Plenary Lectures

THE VALUE OF USELESS STUDIES

CECIL POWELL MEMORIAL LECTURE

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In the late nineteenth century Lord Kelvin and George Francis Fitzgerald, professors of natural philosophy in Glasgow and Dublin, played leading international roles in physics. They had much in common: an Irish background, a passionate lifelong devotion to their subject, high principles, eclectic interests and a strong belief in the power of applied physics to change the world. Kelvin put this into practice in an astonishing series of practical innovations. Fitzgerald's contribution was less direct but he was the principal herald of the age of wireless communication. He defended "the value of useless studies", which we stillneed to do today.

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SEMICONDUCTOR HETEROSTRUCTURES: STATE-OF-ART AND FUTURE TRENDS

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The early history of the semiconductor heterostructures and their applications in different electronic devices is described. The lecture also contains a short historical review of the physics, technology of preparation and applications of quantum wells and superlattices. Recent progress in quantum wires and especially quantum dots structures and future trends and perspectives of these new types of heterostructures are discussed.

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TEACHING ELECTRONS AND PHOTONS NEW TRICKS WITH STATE-OF-THE-ART TECHNOLOGY: QUANTUM CASCADE LASERS, OPTICAL MICROBILLIARDS, AND QED-BASED NANOMECHANICS

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State-of-the-art semiconductor nanostructures based on molecular beam epitaxy (MBE) and microelectromechanical systems (MEMS) based on silicon integrated circuit technology have made it possible to achieve unprecedented control of the boundary conditions of electrons and photons. This has led to the design of new artificial materials and quantum devices with tailored properties, to microstructures in which controlled deformation are used to exploit wave-chaos phenomena for photonic applications and to micromachines based on vacuum fluctuations.
I will illustrate the above with examples from our research: (a) Quantum Cascade Lasers, fundamentally new light sources that cover the entire wavelength range from the mid to the far infrared by tailoring layer thicknesses; (b) Asymmetric microresonators in which KAM transition to chaos, "scars" and high directional emission from bow-tie modes have been observed; (c) High precision measurements of Casimir forces with MEMS and the demonstration of new actuators and sensors that exploit these forces.

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SEMICONDUCTOR SPINTRONICS

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The information revolution, which has surprised us over the last few decades, has occurred due to the restless exponential growth of information amount that can be processed, stored, and transferred per time and area unit of relevant devices. Spin electronics (spintronics) is a young interdisciplinary field of nanoscience. Its rapid development, like that of competing new branches of electronics – molecular electronics, bioelectronics, electronics of polymers, …, – has its roots in the conviction that the progress that is being achieved by miniaturization of active elements (transistors and memory cells) cannot continue forever. Therefore, the invention of future information technologies must involve new ideas concerning the design of both devices and system architecture. The main goal of spintronics is to gain knowledge on spin-dependent phenomena, and to exploit them for new functionalities. Hopes associated with spintronics stem from the well-known fact that the magnetic fields present in the ambient world are significantly weaker than the electric fields. For this reason magnetic memories are non-volatile, while memories based on the accumulated electric charge (dynamic random access memory – DRAM) require a frequent refreshing. Today’s research on spintronics involves virtually all material families, the most mature being studies on magnetic metal multilayers, in which spin-dependent scattering and tunneling are being successfully applied in reading heads of high-density hard-discs and in magnetic random access memories (MRAM). However, in the context of spintronics particularly promising are ferromagnetic semiconductors, which combine complementary functionalities of ferromagnetic and semiconductor material systems.

In the talk, recent progress in semiconductor spintronics will be reviewed emphasizing findings important for either classical or quantum information devices. In particular, the demonstration of isothermal and reversible switching of magnetization by light and the *electric* field in ferromagnetic semiconductors will be described. Various schemes enabling injection and manipulation of electronic or nuclear spins in non-magnetic semiconductors and their nanostructures will be discussed. The role of confinement and dimensionality will be presented together with prospects for coherent control of single spins in solid-state environment.

References

For reviews on spintronics, see, e.g., T. Dietl, *Semicond. Sci. Technol.* 17 (2002) 377; *Acta Phys. Polon. A* 100, Suppl. (2001) 139, www.arXiv.org/abs/cond-mat/0201279; S.A. Wolf et al., *Science* 294 (2001) 1488; H. Ohno, F. Matsukura, and Y. Ohno, *JSAP International*, No. 5, January 2002, pp. 4-13, www.jsapi.jsap.or.jp.

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QUANTUM DYNAMICS OF NANOMAGNETS

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We review the past and recent developments in the field of quantum dynamics of nanomagnets. Research in this field started in the seventies with indications of tunneling in domain-wall depinning or in magnetization reversal in ferromagnetic nanoparticles. This field became mature in 1993-1994 after it was shown that Single-Molecule Magnets (SMMs) could have large energy barriers against spin reversal and that such energy barriers could be overcome not only by thermal activation, but also by quantum tunneling of individual molecule spins. This is the case for Mn12-acetate, a molecule with S = 10 and an energy barrier of about 70 K. When an external field causes levels on opposite sides of the barrier to align, resonant tunneling occurs, resulting in an enhanced spin reversal rate. This was the starting point for lively research in both the chemistry and solid-state physics communities, and this is still going on. Some of the single-molecule magnets have shown a remarkable Berry-phase effect in which interference between tunneling paths can produce suppression of tunneling. Recent advances in the field include the observation of a phonon-bottleneck in the low-spin V15 molecule, resonant tunneling in individual Ho^{3+} ions and an exchange-bias effect in coupled Mn4 molecules. These studies on mesoscopic spin systems, in which environmental effects (phonons, nuclear spins, other electronic spins, applied field) are studied in details, certainly constitutes the basis for Quantum Spin Manipulations. Future prospects for these quantum spin systems may be found in such developing fields as molecular spintronics and quantum information.

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PHOTONS AND PHONONS IN MESOSCOPIC SYSTEMS

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Over the last fifteen years artificial structures and/or self-assembled materials have been designed and fabricated in order to control the flow of electromagnetic, acoustic, and elastic waves. A common characteristic of these structures is that they produce gaps (or pseudogaps) in the spectrum of these waves. There are two basic mechanisms responsible for the appearance of gaps (or pseudogaps) : resonant scattering and destructive interference. The latter is greatly enhanced in periodic structures (hence the frequently used name photonic and phononic crystals), while the former is usually (but not always) achieved by matching the wavelength to the characteristic dimension of each elemental scatterer. Several examples will be presented to illustrate the interplay between periodicity (or the lack of it) and resonant scattering in the formation of gaps. Finally, recent work on inelastic light scattering by mesoscopic phonons in self-assembled colloidal periodic or glassy systems will be reviewed.

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THE IMPORTANCE OF BEING DISCRETE:THE EMERGENCE OF COMPLEX SOCIAL DYNAMICS FROM SIMPLE INDIVIDUAL INTERACTIONS

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The discrete microscopic structure of the macroscopic objects was postulated since the time of Democritus. The crucial relevance of this fact for their actual properties became evident in the modern times starting with the Dalton laws in chemistry and culminated in physics with the statistical atomic-molecular mechanics of Boltzmann and Maxwell.

It turns out that in systems with auto-catalytic interactions (proliferation, contagion, information spread) as most biological and social systems are, the discreteness of the elementary components and interactions (e.g. giving birth to a new individual, informing a neighbor of a new product, adoption of a new idea by an individual, contracting a disease) is even more crucial.

Indeed, for many of such systems the continuum approximation (ignoring microscopic discretness) would predict an uniform, static (life-less, trade-less, idea-less) asymptotic state. In reality such systems present generically emergent spatio-temporal localized objects with unexpected collective dynamical properties: adaptability, resilience and sustainability.

I will present this generic mechanism of emergence of macroscopic complexity from microscopic noise and its application to a few social phenomena.

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CROWD CONTROL

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The interpretation of collective human behavior represents a great challenge for sciences. Here we discuss an emerging approach to this problem based on methods of statistical physics. We demonstrate that in cases when the interactions between the members of a group are relatively well defined (e.g, pedestrian traffic, network formation, synchronization, panic, etc) the corresponding models reproduce relevant aspects of the observed phenomena.

Among several realistic situations weinvestigate systems mimicking peple trying to leave a dangerous location during panic (http://angel.elte.hu/~panic). Our results suggest practical ways of minimising the harmful consequences of such events and the existence of an optimal escape strategy, corresponding to a suitable mixture of individualistic and collective behaviour. In addition, another kind of collective human behaviour - the synchronization of expressing satisfaction of audiencies (e.g clapping) - will be described.

The above results have been obtained in collaboration with A-L.Barabási, A. Czirók, I. Farkas, Z. Néda and D. Helbing

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ITER: REALIZING THE PROMISE OF FUSION ENERGY

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For many decades nuclear fusion research has been devoted to pursuing an almost unlimited source of energy. Thermonuclear fusion is in fact one of the very few options, potentially acceptable from the environmental, safety and economic points of view, for providing energy over the long term, which is able to support a growing world population and a move away from consuming fossil fuels. World-wide research efforts have brought the leading programmes to the threshold of conditions that might be expected in a fusion reactor. Advances in understanding in microscopic turbulence affecting energy confinement as well as macroscopic stability affecting plasma pressure have arisen from a range of smaller experiments. These developments together with the development of necessary fusion technologies have brought the global fusion programme to a level of knowledge that allows it now to address the challenge of exploring the physics of a burning plasma in an experimental device incorporating all the key features of fusion technology in reactor-relevant conditions and thus demonstrating the scientific and technological feasibility of fusion power for peaceful purposes. ITER was conceived to meet this objective.

The history of co-operation on ITER began in the mid 80's when government leaders in summit meetings called for more substantial international co-operation in order to increase the efficiency and minimize the cost of fusion power development. After a decade of focused work, both in engineering and in physics, the ITER Engineering Design Activities (EDA) led to a design that gives confidence in the achievement of its technical objectives and in demonstrating the environmental attractiveness of fusion.

The success of the ITER EDA demonstrates feasibility and underlines the desirability of jointly implementing ITER in a broad-based international collaborative frame. It supports the ITER Parties' declared policy to pursue the development of fusion through international collaboration. Their entry into negotiations on a Joint Implementing Agreement for ITER construction and operation, which will fix the site, choose the Director-General, and determine their financial and technical share of each Party, is a very positive step in their commitment to the implementation of this policy. Given the expected success of these negotiations, a new era is opening in which fusion laboratories will have more dependable external support where they follow programmes focused on the immediate needs of developing fusion as an energy source.

This paper clarifies the above remarks, offers an outlook of the main issues of fusion plasma physics, and covers the principal features of the ITER design in relation to the groundwork it is expected to cover along the path to developing a viable and attractive source of power generation.

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RECENT PROGRESS AND FUTURE DEVELOPMENTS IN GRAVITATIONAL PHYSICS

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After the renaissance of gravitational physics in the sixties of the last century, progress in the field of high precision measurements resulted in new steps in the development of gravitational physics towards the realization of gravitational wave astronomy and, more remotely, the unification of all forces.

The talk summarizes the past and future experimental activities in both areas of gravity. Emphasis will be given to Earth-based and space-borne experiments for (i) testing the foundations of general relativity, particularly the equivalence principle for which Loránd von Eötvös became famous in relativity and the universality of gravitational redshift; (ii) verifying gravitomagnetism with high precision; (iii) revealing the wave content of the gravitational field; and (iv) proving the very existence of black holes. The gravitational wave astronomy will be sketched and schemes for the unification of all forces will be mentioned includinga short discussion of cosmology.

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THE ORIGIN OF COSMIC RAYS

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The facts that the energy density of cosmic rays is the same as that of starlight, the energy range - per particle - extends to the highest energies known to mankind and that we do not know where cosmic rays come from all lead to the subject of origin being an exciting one.

The lecture will survey the scene - from 10^9 eV to 10^{20} eV - and give the author's own preferences.

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DECONFINED NUCLEAR MATTER, WHAT HAVE WE LEARNT FROM THE SPS?

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In calculations within lattice QCD at finite temperature a phase transition is found where partons become deconfined and chiral symmetry is restored. The new phase formed is called the Quark-Gluon Plasma. The current best temperature for the phase transition is 170 MeV at zero net baryon density. With increasing density the critical temperature decreases. In the laboratory temperatures in this range can be achieved in collisions of atomic nuclei at relativistic energies. The experimental program to study the formation of the Quark-Gluon Plasma started at the CERN SPS in 1986, initially with light beams of oxygen and sulfur of 200 GeV per nucleon. Since 1994 also lead beams have been used. This talk will summarize results obtained by the seven experiments in this program. There is strong evidence from the combined data on production of hadrons, di-leptons and photons that indeed in such heavy ion collisions a new form of matter is formed. The system is at the critical temperature at the time when hadron yields are frozen in and at a significantly higher energy density earlier. The various observables and their connection to the Quark-Gluon Plasma formation will be discussed. A short outlook to the collider program will be given.

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HOW MUCH COULD NUCLEAR POWER CONTRIBUTE TO THE MITIGATION OF CO_2 EMISSIONS

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Temperature stabilization requires that CO_2 emissions be limited to less than 2-3 Gt Carbon equivalent, from the present level of more than 6 Gt. Using the WEC-IIASA models as predictions for world energy consumptions and renewable energies contributions, while increasing as much as reasonably achievable, the nuclear contribution at the expense of fossile energies, we find that, even for the most energy consuming scenario with an increase of primary energy demand by 250% in 2050, a nuclear intensive scenario assuming the development of a 2000 GWe pool of PWR reactors by 2030 and of an additional 6000 GWe pool of U-Pu or Th-U breeding reactors by 2050 would lead to temperature stabilization at a level 2 degrees above the pre-industrial level.

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HIGH ENERGY DENSITY PLASMA SCIENCE WITH ULTRARELATIVISTIC ELECTRON BEAMS

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An intense, high-energy electron or positron beam can have focused intensities rivaling those of today's most powerful lasers. For example, the 5 ps (FWHM), 50 GeV beam at the Stanford Linear Accelerator Center at 1 kA and focused to a 3 micron rms spot size gives intensities of > 10^{20} W/cm^{-3} at a repetition rate of 10 Hz. Unlike a ps or fs laser pulse, the particle beam can readily bore through several mm of steel due to the rigidity of its flux component. However, the same particle beam can be manipulated quite strongly by a plasma that is a million times less dense than air! This is because of the incredibly strong collective fields induced in the plasma by the Coulomb force of the beam. The collective fields in turn react back onto the beam leading to many clearly-observable phenomena. The beam can be: (1) deflected leading focusing, defocusing, or even steering of the beam; (2) undulated causing the emission of spontaneous betatron x-ray radiation and; (3) accelerated or de-accelerated by the plasma fields. Using the 28.5 GeV electron beam from the SLAC linac we have carried out a series of experiments that demonstrate clearly many of the above mentioned effects. The results are compared with theoretical predictions and 2D and 3D, one-to-one, PIC code simulations. These phenomena may have practical application in future technologies including optical elements in particle beam lines, synchrotron light sources, and ultra-high gradient accelerators.

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WHAT HAVE WE LEARNT WITH THE LEP MACHINE?

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Twelwe years of physics at the LEP electron-positron collider of CERN have brought an impressive harvest of results. The Standard Model (SM) of Particle Physics has been tested quantitatively at the per mil level and found to provide an excellent description of all experimental facts. Theories attempting to go beyond the SM in order to cure some of its generic defects have been severely constrained. The extreme accuracy of several measurements gave access to the effect of virtual particle exchanges and provided key information on their existence and/or properties. The evolution of the couplings of the basic forces with the energy scale has been measured, suggesting the possibility of a Grand Unification at very high energy, in an extension of the SM called Supersymmetry. The highest energies obtained at LEP allowed to perform direct searches for the Higgs boson or alternative scenarios of Electroweak Symmetry breaking. New particles postulated by Supersymmetry were also looked for. No discovery was made, but some significant limits were set. All these experimental achievments were due to several technological and instrumental breakthroughs that I will briefly describe.

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THE HIGGS PARTICLE: FACT AND SPECULATION

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First an elementary introduction to the Higgs system will be given. The scanty knowledge about the Higgs system will be sketched, including the information obtained from the LEP machine. Some speculations will be considered, including the "relation" with supersymmetry. The importance of the Higgs system for our understanding of basic physics will be made clear.

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THE SCIENCE PROGRAMME 'LA MAIN À LA PÂTE' IN FRENCH SCHOOLS

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IS PHYSICS THE PRIVILEGE OF DEVELOPED COUNTRIES?

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Despite the poor economic situation in most of the Latin American countries, there was important scientific activity in the region during the last century. Some examples, extracted from those countries, show that physics is not restricted to wealthy countries.

The first physics research activity in Latin America dates from the late 1940s. With the exception of some experiments on cosmic radiation, early physics research was almost completely theoretical. Along with a well organized scientific activity, undergraduate programs in physics first appeared in the 1940s and graduate programs only in the 1950s. After sixty years of continuous education, in general, the number of physicists is still too small to contribute significantly to the economic development of this large region. Exceptions are Brazil, Mexico, and Argentina, countries that have an important number of physicists that started to contribute to achieve better economic standards. In these countries, there is a growing interest at some universities and research centers to establish bridges with industry.

The first research groups worked mainly in theoretical physics, including cosmic radiation, gravitation, and nuclear, atomic, and high energy physics. Research in optics, statistical physics, and solid state physics developed in the 1970s. Nowadays the most active field of research is materials science. Most of the contributions meet the highest international standards.

One can conclude that the precarious economic development in Latin American countries in the past century did not hinder the implementation of educational programs in physics and the creation of important research groups.

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NEW EFFECTS OF SYMMETRY BREAKING IN MAGNETIC FIELDS

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The interaction of light with matter can be strongly influenced by magnetic fields and sometimes in quite unexpected ways. A powerful and elegant way to predict the effects of magnetic fields is the use of symmetry arguments, as will be illustrated. Along these lines, we will discuss the observations of several new magneto-optical phenomena, like the photonic Hall effect and magneto-resistance, magneto-chiral anisotropy and magneto-electric Jones birefringence. These new effects illustrate the usefulness of the symmetry approach, and show at the same time that our detailed understanding of light-matter interaction is still incomplete. Underlining the universality of the symmetry approach, we will show that these new effects have ramifications into other areas of solid state physics and chemistry.

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ULTRA-SLOW AND STOPPED LIGHT AND SUPERFLUID SHOCK WAVES AT THE 'LIGHT ROADBLOCK'

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We succeeded in slowing light pulses in a Bose-Einstein condensate to only 17 m/s, more than seven orders of magnitude lower than the light speed in vacuum. In our later experiments, we observed light pulse velocities as low as 50 cm/s. This method was brought to its logical extreme when we completely stopped and stored light pulses in an atomic medium for up to several milliseconds. Associated with the dramatic reduction factor for the light speed is a spatial compression of the pulses by the same large factor. A light pulse, which is 1-2 miles long in vacuum, is compressed to a size of ~50 μm, and at that point it is completely contained within the atom cloud. The extremely low light speeds, and stopped light, are obtained in a new optical medium created by illuminating ultra cold atoms with laser beams.

With the most recent extension of our method, the *light roadblock*, we have compressed light pulses from 2 miles to only 2 μm. We have used this system to generate extremely localized defects and dramatic excitations in Bose-Einstein condensates and directly revealed the superfluid nature of the condensates. We have generated the superfluid analogue of shock waves: *Quantum Shock Waves*. These excitations result in the formation of solitons that in turn decay into quantized vortices. The vortices are created far out of equilibrium, in pairs of opposite circulation.

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QUANTUM INTERFERENCE OF INDIVIDUAL QUANTUM SYSTEMS

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Recent years have seen an impressive progress in interference with individual quantum systems. Experiments with individual photons are now daily routine in many laboratories. An important theme of present research is to extend such experiments to increasingly more complex systems. This includes many different aspects. Entanglement has been become a central focus of research paving the way for new ideas in communication and computation, including quantum teleportation. One line of development is the realisation of entanglement of more than two systems and with systems carrying more than two degrees of freedom. Using that kind of entanglement of the orbital angular momentum of photons recently the first demonstration of a Bell inequality for qutrits, i.e. 3-valued observables, was achieved.

Another line is quantum interference of increasingly larger and complex molecules. A remarkable feature of our experiments with fullerenes is that these molecules were at a temperature as high as 900 K and thus not fully decoupled from the environment. Nevertheless they showed perfect interference fringes.

The talk will conclude with a view at future research extending, among others, to quantum interference with biological macromolecules. Recent experiments with Porphyrine molecules are very encouraging in that respect demonstrating quantum interference of molecules with low symmetry.

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SINGLE ATOM EXPERIMENTS AND THE TEST OF QUANTUM PHYSICS

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In recent years quite a few experiments on the interaction of radiation with single atoms in cavities and traps have been performed emphasising the quantum features of the interaction. A brief review of recent experiments of this type will be given. Since traps allow to probe the same atom for a long time and in addition to study the detailed time behaviour of the radiation-atom interaction e.g. by observing quantum jumps, it is promising to combine optical cavities with high quality factors with the known trapping techniques. It has been shown that a single atom laser with interesting new features can be realised. In the talk special emphasis will be given to the application of trapped ions for quantum information processing and to frequency standards.

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REMEMBERING EUGENE WIGNER AND PONDERING HIS LEGACY

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We celebrate the centenary of Eugene Wigner who was almost of the same "quantum age" as Heisenberg and Pauli. However, the latter were intimately involved in adapting Bohr's quantum theory to the mathematical description of atomic spectroscopy and were among the main architects of the upgrading of old quantum theory into quantum mechanics (QM). By contrast Wigner graduated in 1925 as chemical engineer in Berlin. Although he was fascinated by the quantum theory he was exposed to at the Berlin Colloquium, he returned to Budapest to work in the tanning factory where his father was director. His mentor Michael Polanyi soon rescued him by getting him invited as an x-ray technician to Berlin. The factory was a total dead-end, but I will argue that the chemical training and his sensitization to mathematics in school were positive influences, since QM was basically a novel confluence of physics, mathematics and chemistry. (See the excellent summary in the November 1977 issue of "Fizikai Szemle".)

Wigner's training prepared him for an important role in the Manhattan Project, where he was put in charge of constructing the plutonium producing Hanford facility. He guided the industrial contractor to upgrade traditional chemical engineering techniques to include nuclear phenomena, thus solving the novel cooling problems.

Years before this event, Wigner's background already helped to shape his contribution to fundamental QM, although in a subtle way. His early experience in x-ray crystallography brought him in contact with symmetry. This resonated with his liking for mathematics stimulated in gymnasium and greatly supported by his prodigy friend Johnny von Neumann. All this added up to a program of applying the theory of group representations to atomic spectroscopy. The papers that he wrote in 1927-9, some of them jointly with Neumann, are seminal in the field. He collected the material in a widely read book that helped to overcome the community's aversion to "Gruppenpest". The issue was the conflict between the analysis of the continuum and the discontinuity of algebra, reflecting the discontinuity of chemistry.

Wigner extended the range of his activities to molecules, solids and nuclear physics, always focusing on problems of symmetry and invariance. His nuclear physics achievements and work on symmetry earned him the Nobel Prize in 1963. Wigner's highly mathematical theory of the Lorentz group will be discussed. His tensor-space parametrization as against the complex spinors of Dirac raises problems of ways to choose the optimal mathematical formalism in the natural sciences.

Wigner has a paper addressing this problem "The unreasonable effectiveness of mathematics in the natural sciences. " This is a widely read paper; it has great charm; it is utterly free of jargon, but its understated yet sharp sense of humor may have caused it not be taken seriously as a philosophical – methodological statement. A considerable effort will be made to counteract this impression, and to show that the paper deserves a serious consideration for improving the methodological habits formed during the halcyon days of the early last century.

In celebrating men of great originality we should heed not only the problems they solved but also those they posed.

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