 TW) of the National Ignition Facility (NIF, Livermore, CA, USA) on a deuterium-tritium capsule produces thermodynamical conditions of plasma density, temperature, pressure and a neutron density close to those of a star. An experiment led by our group in cooperation with Soreq NRC is scheduled at NIF in 2021-2022 to mimic neutron-induced nucleosynthesis in a NIF shot.

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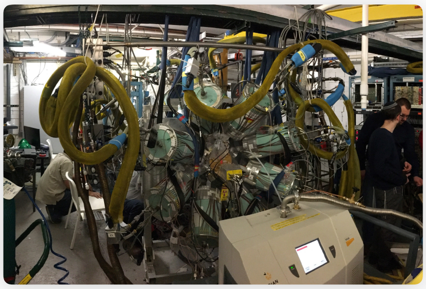

Nuclear Astrophysics is a field at the intersection between Nuclear Physics and Astrophysics that studies questions related to nuclear processes in stars and other astrophysical scenarios. In our lab we are focusing on experimental studies of nuclear reactions that are important for the understanding of explosive stellar nucleosynthesis, or, in other words, synthesis of nuclei in explosive scenarios such as Novae and Supernovae. Our research is helping to provide quantitative estimations of the amount of radiation and the composition of dust ejected from such astrophysical scenarios, and to compare them to models and actual observations.

To conduct our studies, we use state of the art facilities worldwide to produce rare isotopes and to simulate in the lab the relevant conditions in the studied astrophysical scenarios. The work in our lab include detector development, writing computer simulations, conducting experiments in particle accelerators, advanced data analysis and intensive collaboration with scientists from other institutions.

NUCLEAR AND
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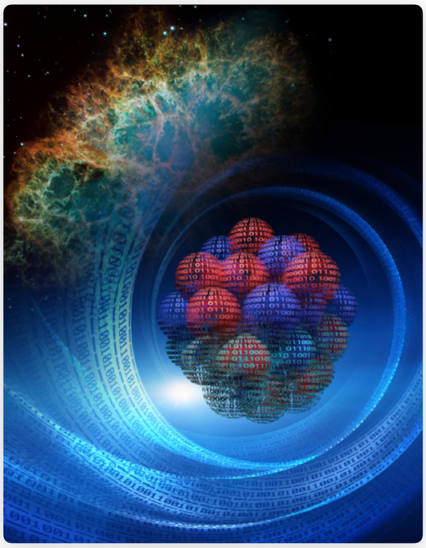

Our research group studies a wide range of questions in strongly interacting quantum systems. We mainly focus on nuclear and hadronic physics but we also have much interest in molecular systems. We employ both analytical and numerical tools.

Three key research areas are listed below:

1. Short Range Correlations

While mean-field approximations, such as the nuclear shell model, provide a good description of many bulk nuclear properties, they fail to capture the important effects of correlations. Specifically, effective nuclear models struggle to describe the short-distance and high-momentum components of the nuclear many-body wave function. In our research group we study these components of the nuclear wave function using the contact formalism. Using this formalism we study and try to relate different phenomena such as electron scattering, nuclear photoabsorption, the magnetic moments and more.

2. Effective Field Theory for Lattice Nuclei

Lattice QCD is the only viable way to study the fundamental theory of the strong interactions (Quantum Chromo Dynamics - QCD) at the low energy limit, relevant to the atomic nucleus. Recently LQCD calculations have reached the point where light nuclear systems can be studied from first principles although for unrealistic quark masses. Using effective field theory we utilize these data to study the properties of lattice nuclei, and to extrapolate them to the natural quark masses.

3. Hypernuclei

Hypernuclei are atomic nuclei where one or more nucleons are replaced by a hyperon, i.e. a baryon like the neutron or proton containing the quark strange instead of the usual up and down quarks. The progress in lattice QCD calculations and in heavy ion collisions provides a unique opprtunity to understand the fundamentals of nucleon-hyperon and hyperon-hyperon interactions. Using effective field theory and numerical tools designed to solve the Schrodinger equation for fewbody systems we utilize the available experimental data to devise a theory for the hypernuclei and predict their properties.

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