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**String theory: challenges, successes and magic**

2004

**Acoustics and metastable liquids**

**Shining light on electron quantum liquids in two dimensions**

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**Exotic nuclei: why and how to make them?**

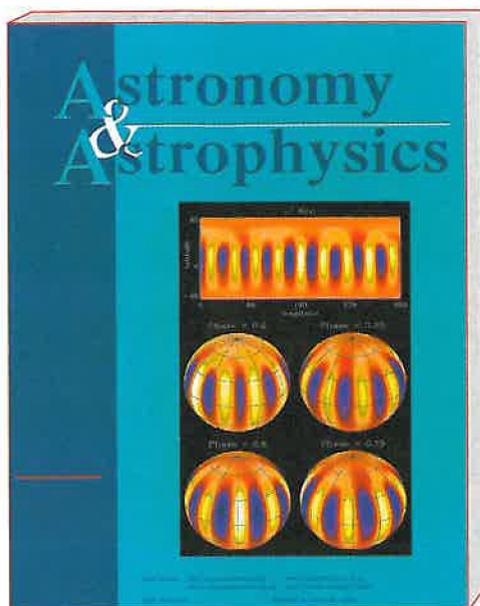
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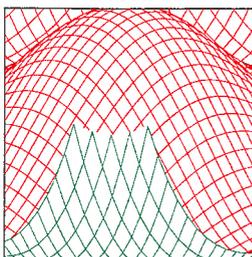
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# Acoustics and metastable liquids

Sébastien Balibar

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Medical doctors know how to break kidney stones with ultrasound. We break pure liquids in a similar way. This has led us to general questions on the metastability of liquid matter with respect to a gaseous or solid state.

## Acoustic cavitation

Can one really break a liquid with ultrasound waves? Is this what happens in an ultrasonic cleaning bath? In such a device, the sound pressure oscillates strongly enough for bubbles to nucleate in the minima of the wave, and the subsequent collapse of these bubbles cleans walls. When evaporating into the gas bubbles, molecules separate from their neighbors in the liquid phase, so that, in a sense, one could say that the cohesion of the liquid is broken by the intense sound. Now, in this particular situation, the nucleation is called "heterogeneous" because it is not an intrinsic property of the liquid. In fact, micro-bubbles of air are already present in the bath, especially on wall defects. They grow under the effect of moderate depressions, and an ultrasonic cleaning bath does not require a very intense sound field. The liquid in this cleaning bath is fragile, like a solid piece which contains many micro-fractures.

Ocean water is just as fragile: it also breaks at moderately negative pressures, around  $-1$  bar.<sup>1</sup> This is the reason why bubbles appear behind the propellers of fast moving boats. A local increase in flow velocity reduces the pressure: Bernoulli's law tells us that the quantity  $(P + 1/2 \rho v^2)$  is constant in an inviscid fluid ( $P$  is the pressure,  $\rho$  the density and  $v$  the local fluid velocity). As a consequence, if  $v$  equals  $15$  m/s somewhere, the pressure is reduced by  $2$  bar with respect to a fluid region at rest. This usually happens near the core of vortex lines behind each propeller blade, where the pressure is  $1 - 2 = -1$  bar. This is the typical negative pressure at which micro-bubbles of air grow in the ocean. Cavitation behind a submarine depends on the quantity and size of micro-bubbles which itself depend on depth, latitude, temperature etc. After growing in a

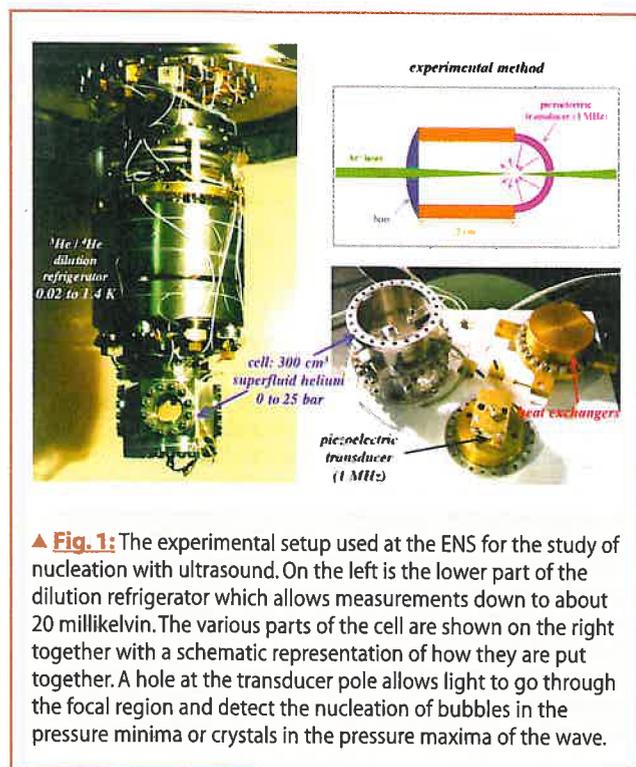
<sup>1</sup> Some people have difficulties in considering negative pressures, although there is not much mystery about them [1]. They are just positive stresses, and a pressure is nothing but an isotropic stress. If one pushes on a piston closing a chamber filled with some fluid, the pressure increases. On the contrary, if one pulls on the piston, one applies a positive stress that is a negative pressure. Of course, in a gas, the pressure cannot be negative; it tends to zero proportionally to the density (according to the perfect gas law). In a liquid, the pressure can be negative because of the existence of attracting forces between molecules. These forces ensure the cohesion of the liquid, i.e. a non-zero density at zero pressure. At negative pressure, matter is not stable but it can be metastable for very long times. This is the case of our liquid under extension: if bubbles appeared, they would grow and bring the liquid back to some positive pressure, but if no bubbles are present the stretched liquid state can stay for very long times. This may even happen in nature, for example at the top of a large tree, where the water in the trunk is stressed by the whole liquid column: the pressure is negative as soon as the height is larger than 10 meters.

region of negative pressure, bubbles move away and collapse in a region of positive pressure. This makes noise and may also damage the propeller blades, so that it is a serious technological problem.

Would it be possible to eliminate walls, defects, and impurities? What would happen then? This is in fact the motivation of our present research. We eliminate heterogeneous nucleation by focusing a sound wave in the bulk of an ultra pure liquid containing no dissolved gases. For this, we have started with the purest possible liquid, which is liquid helium because it is colder than any other one, so that all possible impurities are frozen and easy to filter. In this ideal situation, we observed "homogeneous" nucleation, an intrinsic property of the liquid. After about a decade of research, we have proven that the intrinsic tensile strength of liquid helium is  $-9.4$  bar in the low temperature limit. This is close to the "spinodal limit" where the attractive forces responsible for the cohesion of the liquid can no longer stand the negative pressure of the acoustic wave.

Some people consider that liquid helium has been studied for too many years! In fact, we take advantage of this situation: the thermodynamic properties of liquid helium are so accurately known, in particular its equation of state  $P(\rho)$  is so well established, that one could calculate the spinodal limit for the liquid-gas transition, and compare with the measured one. In our opinion, liquid helium is a remarkable model liquid.

For our measurements, we focus bursts of ultrasound waves, as was first done by J. Nissen *et al.* [2]. A hemispherical piezoelectric transducer is excited at resonance in its first thickness mode, near  $1$  MHz. For our first experiments with M.S. Pettersen in 1994 [3], we used rather long bursts but we now use short ones [4,5], typically with  $1$  to  $6$  oscillations only. As a consequence of the geometry, the sound waves converge at the center, far from any wall (see Fig. 1). There, at the acoustic focus, we obtain typically  $10$  bar sound amplitude for bursts of  $6$  oscillations with  $20$  Volt excitation, enough to reach  $-9$  bar if the static pressure in the cell is  $+1$  bar. The accuracy of our measurements has continuously improved, and, together with F. Caupin [4], we have demonstrated the existence of a reproducible cavitation threshold at  $-9.4$  bar in liquid helium at low



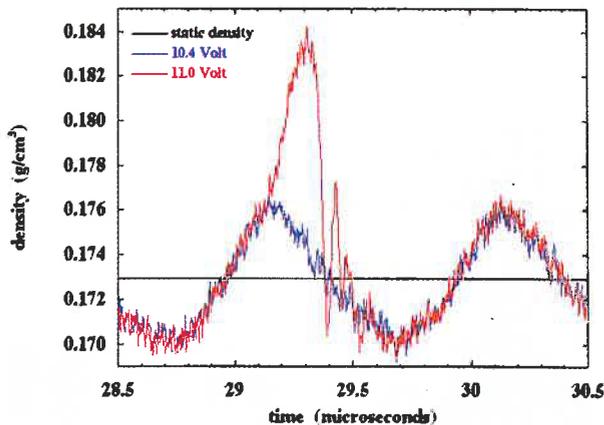
▲ Fig. 1: The experimental setup used at the ENS for the study of nucleation with ultrasound. On the left is the lower part of the dilution refrigerator which allows measurements down to about 20 millikelvin. The various parts of the cell are shown on the right together with a schematic representation of how they are put together. A hole at the transducer pole allows light to go through the focal region and detect the nucleation of bubbles in the pressure minima or crystals in the pressure maxima of the wave.

temperature. This is 0.2 bar only above the theoretical spinodal limit (-9.6 bar) which was calculated by three different methods [6].

At this limit, the liquid is unstable because its compressibility diverges, it is infinitely soft and the sound speed vanishes. Not only is our measured value close to the theoretical value, in fact we understand this slight difference: -9.6 bar is the negative pressure at which liquid helium would be totally unstable, even if one observed it during an infinitely short time and in a vanishingly small volume. In our experiment, we look for cavitation in a time of order 100 ns, i.e. a tenth of the sound period, and in a volume of about  $10^{-7}$  cm<sup>3</sup>, a fraction of the acoustic wavelength cubed. This is why we find an instability at a slightly less negative pressure. In summary, we have shown with this model liquid that studying cavitation in clean conditions gives information on the internal cohesion of the liquid.

Is this another curiosity of helium, or could one use this method to learn something about other liquids? We are currently generalizing it to more classical liquids, in particular to the most important one, namely water, of course. Frederic Caupin and Vincent Fourmond [7] have first observed homogeneous cavitation in freon, then ethanol, and they are studying pure water now. The tensile strength of water is expected to be near -1500 bar at room temperature (+ 35°C), and reaching the necessary sound amplitude is becoming a real challenge. Why is it so interesting to do this? It happens that, even at the beginning of the 21st century

...even at the beginning of the 21st century... the theory of water is not well established.



▲ **Fig. 2:** Acoustic crystallization on a glass plate. This recording from X. Chavanne *et al.* [5] shows a high amplitude wave propagating in liquid helium 4 (blue curve). With 11 Volt excitation, a pressure oscillation of  $\pm 4.3$  bar is obtained at the acoustic focus, which corresponds to a 2% oscillation in density around the static density in the cell (0,173 g/cm<sup>3</sup>). Beyond this threshold, liquid helium crystallizes, and one measures a sudden increase in density (red trace). Crystals can grow up to a size of 10 microns in 100 ns, which means at velocities of 100 m/s, close to the speed of sound (360 m/s). This recording was obtained when the acoustic wave was focused on a clean glass plate; it allowed a measurement of the instantaneous density from the reflectivity of light at the glass/helium interface in the acoustic focal region.

where physics has reached a rather high level of power and complexity, the theory of water is not well established. F. Caupin expects his measurements to discriminate between two different theories, the one by R. Speedy *et al.* [8] and the one by S. Sastry *et al.* [9].

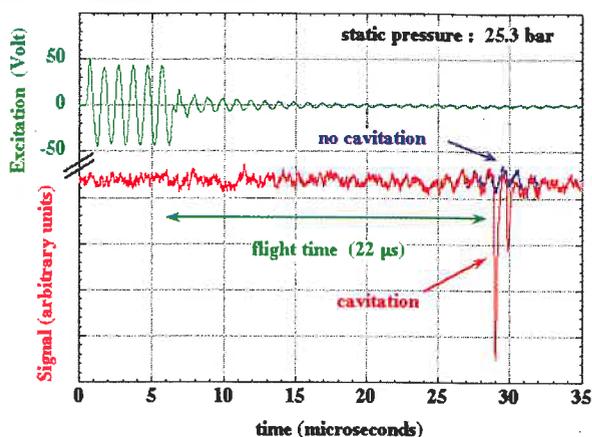
It is going to be a test because the temperature variation of the cavitation threshold is linked to the sign of the thermal expansion coefficient. One knows that, at ordinary pressure and below 4°C, water expands when cooled down. This anomalous behavior comes from the fact that when H<sub>2</sub>O molecules cool down, they bind to each other thanks to “hydrogen bonds”, and a local symmetry is forced, which is tetrahedral, i.e. not compact; as a consequence, H-bonds take space. Now does this expansion occur in stretched water as well, i.e. at large negative pressure, or not? This is where Speedy and Sastry disagree. If Speedy is right, then the tensile strength of liquid water should decrease with temperature; but if Sastry is right, it should increase. It thus seems that Caupin’s measurement should easily tell the truth; we hope to know soon.

One reason why Caupin is optimistic is that he also studied the light isotope of helium, helium 3, and he has already observed a similar effect. He first observed that liquid helium 3 is three times more fragile than liquid helium 4 (it “breaks” at -3.1 bar instead of -9.4). He then observed an anomalous temperature variation of its cavitation threshold pressure: below 0.3 K, it decreases with temperature, and he could relate this to the thermal expansion coefficient being negative; it is negative because helium 3 is a Fermi liquid where the effective mass of quasiparticles increases with pressure, a reason which has nothing to do with H-bonds in water, but the consequence on cavitation is the same, and Caupin could observe it. He only has now to focus acoustic waves of 1500 bar amplitude. This corresponds to 1.5 MW/cm<sup>2</sup> or 220 dB, a very large power density, about 20 000 times more than that used by surgeons to break kidney stones. If the physics of helium could lead us to learn something crucial about water, this would of course be a great success. But this is far from being the only question of interest to us, when playing with high intensity acoustic waves.

### Acoustic crystallization

What about the pressurization during the positive swings which immediately follow the negative ones in the acoustic waves? Could it be sufficiently strong to crystallize the liquid in the path of the wave? The answer is yes, and we observed this phenomenon for the first time in 2001 [5]. The physics is similar but the nucleation of crystals is usually favored by walls. In all practical situations, crystals nucleate on walls or have not enough time to grow during one sound period, and that’s probably why acoustic crystallization had not yet been observed. To eliminate the influence of walls is clearly difficult, although it has been done by G. Seidel and his colleagues, who studied the crystallization of droplets of liquid hydrogen [10].

But let us first consider the case of water again. One knows that liquid water can be supercooled below 0°C. For example, in clouds, the liquid droplets freeze around -20°C, a temperature that depends on pollution. Now, it has been a long standing puzzle to understand why water could never be supercooled below -40°C. It seems that Peter Taborek has solved this problem with his 1985 experiment [11]. According to the standard theory of nucleation, it is the value of the surface tension that governs the limit beyond which a liquid can no longer stay in its metastable supercooled state. For a nucleus of the stable state to appear, a liquid-solid interface needs to be formed, whose energy is proportional to the surface tension, a free energy per unit area. According to Taborek, the free energy of the ice-to-water interface is 28 erg/cm<sup>2</sup>, and this explains the maximum undercooling of liquid water. Now, measuring the surface tension of a crystal is far from easy, and the value



▲ **Fig. 3:** Homogeneous acoustic cavitation. In liquid helium at high pressure and far away from any wall, a high intensity acoustic wave—here 35 bar in amplitude—produces cavitation in its negative swings, no crystallization in its positive swings. This cavitation is random, and recordings at the threshold show cavitation with a probability 0.5. One easily distinguishes a cavitation signal from a crystallization signal by studying the dependence of the phenomenon on the static pressure in the experimental cell.

of this quantity was not known for ice. Taborek's value is reasonable and probably right, but so far there seems to have been no independent check that his value is correct, so that the whole issue is still somewhat controversial.

What about helium, then? Would it be possible to use it once more as a model system to understand the metastability limit of a liquid against its crystallization? This is exactly what we are presently doing, and we take advantage of the fact that, in the case of helium crystals, the surface tension has been accurately measured thanks to the possibility of propagating crystallization waves at their surface [12].

A first important step was the recent observation of crystallization by acoustic waves on a clean glass plate [5]. This plate allowed a local and instantaneous measurement of the density at the acoustic focus, from the reflectivity of light at the glass/helium interface (Figure 2). We found that helium crystals nucleated 4.3 bar above the equilibrium pressure between solid and liquid helium (25.3 bar). This overpressure was about 1000 times larger than what had been observed during ordinary experiments in ordinary cells, namely a few millibar. This we understood in that, in ordinary cells, favorable nucleation sites existed, such as graphite dust particles probably [13], while our clean glass plate had none of these dust particles. Still, from the value of the surface tension of helium crystals, it has been predicted that homogeneous nucleation of helium crystals should occur around 65 bar. We thus guessed that the glass plate favored the nucleation, probably because of the van der Waals attraction it exerts on liquid helium, and of the presence of a few irregularities at its surface that may amplify the effect of the van der Waals attraction. We verified this hypothesis by measuring the energy barrier for the nucleation of crystals on the glass plate and also the number of nucleation sites, which we found of order one. Given this, we removed the glass plate in our setup (Fig. 1) and continued our search for homogeneous nucleation of helium crystals.

As in the previous experiment, a green laser was focused in the acoustic focal region. Since we had shown that the light scattering

technique was sensitive enough to detect the nucleation of crystals in the presence of a glass wall, there was no reason to think that, in the absence of glass wall, we could miss nucleation events. Moreover, when using higher amplitude waves, the crystals should grow even faster and be larger and easier to see. As already mentioned, the standard nucleation theory predicts homogeneous crystallization at 65 bar. We reached this overpressure, then reached 110 bar, finally 160 bar at the end of 2003 [15], but we never detected any crystallization, only cavitation in the negative swings of the wave (see Fig. 3).

A first consequence of our experimental observations is of course that the standard theory fails in predicting the nucleation threshold for helium crystals from overpressurized liquid helium. It is clearly too simple to predict the properties of liquids that far from their stable region of existence. For example, in order to describe the energy of the nucleus surface, it uses the value of the liquid-solid interfacial tension at the equilibrium pressure, where the respective densities of the liquid and the solid are 0.17 and 0.19 g/cm<sup>3</sup>, while the density of liquid helium at 160 bar is larger than 0.22 g/cm<sup>3</sup>. F. Caupin and H.J. Maris have proposed that the liquid-solid interfacial tension increases with pressure, so that the solid should never nucleate, except if one reaches some instability at a certain critical pressure. Could this happen?

A long time ago, Schneider and Enz [16] proposed that liquid helium should be unstable against the formation of a periodic state if the "roton gap" vanished. The rotons are the particular excitations that were introduced by Landau to explain the thermodynamics of superfluid helium. They correspond to a local minimum in the dispersion relation  $\omega(q)$  of phonons, and, since Landau's time, one has understood that the roton energy reflects the local order of the liquid around the atoms. As the pressure increases, the local order increases and the roton energy decreases, and this has been very accurately measured by successive neutron scattering measurements. The roton wavevector  $q$  being roughly equal to  $2\pi/a$  where  $a$  is the interatomic distance, the liquid is expected to be unstable against the formation of a periodic state whose periodicity is the atomic distance, and this looks very close to a crystal. As a consequence, one expects a liquid-solid spinodal to exist at the pressure where the roton energy vanishes, and this has been recently predicted to occur around 200 bar [17]. We are not far from this possible limit, and we hope to reach it soon, for example by using two hemispherical transducers facing each other, instead of one. An observation of this instability would be a three-dimensional analog of the one occurring in two dimensions, at the surface of ferrofluids where a surface mode with finite wavevector also becomes soft, this time as a function of the applied magnetic field.

Now, the possibility that the free energy of the liquid-solid interface increases with pressure is not the only possible explanation of our recent experiments. We have shown that, if the liquid is superfluid, then the crystals grow very fast after their nucleation, so that their observation is easy. But is liquid helium superfluid when its density is 30% larger than at equilibrium? If a superfluid to normal transition occurs, liquid helium might be very viscous at 160 bar and its dynamics jammed as in a glass. In fact this is certainly what happens with ordinary liquids after a high pressure quench. The question is thus: is a system of Bose spheres necessarily superfluid at zero temperature? If not, it might explain why we did not observe the crystallites: they don't grow and they are too small to be detected. This last question is rather open but has already triggered several theoretical works, by P. Nozières and by D. Ceperley *et al.* If we could observe nucleation near the instability at 200 bar, we should see some effect of a superfluid to normal transition on

the temperature variation of the nucleation limit at high pressure, as we did at low pressure for the cavitation limit.

It seems that, by repeatedly asking naive questions on the effect of high intensity acoustics in both liquid helium and water, on surface tensions and on the way that stable nuclei appear when matter changes state, we have encountered several unsolved problems. We have found a few answers to several questions, but a lot remains to be understood.

### About the author

Sebastien Balibar leads a research group at the ENS in Paris. His main achievements concern roughening and other surface properties of crystals, quantum evaporation, wetting and critical phenomena, nucleation of bubbles and crystals using acoustic waves.

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# Shining light on electron quantum liquids in two dimensions

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The itinerant carriers that play pivotal roles in many of the properties of a solid originate from the valence electrons of constituent atoms. A simple assembly of itinerant electrons at densities of conventional metals behaves as a liquid of fermions that supports well-known electrical transport properties and collective behaviour with excitations such as plasma waves. The early work of E.P. Wigner and F. Bloch created an awareness of the intricate many-electron physics that may emerge when reaching the low-density limit [1]. As the electron density reduces, new highly correlated phases are expected as quantum mechanical interactions dictate key behaviours of the electron assembly. The difficulties in achieving the required low critical values of the density in high quality systems with very long electron relaxation times hinder the manifestation of broken-symmetry phases such as the electron crystal and ferromagnetic state proposed by Wigner and Bloch.

The endeavours linked to the creation, study and manipulation of new collective electron phases are among the most central areas of contemporary condensed-matter science. A key development in these branches of fundamental and applied science, that continues to have a major impact on current research, was the introduction of modulation-doped semiconductor quantum structures at the end of the 70's [2]. This advance in fabrication, by Molecular Beam Epitaxy (MBE) methods [see Figure 1a], enables creation of electron fluids in two dimensions (2D) in which scattering due to imperfections is highly suppressed to levels below those of intrinsic mechanisms (phonons) even at the lowest temperatures. The availability of nearly perfect electron systems in modulation-doped artificial quantum structures has stimulated the phenomenal expansion of studies of low-dimensional systems that continues to the present [3].

The discoveries of the integer and fractional quantum Hall effect are key milestones in condensed matter sciences [4,5]. The search for the elusive electron-crystal state in modulation-doped quantum structures led to the unexpected discovery of fractional quantization of the Hall effect of the two-dimensional electron gas in a perpendicular magnetic field [5]. The transport signatures of the fractional quantum Hall effects are seen as macroscopic manifestations of a quantum fluid in which the highly correlated electron liquid is represented by a quantum state with a single many-particle wave function [6]. Experimental and theoretical studies of quantum Hall electron liquids have uncovered some of the more intriguing many-body behavior in contemporary physics. The multiplicity of quantum Hall states seen in superior quality systems at low temperatures [see Figure 1d] can be regarded as sequences of 'compressible' (metallic) and 'incompressible' (insulating) states that occur as the external

magnetic field changes. These are quantum phase transitions (QPT) that emerges at constant temperature ( $T \rightarrow 0$ ) and are driven by changes in interactions linked to changes in magnetic field [7].

Quantum Hall liquids have characteristic low-energy collective excitations that represent time- and space-dependent oscillations of the charge or the orientations of spin of the many-electron system. The excitation modes are described by characteristic energy vs. wave-vector dispersions [8]. In continuous QPT's the transformations are linked to softening of low energy excitation modes, because the energy required to cause the change that is associated with the collective mode coordinate vanishes. This softening thus induces an instability in which the 2D electron system changes quantum ground state by incorporating properties associated with the excitation. When the soft mode has vanishingly low energy ( $\omega \rightarrow 0$ ), the spontaneous broken symmetry phase has a continuous order parameter that vanishes at the critical point of the transition [9].

In this article we describe inelastic light scattering methods that explore the collective excitation spectra of remarkable electron fluids in the quantum Hall regimes. Light scattering measurements access spin and charge excitations and offer unique insights on the ground-state configurations of the electron quantum liquids and on the QPT's that link the different states. This introduction is followed by a short overview of quantum Hall liquids and their excitations. We continue with a description of the conceptual framework that applies to light scattering processes in 2D electron layers in semiconductors. We end with a description of recent results from spin-aligned quantum Hall ferromagnets that highlight the physics of electron quantum fluids in two dimensions that is revealed by inelastic light scattering experiments.

### Quantum Hall systems

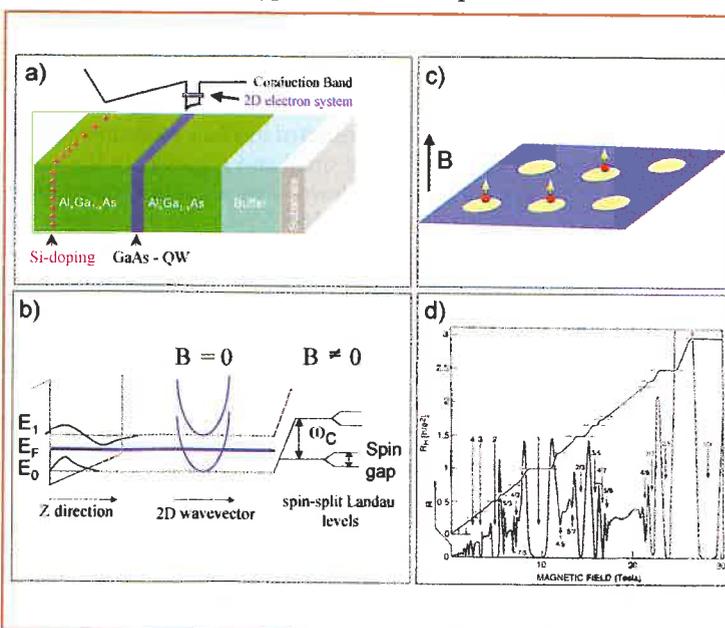
Figure 1a shows a typical layer sequence of a modulation-doped (Si-doping) quantum well GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As sample. The design of the artificial structure allows fine control of parameters such as density, mobility and level splitting. In the quantum structures designed for optical experiments the aluminium composition is kept at  $x \leq 10\%$  to minimize the impact of layer width fluctuations and other disorder [11]. Low-temperature electron mobility above  $5 \times 10^6$  cm<sup>2</sup>/Vs are typical for these samples. Free electron

density below  $10^{10}$  cm<sup>-2</sup> was reported [12]. As shown in Fig. 1b, in a magnetic field  $B$  perpendicular to the 2D plane the in-plane kinetic energy becomes quantized into discrete macroscopically-degenerate Landau levels (LLs), and coupling of  $B$  to electron spin further splits each LL into spin-up and spin-down states separated by the Zeeman energy  $E_z$  (spin gap). Landau level quantization is linked to cyclotron motion of the electrons with orbits of semiclassical radius related to the magnetic length  $l_0 = (\hbar c / eB)^{1/2}$  as shown in Fig. 1c. This orbital motion defines the cyclotron gap  $\omega_c = (eB / m_e)$ , where  $m_e$  is the electron effective mass, that separates LLs with same spin. The filling factor  $\nu = n2\pi(l_0)^2$  defines the number of occupied LLs. For integer or 'magic' fractional values of  $\nu$ , the longitudinal resistivity  $\rho_{xx}$  is vanishingly small and the Hall resistance  $R_H$  is quantized with extreme precision at values  $h/\nu e^2$  (see Fig. 1d). The pioneering experiments by Klaus von Klitzing, Gerhard Dorda and Michael Pepper [4], and by Horst Stormer, Dan Tsui and Art Gossard [5] and the theoretical work done by Robert Laughlin [6] led to Nobel prizes in Physics in 1985 and 1998 for the discoveries and interpretations of the quantum Hall effects.

Figure 1d shows that there is absence of dissipation in quantum Hall states at the lowest temperatures. The longitudinal conductivity in a perpendicular magnetic field

$$\sigma_{xx} = \rho_{xx} / (\rho_{xy}^2 + \rho_{xx}^2),$$

shows that the quantum Hall states are also insulating ( $\sigma_{xx} \rightarrow 0$ ), i.e. there is a gap in their excitation spectrum. The gaps in the integer  $\nu$  states (IQHE) can be understood in terms of cyclotron or spin gaps. In states with fractional  $\nu$  (FQHE) the gaps are linked to the emergence of 'incompressible' quantum liquids [6] driven by fundamental electron interactions. The quantum liquids emerge in response to the deceptively simple Coulomb repulsion in 2D and the Pauli principle that applies to fermions. In recent years light scattering spectroscopy has evolved into a primary experimental tool for the study of gap excitations in the quantum Hall regimes, and offer direct tests of key predictions of theories of the electron fluids. In studies of the quantum fluids of 2D electron systems in perpendicular magnetic fields light scattering experiments play roles similar to neutron and X-ray scattering studies of elementary excitations in superfluid liquid Helium.



◀ **Fig. 1:** a) Sequence of layers in a typical GaAs/AlGaAs modulation-doped heterostructure grown for light scattering studies. The conduction-band profile along the growth axis is also shown. The high-mobility 2D electron system resides in the GaAs quantum well. Buffer and substrate layers are of GaAs. b) From left to right: schematic of the two lowest quantized energy levels  $E_0$  and  $E_1$  and wave functions along the growth direction;  $E_F$  is the Fermi energy. Sketch of the subband dispersion as a function of the in-plane wave-vector at zero magnetic field  $B$ . Quantization of the in-plane kinetic energy into Landau levels under the application of  $B$ .  $\omega_c = eB/m_e c$  ( $m_e = 0.067 m_0$  is the effective electron mass in the GaAs semiconductor with  $m_0$  being the free electron mass) is the cyclotron gap.  $E_z = -g\mu_B B$  ( $g = -0.44$  is the effective gyromagnetic factor in the GaAs,  $\mu_B$  the Bohr magneton) is the Zeeman energy (spin gap). c) Schematic semi-classical representation of electrons with spin moving into cyclotron orbits in a perpendicular magnetic field. The drawing shows occupied and empty states in the lowest Landau level with filling factor  $\nu < 1$ . Vertical arrows identify the orientation of the spin. d) Manifestations of the integer and fractional quantum Hall effects in magneto-transport experiments. The values of the quantized values of  $\nu$  are also shown (after Ref.[10]).

features

### Collective modes of quantum Hall liquids

Collective excitation modes of quantum Hall states are built from neutral particle-hole pair transitions. In these excitations a quasi-particle is promoted to an empty state and a quasi-hole is created in the ground state as shown schematically in Fig.2a. In excitations of the charge degree of freedom the spins of the particle and hole are identical. In spin excitations there is a spin flip. These pairs are the building block of the collective modes and can be regarded as magnetic-excitons with a dipole length  $x_0$  [3,8], where  $x_0$  represents the displacement between the centers of the two cyclotron orbits (see Fig.2a). From a semiclassical point of view, the balance between the Lorentz and Coulomb forces leads to a center-of-mass velocity of the neutral pair that is inversely proportional to the separation between the particles. The excitonic pairs are thus characterized by the in-plane wavevector  $q$  that is a quantum number for the excitation with  $x_0=ql_0^2$ . The coupling between particle and hole in the neutral pairs gives rise to many-body terms that have a strong  $q$ -dependence [3]. The roton (or magneto-roton), a minimum of the dispersion at finite wavevector of the order of  $1/l_0$ , is the characteristic manifestation of these interactions. It is caused by excitonic terms (called vertex corrections) of the Coulomb interaction that bind particle-hole pairs and greatly reduce their energy. Figure 2b shows the roton in the dispersion of charge excitation modes (CDE) predicted at  $\nu=1/3$  [13]. At the roton wavevector there is a peak in the structure factor of the quantum Hall liquid in analogy with that for excitations in superfluid He<sup>4</sup>. As the lowest energy excitation of the liquid, the magneto-rotions are barometers of its stability. Roton instabilities have been predicted to trigger transitions from liquid to Wigner crystal states [13,14].

Different Coulomb interaction terms enter in the dispersions of spin and charge modes. In CDE (see caption to Fig.2), the direct

term of the Coulomb interaction (depolarization term) adds to the excitonic term mentioned above, and to differences in self-energy contributions. In spin excitations the depolarization shift is absent. In the large-wavevector limit both excitonic and direct terms of Coulomb interactions vanish and the mode energy is given by the self-energy terms summed to additional single particle contributions such as cyclotron gaps. However, in the FQHE regime, the lowest collective CDE are intra-Landau level excitations and the opening of the gap is a purely many-body effect. The large wavevector limit ( $q \rightarrow \infty$ ) represents infinitely separated particle-hole pairs. The energies of the lowest charge excitations at  $q \rightarrow \infty$  are conceptually linked to the gaps measured in temperature-activated magneto-transport.

In the case of spin modes there is also an additional contribution due to the Zeeman gap. There are spin wave excitations in which only spin changes, and spin-flip excitations in which other quantum numbers change too (see caption to Fig.2).

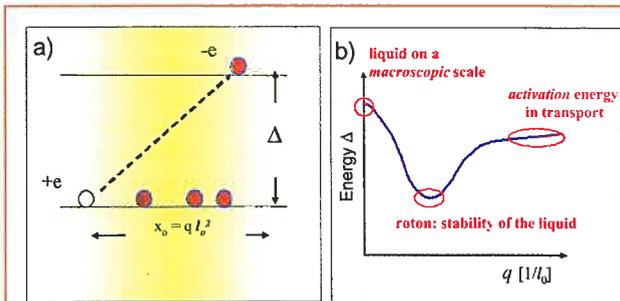
### Inelastic light scattering from quantum Hall liquids

This section presents a basic conceptual framework that applies for resonant inelastic light scattering spectroscopy of collective modes of quantum Hall liquids. First we recall that the kinematics of the light scattering process is dictated by conservation of energy and momentum. In a translational invariant system expected in quantum structures in absence of disorder, conservation of momentum implies conservation of wave-vector (see Fig.3a).

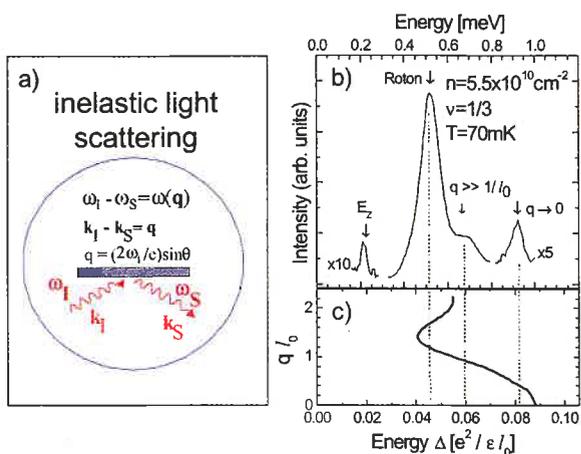
Conservation of energy implies that  $\omega_I - \omega_S = \pm \omega(q)$  (see Fig.3a) where I and S refer to incident and scattered photons. The  $\pm$  signs apply to Stokes and anti-Stokes processes respectively and  $\omega(q)$  is the collective-mode energy at the in-plane wavevector  $q$ . Large resonant enhancements, that are required to observe the excitations of 2D electron systems, occur when  $\omega_I$  and  $\omega_S$  overlap the energies of optical transitions of the semiconductor quantum structure that hosts the 2D electron system. Within time-dependent perturbation theory the resonant light scattering amplitude includes two virtual intermediate valence-to-conduction band optical transitions. Light scattering by spin excitations with change in the total angular momentum  $\Delta J=1$  (see caption to Fig.2) are made possible by spin-orbit coupling in the valence states of the semiconductor. It can be shown that charge- (CDE) and spin-density excitations (SDE) can be separated by specific polarization selection rules. Light scattering by CDE or SDE tends to be stronger when the two polarization vectors of incident and scattered light are parallel or orthogonal, respectively.

An important aspect of resonant inelastic light scattering processes is related to the transferred in-plane component of the wave-vector  $q$ . This value is small and typically in the range  $q \cdot l_0 \leq 0.2$  ( $l_0 \approx 10\text{nm}$ ). Breakdown of wavevector conservation, however, can occur in quantum Hall liquids due to the impact of dephasing mechanisms associated either with residual disorder in the insulating phases or thermally activated by temperature. Light scattering processes with breakdown of wavevector conservation, particularly effective under strong resonance conditions, allow probing excitations at the critical points of the mode dispersions such as the ones at the magneto-roton minimum.

Figure 3b shows an example of a rich light scattering spectrum obtained in the FQHE at  $\nu=1/3$  under resonant conditions (the incident laser light is close to the fundamental band-gap of the GaAs heterostructure). Figure 3c shows the calculated dispersion of the lowest CDE mode (the FQHE gap excitation). The spectra clearly display the three major excitations associated to the critical points of the dispersive CDE and, in addition, the spin-wave mode  $E_z$  at the Zeeman gap. The observation of the  $q=0$  CDE excitation



**▲ Fig. 2:** a) Schematic representation of the particle-hole pairs (magneto-excitons) that enter in the construction of the collective excitations with in-plane wavevector  $q$ . In the integer quantum Hall regime  $\Delta$  is the single-particle gap that separates Landau levels with different quantum numbers and /or spin. In the fractional quantum Hall regime  $\Delta$  is the many-body gap that opens due to electron-electron interactions. The neutral pairs in the collective mode in conduction-band states of GaAs heterostructures can be classified according to a change in the total angular momentum  $J$ . Excitations with  $\Delta J=0$  are the singlets of charge-density modes (CDE). Excitations with  $\Delta J=1$  are triplets in which the spin degree of freedom is changed. Those are spin-density modes without a fluctuating charge density and spin-flip excitations. b) Representative wave-vector dispersion of CDE mode. The dispersion applies, for instance, to the intra-Landau level excitations in the fractional quantum Hall state at filling factor  $\nu=1/3$ . The three critical points correspond to the long wavelength limit ( $q=0$ ) conventionally probed in optical experiments, to the lowest energy excitations at the roton minimum and to the long wave-vector limit ( $q \gg 1/l_0$ ) relevant in magneto-transport studies.



**▲ Fig. 3:** a) Kinematics of inelastic light scattering. b) Inelastic light scattering spectrum (Stokes side) in the fractional quantum Hall effect at  $\nu=1/3$  of the high mobility 2D electron system in a GaAs quantum structure. The horizontal axis is  $\omega_i - \omega_s = \omega(\mathbf{q})$ . The three relevant modes associated to the critical points of intra-Landau level dispersive collective CDE mode are clearly resolved. The spin-wave SW mode across the Zeeman gap is also visible (after Ref.[15]). c) Dispersion of the collective mode at  $\nu=1/3$  (after Ref. [16]).

is intriguing since the  $S(\mathbf{q}, \omega)$  for charge modes in the FQHE is predicted to vanishes as  $q^4$  for small wavevectors [13]. This observation thus highlights the impact of strong resonance enhancements. It also offers direct experimental tests for possible new interpretation of the character of the long-wavelength CDE such as the one in terms of a two-roton bound state [15]. Inelastic light scattering spectra by low-lying rotons of spin excitations have also been reported in the FQHE at  $\nu=2/5$  [17].

Finally we remark that these light scattering experiments require extreme sensitivity, large stray-light rejection and great spectral resolution. These characteristics are achieved by a combination of single-mode tunable lasers with very small linewidths, double or triple spectrometers and small-pixel CCD detectors. In order to keep the electron temperatures at the ultra-low values required for these studies, typical incident powers are kept below  $10^{-3} \text{ W/cm}^2$ .

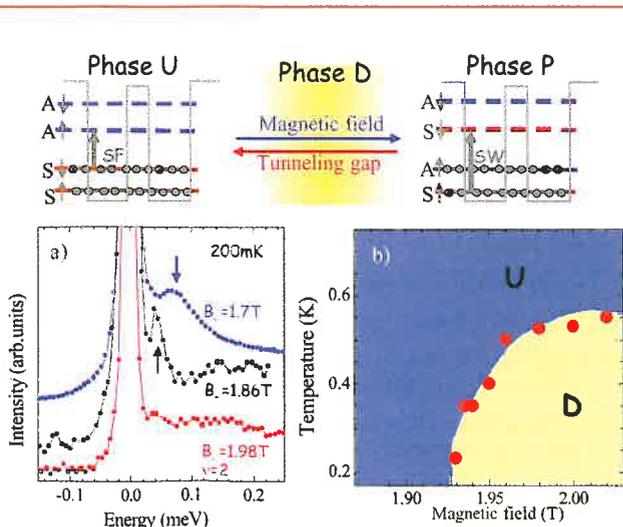
### Instabilities in quantum Hall magnets

The observation of spin modes by inelastic light scattering opens research avenues for the study of the spin polarization of quantum Hall liquids. In several cases, the spin properties of such quantum Hall states are highly non-trivial and driven by many-body Coulomb interactions. At  $\nu=1$ , for example, exchange interaction effects can lead to spontaneous ferromagnetism which in fact can persist even in the limit  $E_z=0$ . The ground state in this configuration is an exceptionally strong itinerant ferromagnet. More exotic ferromagnetic states can be created in bilayer quantum Hall liquids. These systems are composed of two 2D electron layers in close proximity. Here the new degree of freedom associated with layer occupation (described by a *pseudospin* quantum number) creates electron *inter-layer* correlation effects that have no counterpart in the single-layer case. This is the source of novel ground states with peculiar spin and pseudospin properties that are linked through QPTs.

In this section we review our light scattering experiments in bilayer quantum Hall systems that reveal soft (low-energy) excitations at QPTs. These experiments are carried out in modulation-doped double quantum well samples that consist of two identical 18-nm thick GaAs quantum wells separated by an  $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$  undoped barrier (see Fig.4 upper part, grey lines). One intriguing example of QPT occurs at the total filling factor  $\nu=2$ . Tunneling between the two layers determines the splitting  $\Delta_{\text{SAS}}$  (bare tunnelling gap) of the lowest symmetric S and antisymmetric A states as sketched in the upper left panel of Fig.4. The spin configuration of the bilayer depends on the interplay between  $\Delta_{\text{SAS}}$  and the bare Zeeman energy  $E_z$ . When  $\Delta_{\text{SAS}} \gg E_z$ , electrons occupy the lowest spin-split S levels and the electron spin polarization in this phase, called phase U, is zero. This configuration shown in the left upper panel of Fig.4 is a spin-singlet quantum Hall paramagnet.

The lowest energy spin excitations are triplets ( $\Delta J=1$ ) across the tunnelling gap. These excitations are classified according to the change of angular momentum along the magnetic field.  $\Delta J_z = \pm 1$  are spin-flip (SF) modes (one of these two modes is shown in the upper left part of Fig.4) while  $\Delta J_z=0$  mode corresponds to the SDE. Within the Hartree-Fock approximation their energies are given by  $\omega = \omega_{\text{SDE}} \pm E_z \Delta J_z$  where  $\omega_{\text{SDE}}$  is the SDE energy. In the opposite limit  $\Delta_{\text{SAS}} \ll E_z$  (shown in the right upper panel of Fig.4) the electrons are fully spin polarized (phase P). This quantum Hall ferromagnet supports characteristic spin-wave (SW) modes across the Zeeman gap.

features



**▲ Fig. 4:** Upper panel: Schematic representation of the potential in the conduction band of the GaAs/AlGaAs double quantum well. The spin-split symmetric (S) and anti-symmetric (A) levels are also shown. Landau level occupations correspond to filling factor  $\nu=2$ . SF and SW indicate transitions that enter in spin-flip excitations across the tunnelling gap and spin-wave excitations across the Zeeman gap. Phase U is spin unpolarized. Phase P is polarized. An intermediate state with unusual properties, probably linked to disorder, emerges in phase D when the magnetic field increases or the bare tunnelling gap decreases. a) Resonant inelastic light scattering spectra with orthogonal linearly-polarized incident and scattered photons. The peaks labelled with an arrow correspond to the  $q=0 \Delta J_z=0$  spin-density excitation (SDE). At  $\nu < 2.13$  ( $B = 1.86\text{T}$ ) the SDE disappears from the spectra and signals the transformation from phase U to phase D. The background at positive energies is due to luminescence. b) Finite-temperature phase diagram constructed from light scattering results. The phase boundary shown by the red dots is given by the lowest value of the critical temperature at which the SDE peak reappears in the spectra as a function of the magnetic field.

The  $q \approx 0$  SDE is the unstable collective mode discovered in light scattering studies of phase U [18]. Its energy is strongly reduced with respect to the value at zero magnetic field due to excitonic corrections that are maximized at  $\nu=2$ . The impact of this excitonic correction enhancement is shown in Fig.4a where three representative light scattering spectra are displayed. While the SDE mode at  $B=0$  is found at a energy close to 0.5meV (not shown), at 1.7T the mode energy has already diminished to 0.065meV and at 1.86T it has collapsed to the remarkably low value of 0.045meV, which is equal to the value of the Zeeman gap at that magnetic field.

The sudden disappearance of the SDE mode after a further small increase in magnetic field (see the red spectrum in Fig.4a at 1.98T) is interpreted as a soft-mode instability towards a disordered broken-symmetry intermediate phase D that emerges before phase P occurs at higher magnetic fields [18]. The emergence of phase P is monitored by the appearance of the SW in the light scattering spectra. The light scattering results shown in Fig.4a reveal that phase D occurs when the SDE collapses to  $E_Z$  and therefore when the spin-flip mode with  $\Delta J_z=1$ , shown in the upper left part of Fig.4, softens to vanishingly low energies ( $\omega_{SF} = \omega_{SDE} - E_Z \approx 0$ ).

These experiments thus uncover a link between a QPT in the spin degree of freedom and the collective mode (excitonic) instability [18,19]. Further support for the existence of an intermediate broken-symmetry two-dimensional electron state linked to phase D comes from the analysis as a function of temperature. These studies show that the SDE peak that had disappeared at  $T=200$ mK when the electron bilayer is in phase D, recovers at higher temperatures. The abrupt appearance of the SDE excitation at a critical temperature is interpreted as a finite-temperature  $D \rightarrow U$  transition. Figure 4b summarizes the observed critical temperatures (red dots) as a function of B.

Intriguing soft mode behaviour in the spin and *pseudospin* degree of freedoms have been observed in our most recent light scattering experiments in coupled bilayers at total filling factor  $\nu=1$  [20,21]. Here the lowest spin excitations are SF transitions across the tunnelling gap and SW. Within the Hartree-Fock approximation the energy spacing of these excitations at  $q=0$  is given by the bare tunnelling gap  $\Delta_{SAS}$ . The signatures of instabilities are here associated with the marked collapse of the SF mode towards the SW energy as an in-plane component of the magnetic field is applied while keeping the filling factor (i.e. the perpendicular component of B) constant at  $\nu=1$ . The SF collapse is associated with an abrupt change in the energy and temperature dependence of the SW. Although this work is still in progress these unexpected observations suggest that at the critical in-plane magnetic field an unusual situation emerges due to the suppression of the impact of the bare tunnelling gap on the collective properties of the electron bilayer.

## Outlook

More than 70 years after Wigner and Bloch offered a glimpse of the exciting world that emerges from fundamental interactions in many electron systems, research on the infinitely diverse low-dimensional systems is at the frontiers of condensed-matter

science. Resonant light scattering methods offer to these fields unique venues for investigations of the novel behaviours. In this article we have briefly touched on quantum Hall liquids in which new collective spin states can be created and manipulated for them to develop unstable excitations linked to quantum phase transitions. Among examples we have considered is the intriguing role of magneto-rotors that soften due to exciton-like interactions to drive phase transformations to exotic quantum liquids of electrons. This is just one of the multiple roles we envision for light scattering in studies of the remarkable fundamental collective behaviour of electrons in low-dimensional structures.

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Resonant light  
scattering methods  
offer... unique venues  
for investigations of  
the novel behaviours.

# Exotic nuclei: why and how to make them?

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The interaction of neutrons and protons produces an incredible variety of nuclei: all the elements which constitute our universe, from hydrogen, the lightest, to uranium, the heaviest of the natural elements.

Our knowledge of the sub-atomic world has first been constructed by studying the nuclei which we find on Earth, which have been forged by the stars, several billions of years ago.

The stable nuclei are in equilibrium: their cohesion is such that no radioactive transmutation is possible. For a given mass, the proportion of neutrons and protons corresponds to structures strongly bound by the combined action of the various interactions: strong interaction, the pairing, the spin orbit, and the Coulomb repulsion.

Nature, in the processes of nucleosynthesis, and man, with particle accelerators, know how to produce nuclei outside this equilibrium. This is the field of exotic nuclei, the unstable nuclei that do not exist naturally on Earth.

Within the limits of nuclear cohesion, these nuclei will over time join the stable nuclei by transformation of neutrons into protons or inversely. It is the  $\beta$  radioactivity which is responsible for this transformation and the weakness of this interaction explains the very long times for these processes, from several milliseconds to millions of years.

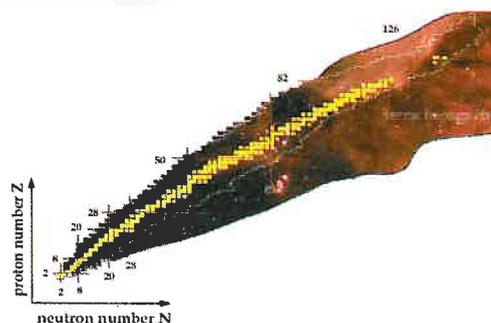
Out of the limits of nuclear cohesion, one or several nucleons are no longer bound, and the system disintegrates quasi instantaneously (in a time of the order of  $10^{-21}$ s) into several pieces. It is this limit of cohesion, called the dripline, which limits the nuclear chart on which each bound nucleus is located by its number of neutrons and protons (figure 1). We seek today to explore this entire chart in order to test our understanding of nuclear cohesion. The goals are clear:

- Identify the different phenomena at the origin of the nuclear properties;
- Develop and test models able to describe these phenomena;
- Establish the foundations of these models.

## To explore the "terra incognita" of the exotic nuclei

According to current estimates, between 5000 and 7000 bound nuclei should exist on this chart, but only 2000 of them have been observed to date. In addition, except for the few 250 stable species, very little information could be obtained on these unstable nuclei. For example, the first excited state of only about 550 nuclear species has been observed.

To probe a nucleus and to characterize its properties, it is necessary to subject it to various nuclear reactions. The stable nuclei can be used as targets and can be bombarded with appropriate particles. Unstable and rare, the exotic nuclei do not live long enough to make a target, and to study the reactions with them therefore seems impossible. The revolution came about from the possibility of constituting beams of exotic nuclei. Instead of sending the probe to the nucleus to be studied, it is sufficient to send the nucleus to the probe. The beams of exotic nuclei thus open a vast field of study.



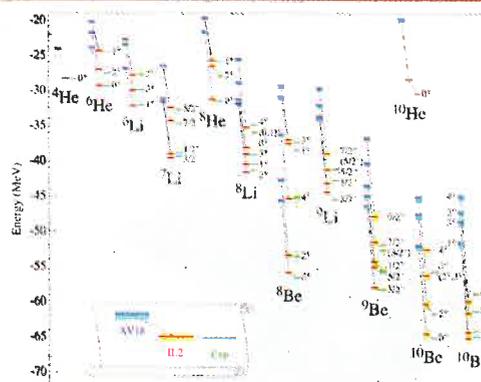
▲ Fig. 1: Chart of the nuclides representing the nuclei according to their number of protons  $Z$  and of neutrons  $N$ . The clear outline shows the limit of the nuclei observed experimentally, and the outline of the brown zone indicates the theoretical limit of nuclear cohesion. The horizontal and vertical red lines represent the magic numbers (2,8,20,28,50,82,126).

The production of secondary beams implies a very big intensity loss when compared to the primary beam, of typically 6 to 12 orders of magnitude. Therefore key experimental requirements are high intensity accelerators and high efficiency detection systems. This review will illustrate their interest with several examples.

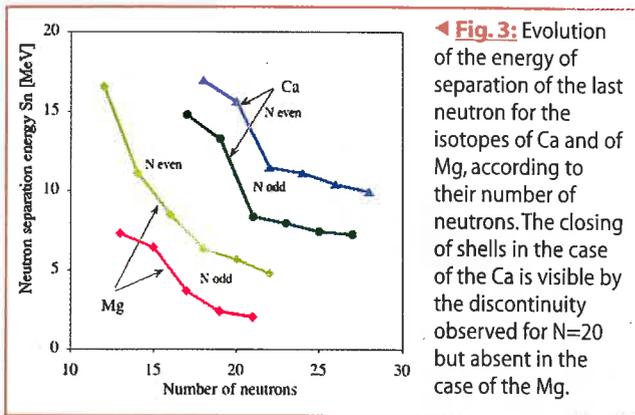
## Light nuclei

An approach to the description of nuclei, which seems obvious and which is entirely satisfactory for atomic physics, consists in trying to consider the nuclear force as the sum of the forces between the individual nucleons. The interaction between two nucleons is currently not understood starting from fundamental principles, but it can be modeled with a high degree of accuracy by adjusting it on a broad basis of experimental data for  $p$ - $p$ ,  $p$ - $n$  and  $n$ - $n$  scattering, corresponding to two body forces. Recently, it has become possible to do exact ab initio calculations for the systems of  $n$ -bodies up to  $A=12$  with these realistic forces.

These model calculations show that it is necessary to include in the models a three-body force to reproduce, for example, the binding energies of these nuclei. Just as the two-body force, this three-body force cannot be calculated from fundamental principles. Figure 2 illustrates the results obtained. In this region, only 5 stable nuclei exist, not enough to fix the parameters of the model.



▲ Fig. 2: Binding energies of ground states and of the first excited states calculated using a two body interaction labelled AV18 on the figure, and using a three body interaction labelled IL2, are compared to experimental results (from S. Pieper *et al.*, Phys. Rev. C64, (2001), 014001 and private communication).

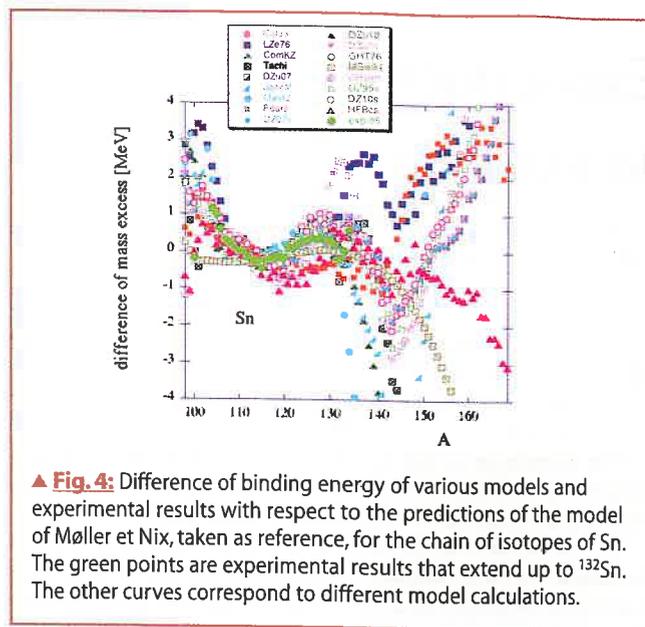


◀ **Fig. 3:** Evolution of the energy of separation of the last neutron for the isotopes of Ca and of Mg, according to their number of neutrons. The closing of shells in the case of the Ca is visible by the discontinuity observed for N=20 but absent in the case of the Mg.

The 7 unstable nuclei such as  ${}^{6,8,10}\text{He}$  are therefore essential to establish and control the model. An unexpected result is obtained: the contribution of the three body forces reaches 50% of the binding energy for  $A=8$ . The light exotic nuclei are therefore an excellent test bench for our understanding of the nuclear forces. It is why a significant experimental and theoretical effort is being made at the moment to understand the structure of these nuclei and to explore the properties of new systems such as  ${}^5,7\text{H}$ , or the quadrineutron  $4n$ , even further from equilibrium. This illustrates the interest of exotic nuclei as a testing ground to establish the foundations of models.

**Nuclei of intermediate mass and the shell model**

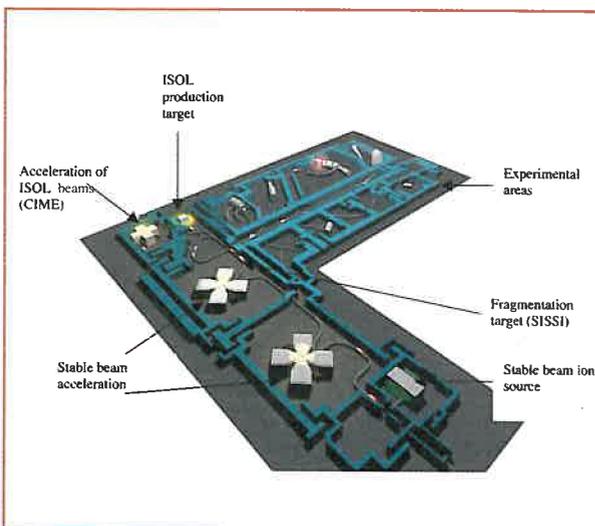
New experimental results (binding energy, properties of first excited states, ...) question increasingly our understanding of the shell structure of nuclei such as was developed for the stable nuclei. At the moment, the dependence of independent-particle orbits as a function of the neutron excess and of the binding energy is the most commonly used explanation for the disappearance of magic numbers valid for the nuclei close to stability and for the appearance of new shell closures. The most studied example at the present time is the  ${}^{32}\text{Mg}$  nucleus for which the experiments clearly show that this nucleus is very deformed, contradicting all the theoretical models which predict it as spherical, according to its neutron magic number  $N=20$ . This loss of magicity of  ${}^{32}\text{Mg}$  is illustrated in figure 3, where the evolution of the binding energy of the last bound neutron is plotted as a function of the number of neutrons, for the isotopes of Ca and of Mg. In the case of the  ${}^{40}\text{Ca}$  (20 protons, 20 neutrons), located in the valley of stability, the shell closure appears



▲ **Fig. 4:** Difference of binding energy of various models and experimental results with respect to the predictions of the model of Møller et Nix, taken as reference, for the chain of isotopes of Sn. The green points are experimental results that extend up to  ${}^{132}\text{Sn}$ . The other curves correspond to different model calculations.

as an abrupt change of slope for  $N=20$ , whereas for the  ${}^{32}\text{Mg}$  (12 protons, 20 neutrons), with a large excess of neutrons, this behaviour is not observed. More recent shell model calculations interpret this disappearance of the magic number  $N=20$  by the inversion of the order of the shells due to the dependence of the neutron-proton interaction on the combination of their spin in the nucleus (nucleon-nucleon spin-isospin  $V_{\sigma\tau}$  interaction). These calculations also predict that the magic number  $N=20$  should be replaced by  $N=16$  for the nuclei in this region very far from stability, and that this phenomenon should occur over all the chart of the nuclei. In particular, the non-observance of  ${}^{28}\text{O}$ , a doubly magic nucleus in theory, could also be explained by this modification of its shell structure.

The experimental results obtained in this area of nuclei have already therefore brought many surprises, have permitted a better understanding of the underlying physical phenomenon and consequently a better use of the models. For example, the discovery of the importance of the spin-isospin coupling mentioned above, has opened new directions for nuclear mean-field theories. These results could only be obtained thanks to an increase in the sensitivity of the experimental devices and to the availability of high beam intensities. This made it possible to reach areas of the chart of nuclei previously inaccessible.



◀ **Fig. 5:** To produce exotic nuclei and to make beams of them, two methods are used. In the first, often called the 'in flight method', the secondary beams are produced in relatively thin targets, so that they retain on exit from the production target a significant part of the speed of the primary beam. They can therefore be directly transported in the beam lines towards the experimental room, after being focused and sorted. This method is that used at GANIL on the LISE separator, and SISSI, which allows the sending of secondary beams to all the experiment rooms of GANIL. The selection of the nucleus of interest is achieved with the help of magnetic sorting and the properties of energy loss of the ions in materials. The second method is the on-line separation, often called the ISOL method (Isotope Separation On Line). It is this, that is used in SPIRAL (Système de Production d'Ions Radioactifs Accélérés en Ligne), inaugurated in 2001 at GANIL. Just as in the preceding method, the beam of stable ions delivered by the GANIL cyclotrons is sent onto a target where the exotic nuclei required are produced. The target is heated to around  $2000^\circ\text{C}$ , which makes it possible to extract in a relatively short time these nuclei by the phenomenon of diffusion. On leaving the target, they will be ionized. The CIME cyclotron accelerates the ions and at the same time carries out the selection, so that only the exotic nucleus of interest is sent to the experiment room.

## Heavy nuclei and mean-field models

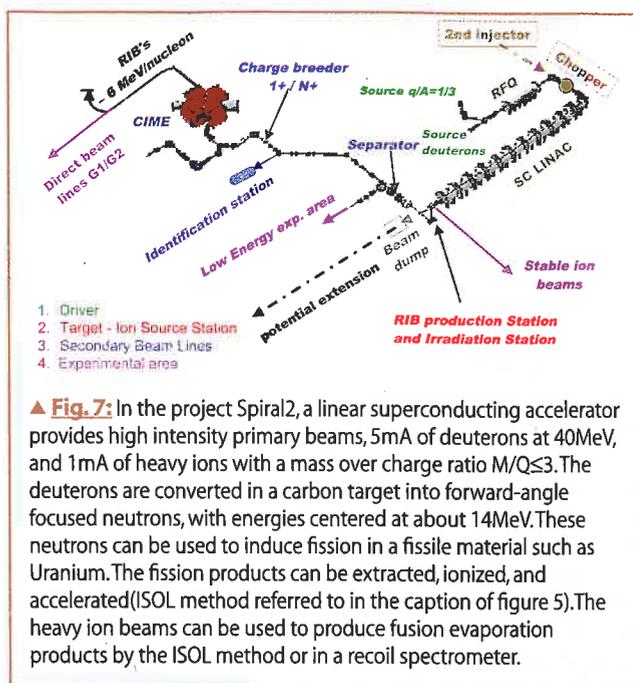
For heavy nuclei, the shell model does not provide reliable calculations. However, an evolution is possible in the future with Monte-Carlo shell model calculations. Self-consistent mean-field calculations give a good reproduction of the properties of medium mass and heavy nuclei, in particular average properties such as the radii, the binding energies and deformations. Figure 4 presents a comparison between different theoretical calculations and the experimental results for the binding energies of Sn (tin) isotopes. If a good agreement is obtained between the different models and the experimental results for the nuclei relatively close to stability, the predictions diverge when one moves away from the zone where measurements were feasible. This stresses the necessity to extend the experiments to a larger area of the chart. With respect to deformation, the series of the isotopes of Kr constitute an excellent test for the models which predict transitions between spherical nuclei in the vicinity of the valley of stability and very deformed nuclei when one moves away both to proton and neutron rich isotopes.

Furthermore, the understanding of the nucleosynthesis implies a precise description of nuclei very far from stability, often out of experimental reach. For example, the r-process, responsible for the formation of the heavy nuclei in the Universe, by a rapid succession of neutron captures and  $\beta$  decays, implies the existence of nuclei far from stability, such as  $^{192}\text{Dy}$  and  $^{240}\text{Pb}$ , whereas at the present time the last nuclei known in these regions are  $^{173}\text{Dy}$  et  $^{214}\text{Pb}$ .

For such exotic nuclei, the only means of having a good description of these processes is therefore to have reliable nuclear models, established and checked over as large as possible region of the chart.

## Accelerators

Nuclear reactions are the tools to produce exotic nuclei in the laboratory. Various mechanisms are used, depending on the nature of the primary beam and its energy, and the nuclei to be produced. With the heavy ion beams of GANIL, fragmentation reactions occur when the primary beam has an energy greater than several tens of MeV/nucleon, which correspond to speeds of the order of 30 to 50 % of the speed of light. In these reactions, the projectile and the target loose part of their nucleons, thus producing all sorts of nuclei lighter than the beam particles, of which some can be very exotic. The fragments of the beam produced during this process keep kinematic characteristics relatively close to those of the primary beam (slightly lower speed, angle of emission concentrated in



▲ **Fig. 7:** In the project Spiral2, a linear superconducting accelerator provides high intensity primary beams, 5mA of deuterons at 40MeV, and 1mA of heavy ions with a mass over charge ratio  $M/Q \leq 3$ . The deuterons are converted in a carbon target into forward-angle focused neutrons, with energies centered at about 14MeV. These neutrons can be used to induce fission in a fissile material such as Uranium. The fission products can be extracted, ionized, and accelerated (ISOL method referred to in the caption of figure 5). The heavy ion beams can be used to produce fusion evaporation products by the ISOL method or in a recoil spectrometer.

a forward angle cone). With lower energy, the reactions of fusion-evaporation make it possible to form heavy nuclei very deficient in neutrons, because in a fusion reaction mainly neutrons are evaporated from the compound nucleus, that is already neutron deficient due to the curvature of the valley of stability in the N-Z diagram. From a technical point of view, two methods are used: the in-flight method and the on-line method or ISOL (see figure 5). These two methods have their advantages and their drawbacks, but are perfectly complementary.

First of all, with regard to the energy, the in-flight method is well adapted to the production of secondary beams of energy higher than a few tens of MeV/nucleon, whereas the ISOL method produces nuclei at rest, which can then be accelerated to the energy desired. One of the advantages of the ISOL method is the optical quality of the secondary beams, which is as good as that of the primary beams, whereas the beams produced in flight have larger spatial and angular emittance. The purity of the ISOL secondary beams is generally excellent whereas it is often difficult to completely eliminate the contaminants in the beams produced in flight. But all nuclei with a life



◀ **Fig. 6:** In order to be able to study nuclei at the limit of stability in good conditions, new detectors of very high detection efficiency were designed and built. The equipment finalized at GANIL for the experiments with secondary beams are the VAMOS spectrometer and the EXOGAM multi-detector dedicated to the detection of  $\gamma$  radiation. The principal characteristic of VAMOS (bottom photo) is its large angle and momentum acceptance. VAMOS is composed of two quadrupoles, a velocity filter and a dipole, these elements being able to function individually or together, which makes it possible to use the spectrometer in different modes (Variable MOde Spectrometer). The EXOGAM design (top left photo), a powerful  $\gamma$  spectrometer made of 16 Germanium detectors, achieves an efficiency of detection of 20% for a total energy deposition (photo-peak efficiency). EXOGAM and VAMOS can be used separately or together (cf top right photo: EXOGAM assembled around the target point of VAMOS), possibly joined to other detectors, in particular those of charged particles, such as TIARA or MUST2. These two detectors were built within the framework of European collaborations. VAMOS was defined by a European RTD project which involved laboratories in France (GANIL, SPn Saclay, CENBG Bordeaux, LPC Caen, IPN Orsay), Germany (GSI), U.K. (Liverpool, Manchester, Surrey Universities, CCLRC Daresbury), and Czech (NPI Rez). EXOGAM is the fruit of a vast collaboration involving France, Germany, U.K., Spain, Sweden, Finland, Denmark, Poland and Hungary.

features

time longer than their time of flight from the production target to the reaction study target, i.e. of the order of  $1\mu\text{s}$ , can be studied if they are produced in flight. This is not the case with the ISOL method where the chemistry of materials plays a significant role since the atoms produced must be extracted from the target and arrive at the source by a diffusion-effusion process. For example, the first beams produced by SPIRAL at GANIL are only rare gases for which the exit times are relatively short. For the other chemical elements, new target-ion source combinations are being studied to optimize this time of diffusion-effusion out of the target. In practice, the ISOL method is mostly limited to nuclei of a life span of the order of 0.1 to 1 second.

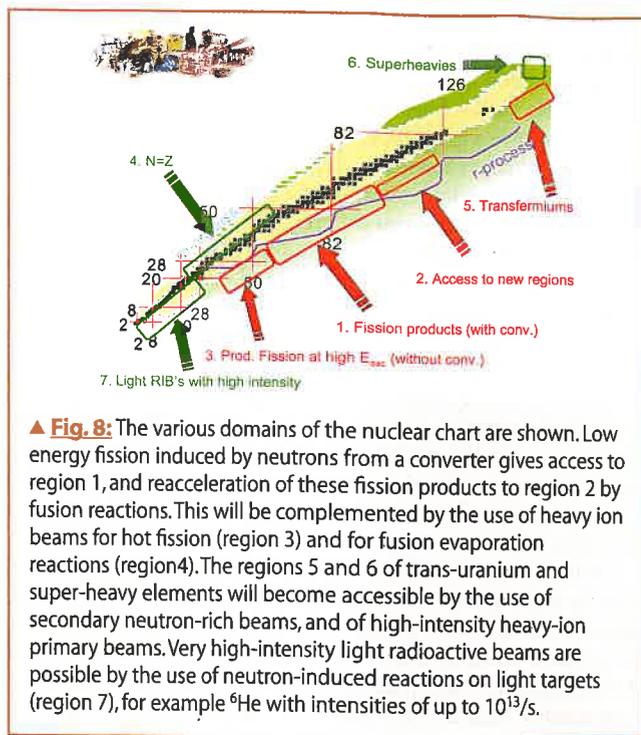
### Measuring instruments

Experiments using secondary beams have brought a revival to the discipline, not only with regard to the physics involved, but also because they required a new methodology and the development of new instruments. Indeed, just as in the past, physicists started by sending beams of protons, or at least particles of relatively simple and well known structure, onto targets which they wanted to study, the first experiments relating to reactions induced by exotic nuclei have been made with targets of protons, deuterons or of helium. In this inverse kinematics (the projectile is the heavier nucleus, the target nucleus the lighter), the characteristics of the fragments to be detected are very different from those usually met in the case of direct kinematics.

The detectors thus have to be adapted to these new conditions. Another important difference between an experiment carried out with a stable beam and another carried out with a secondary beam is connected to the intensity of the beam. Indeed the intensity of a secondary beam is several orders of magnitude lower than that of the stable beams. As the times allocated for experiments cannot be extended indefinitely, it is therefore necessary to compensate, at least partly, for this loss of intensity by an increased effectiveness of the detectors. Whereas the experiments with stable beams use typically intensities of the order of  $10^9$  to  $10^{12}$  particles per second, fairly detailed spectroscopic information has already been obtained with beam intensities going down to 1 particle per second, which represents a gain of experimental efficiency of around 10 orders of magnitude, realized in 2 decades. An additional difficulty is related to the radioactive nature of the secondary beams. Their disintegration generates a background noise that can mask the signal sought. The new detection devices have therefore been designed to be able to suppress as far as possible this background noise. The use of several detectors allows, by carrying our coincidences, the reactions of interest to be the tagged (see figure 6).

### The future

At present, experimental studies are still often limited to the lightest exotic nuclei, because only these beams are available with sufficient intensities. Future accelerators will make it possible to widen the range of the nuclei which can be studied, and to increase the intensities available to be able to carry out more selective and detailed experiments. This will deepen our understanding of the nucleus, and hence better establish and constrain nuclear models. The SPIRAL II project (see figure 7) proposes the use of fission in a target of uranium carbide for the production of neutron-rich nuclei. The fission will be induced by neutrons produced by a high-intensity beam of deuterons (5 mA, 40MeV) on a carbon converter. The fragments from the fission of the Uranium, extracted by the ISOL method, will make it possible to explore a region of neutron-rich nuclei of mass ranging between 80 and 160, still comparatively unknown. Proton-rich nuclei, on the other side of the valley of stability, can be formed by fusion-evaporation reactions using



▲ **Fig. 8:** The various domains of the nuclear chart are shown. Low energy fission induced by neutrons from a converter gives access to region 1, and reacceleration of these fission products to region 2 by fusion reactions. This will be complemented by the use of heavy ion beams for hot fission (region 3) and for fusion evaporation reactions (region 4). The regions 5 and 6 of trans-uranium and super-heavy elements will become accessible by the use of secondary neutron-rich beams, and of high-intensity heavy-ion primary beams. Very high-intensity light radioactive beams are possible by the use of neutron-induced reactions on light targets (region 7), for example  ${}^6\text{He}$  with intensities of up to  $10^{13}/\text{s}$ .

heavy-ion beams that will be available with very high current, up to 1mA, with energies up to 14MeV/nucleon. The secondary beams can be accelerated in the existing CIME cyclotron to energies up to about 20MeV/nucleon, depending on the charge-state. The domains of the nuclear chart that will be covered with this project are shown on figure 8. SPIRAL II is a first stage to increase the intensities and the variety of the beams at GANIL and integrates present European developments for the medium and long term. In Germany the GSI project, proposing very intense heavy beams of 1GeV/nucleon, has cleared an important decision stage, with an agreement of principle from the Research Ministry. EURISOL is a large project for beams produced by the ISOL method and is the subject of a vast European collaboration.

Different projects are also being studied in other parts of the world. In Japan, the RIBF (Radioactive Ion Beam Factory) is under construction at RIKEN, using the fragmentation of heavy ion beams at several hundred MeV/nucleon. RIA (Rare Isotope Accelerator) is the ambitious American project, in the same field of energy. Extension to existing machines are also in progress in Canada (TRIUMF-ISAAC at Vancouver), in China (Lanzhou), in Russia (Dubna), in Italy (Catania, Legnaro), and at CERN (ISOLDE).

### Further reading

Special issue on Research Opportunities with Accelerated Beams of Radioactive Ions, Nucl. Phys. A693 (2001) Nos 1,2 published by I. Tanihata.

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# String theory: challenges, successes and magic

*Eliezer Rabinovici, Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

## No NOH principle

An essential catalyst in the process of the formation of string theory was urgency, the urgency created out of the near despair to understand the amazing novel features of the hadronic interactions. String theory was revitalized by the urgency to understand together all of the four known basic interactions. Here I shall briefly review some of the motivation to study a theory of extended objects and discuss the challenges string theory faces, the successes it has had, and the magic spell it casts. We start by reviewing a hardware issue, the hard wiring of some scientific minds. Researchers using string theory are faithful followers of an ancient practice, that of ignoring the NOH principle. The NOH principle is very generic, it states that Nobody Owes Humanity neither a concise one page description of all the basic forces that govern nature nor a concise description of all the constituents of matter. Actually no reductionist type description is owed. Time and again physicists driven by their hard wiring processed the experimental data utilizing theoretical frameworks and were able to come up with explicit formulae; formulae that were able to express on less than one page the essence of a basic force. A key assumption used and vindicated was that the basic constituents of nature are point-like. The electromagnetic forces, the weak interactions and even the powerful color forces were rounded up one by one, straddled by the rules of quantum mechanics and then exposed on a fraction of a page. Using these formulae, an accomplished student abandoned on an isolated island can predict with an amazing accuracy the outcome of some very important experiments involving the basic forces. The level of accuracy ranges from a few percent in the case of some aspects of the color forces to better than  $10^{-10}$  for some features of the electromagnetic interactions.

## Why change a winning team: extended constituents are called upon to replace point like ones

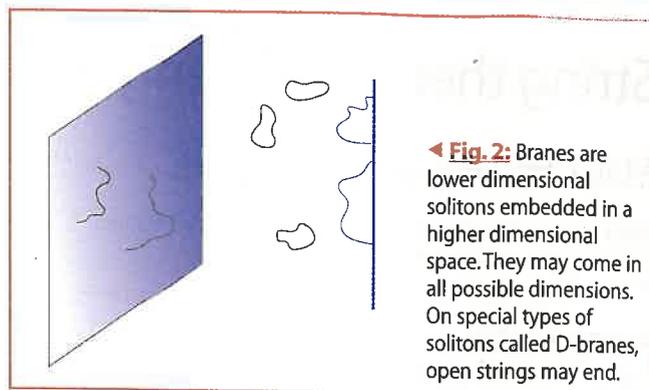
Point particles have done a tremendous job in shouldering the standard model of particle interactions. Why replace them by extended objects? The standard model does reflect the enormous progress made in the understanding of particle physics but it is not perfect, at least as seen by a critical theorist. The model is afflicted with tens of parameters as well as what are termed naturalness problems. The values of some physical quantities, such as the mass of the Higgs particle, are required to be much lighter than the theory would naturally suggest. Ignoring the NOH principle, scientists find themselves once again on the path of searching for a more concise description. One effort was directed towards unifying the three interactions, thus following the conceptual unification of the electromagnetic and weak interactions, described each by a gauge theory. That direction led to possible unifications at scales not so distant from where quantum gravity effects are definitely supposed to become important. In fact, gravity, the first of the basic forces that was expressed by a mathematical formula, is the remaining unbridled known force which is considered currently as basic. Here the quantum breaking methods based on the concept of a basic

point like structure have failed. Sometimes what is considered failure is also a measure of intellectual restlessness, still it made sense to search for alternatives. Actually even with no apparent failure lurking upon basic physics, a study of a theory of fundamentally extended objects is called for. After all, why should the basic constituents be just point-like? String theory is a natural extension of the idea that the basic constituents are point-like. It is an investigation into the possibility that basic constituents are ab initio extended objects, the simplest such extended objects being one-dimensional, that is strings. In a sense one may regard also point particles as extended objects dressed by their interactions. The direct consequences in this case are however totally different. It turned out that such a generalization did eventually reproduce many properties of point particle interactions and in addition enabled one to formulate what seems as a theory of gravity. This it should do, following the tradition of subjecting any new theory to the test of the correspondence principle. The theory is well defined up to several orders and perhaps to all orders in perturbation theory. The perturbations are small at the vicinity of a very small distance scale called the string scale; as small as that distance is, it is expected to be larger than the Planck length and thus is associated with lower energies than the Planck energy (it is related to the Planck scale by the string interaction coupling). Interactions among strings are, to a large extent, softer and fuzzier than those among point particles. Recall that a large number of successes of particle physics consisted of explaining and predicting the physics of the various interactions at scales at which they were weakly coupled, otherwise, a large dose of symmetry was essential. This is perhaps the most significant achievement of string theory. It is also its major source of frustration. If the string scale is indeed of the order of  $10^{-32}$  cm or even slightly larger, it is not known today how to verify, experimentally, any prediction resulting from perturbative string theory. It is very difficult to imagine, for example, how to set up an experiment measuring the differential cross section of graviton-graviton scattering at the string scale. We will return to this extremely important issue later on and continue to follow for a while the path of the theoreticians.

## New questions

The impact of scientific progress can be tested by the type of questions it makes us aware of, as well as by the answers it eventually provides for them. By studying string theory new questions do arise. Values taken for granted are subjected to query and downgraded to being parameters. String theory suggests questioning the values of some such physical quantities and in some cases offers scientific answers to the question. A prime example is that of the number of space-time dimensions. In a point-like constituent theory there is a very large degree of theoretical freedom. As far as we know spin-zero point particles, for example, could have propagated in any number of dimensions, their interactions would have been different depending on the dimension of space-time but nevertheless they would have been allowed. Strings are much fussier than particles, like the princess sensitive to a grain of pea hidden under 17 mattresses, (super) strings can propagate quantum mechanically only in a limited number of dimensions. In fact, not only are the number of allowed possible dimensions dramatically reduced, the allowed values of the number of space-time dimensions do not include the value 4. These dimensions are usually required to be 10 or 26. (The origin of this basic number is, at this stage, disappointingly technical.) But setting that aside, one would like to detect this experimentally. As the idea of having extra dimensions was raised originally in field theory, upper bounds on the length of such dimensions were already available.

More recently under the security net of string theory these bounds have been revised (they have been relaxed by more than 10 orders of magnitude and brought up to the sub micron regime). In fact I am not aware of any bound on a fundamental quantity in physics that has been altered to such an extent by a theoretical idea. One should note that though, strictly speaking, the number 26 does indeed appear in string theory, it is not always possible to associate this number with the number of dimensions. Sometimes the background on which the string can propagate has no obvious geometrical description, just an algebraic one. This fact about strings illustrates the tension inherent in attempts to search for experimental verification of extremely basic but very weakly coupled phenomena. Sitting in our chairs we sometimes forget how frail gravity is. It is all of the planet earth that gravitationally pulls us towards its center, yet all this planetary effort is easily counter-balanced by the electromagnetic forces (and by the Pauli Exclusion Principle) applied by the few tiles beneath our chair. Although string theory sets constraints on the possible number of dimensions, that is not to say that point particles allow everything. The number of known restrictions is however much smaller. The interactions could be of an infinite (sometimes classifiable) variety, the color group, which happens to be  $SU(3)$ , could have been for all the theory cares,  $SU(641)$ , the electromagnetic force could have been absent or there could have been 17 photons. Not everything is allowed, but an infinite amount of variations could have been realized instead of what one actually sees in nature today. The same goes for many (but not all) of the properties of the space-time arena in which all the interactions are occurring, in particular effective low energy theories (and one seems to be constrained to use only such theories for a long time to come) contain many more free parameters such as masses and some of the couplings. In a string theory one may have expected that all or most of these parameters

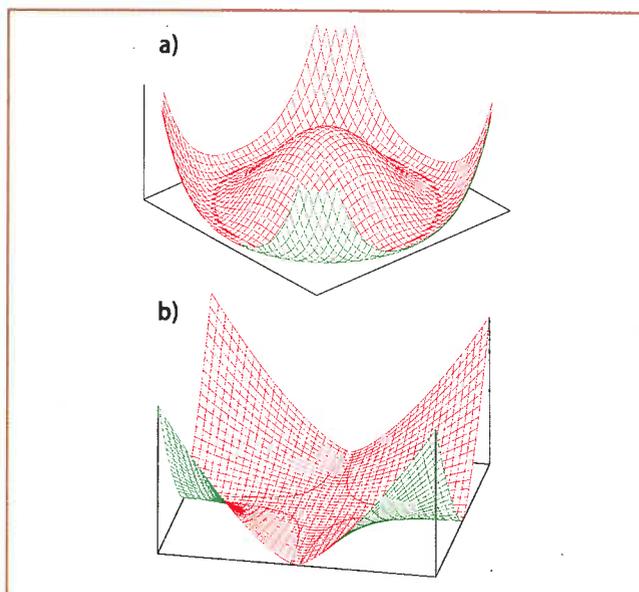


◀ **Fig. 2:** Branes are lower dimensional solitons embedded in a higher dimensional space. They may come in all possible dimensions. On special types of solitons called D-branes, open strings may end.

are fixed in some manner. Actually it is more complicated, for some string backgrounds, some parameters are fixed, while other parameters are not. In addition there seemed to be several string theories leading to even more possibilities.

### The one and only?

As we have discussed the desire to find the one and only theory encompassing all fundamental physical phenomena seems hard wired in many scientific minds. Is string theory an example of such a theory? Before addressing this question let us reflect upon the limitations of the methods used. What would in fact satisfy the purest (or extremist) of reductionists? A one-symbol equation? Be her desires, what they may be, one should recall that one is using mathematics as our tether into the unknown. This tool, which has served science so well, has its own severe limitations, even ignoring the issue of using differential equations as a tool to probe short distance, a generic problem in mathematics can't be solved. Maybe the NOH principle will eventually have its day, one will run out of interesting questions which have answers, maybe that day is today! (Although some mathematicians suggest using physicists as hound dogs that will sniff their way towards interesting and soluble problems). Having this in mind the key question is posed in the hope that it does have an answer: find the unique theory describing the fundamental forces. There have been ups and downs for the proponents of the one and only string theory. The understanding of the situation has passed several evolutionary stages. From the start it was recognized that one may need to settle for more than only one string theory. It was thought that a distinction could have been drawn between a theory of only closed strings and a theory containing both open and closed strings. A theory with only open strings was realized to be perturbatively inconsistent. Even those theories needed not only a fixed dimension but in addition an extra symmetry, supersymmetry, to keep them consistent. It was very quickly realized that actually there are an infinite varieties of backgrounds in which a string could move. For example, consider 26 dimensional spaces in which one dimension is actually a circle of radius  $R$ . It turned out that all possible values for the radius,  $R$ , of the circle are allowed. It was then realized that there is a large variety of 22 dimensional compact manifolds in the case of bosonic strings (6 dimensional compact dimensions in the case of the super symmetry), which could accompany the four dimensional Minkowski space-time one is familiar with. Each such compact manifold was called a string compactification. Next it was suggested that actually all possible compactifications are nothing but different solutions/ground states of a single string theory, each of the solutions differing from each other by the detailed values of the physical parameters it leads to. But the ground states have also many common features, such as generically the same low energy gauge group. To appreciate this consider the difference between the potential of



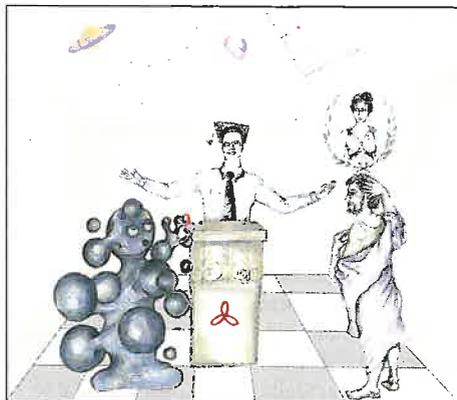
▲ **Fig. 1:** a) The potential, familiar from the standard model, has a shape of a sombrero. In the figure, its minima lie on a circle; each point along the circle, can be a basis for a ground state. The physics around each is equivalent. In string theory and in supersymmetric systems flat potentials arise. b) The potential has two orthogonal flat directions. The landscape of the valleys is generically more elaborate. Each point along the flat directions can serve as a basis of a ground state. In many cases, the physics around each ground state is different.

the Higgs particles which may describe the mass generation of the carriers of the weak interactions and the effective potential leading to the ground states in string theory. For the electro-weak interaction case the potential has the form of a Mexican hat. The ground state may be described by any point in the valley (figure 1a) but all choices are equivalent, they describe exactly the same physics.

In the case at hand the valley of minima is flat and extends all the way to infinity. Any point along the valley can be chosen as a ground state as they all have the same energy and yet each describes different physics. The manifold describing the infinity of these degenerate ground states is called the moduli space when they are continuously connected (figure 1b).

These connected regions of valleys trace out very elaborate geography and describe different possible solutions of string theory. All known stable ones share in common the property of describing a supersymmetric theory. In such theories each bosonic particle has a fermionic particle companion. It then turned out that there actually are several different types of string theories, each having its own infinite set of degenerate ground states. What made the string theories different were details, most of which are rather technical, which seemed to affect the particle content and gauge symmetries of the low energy physics. There was a stage, in the eighties of the last century, at which some researchers imagined they were on the verge of being able to perform reliable perturbative calculations of a realistic theory containing all the aspects of the standard model. That turned out not to be the case. However, in the process, the geography of many interesting ground states was surveyed. Next, a large amount of circumstantial evidence started to accumulate hinting that all these theories are after all not that distinct and may actually be mapped into each other by a web of surprising dualities. This led once again to the conjecture that there is but one string theory. This time the theory that was supposed to encompass all string theories and bind them was given a special name, M theory. Even in this framework all string theories brought as dowries their infinite moduli space. M theory still had an infinite number of connected different degenerate supersymmetric ground states; these were elaborated and greatly enriched by what are called brane configurations. Branes are a special type of solitons that appear in string theory. They come in various forms and span different dimensions (figure 2). What is common to several of them, is that open strings may end on them.

Thus what was thought to be a theory of only closed strings contains open strings excitations in each of its sectors that contain branes. Moreover, every allowed brane configuration leads to its own low energy physics. In fact there are suggestions that our four dimensional experience results from us living on one or several branes all embedded in a larger brane configuration placed in a higher dimensional space-time. How does that fit with the expectations to have the One and Only string theory? Well, in this framework there is one theory but an infinite amount of possible ground states. Are we owed only one such state? There are those who hope that the vacua degeneracy will be lifted by some yet to be discovered mechanism leaving the one unique ground state. Others are losing their patience and claiming that the NOH principle takes over at this stage, that the theory will retain its large number of ground states (figure 3).



▲ **Fig. 3:** A match made in heaven? A Democritus is offered in a shot-gun marriage the continuum plus discrete Hydra of universes. Will this Democritus give up his dream of the one and only? Does Hydra think he is good enough for her?

Moreover a crucial ingredient of string theory at present is super symmetry, a beautiful symmetry not yet detected in nature, and even if detected, it seems at this stage to play only a role of a broken symmetry. It is not easy to obtain even remotely realistic models of string theory in which supersymmetry is broken (that is the symmetry between fermions and bosons is broken), a nearly vanishing cosmological constant and light particles whose mass values are amenable to a calculation within 'a reliable approximation'. Candidates for such ground states have been suggested recently; these particular candidates consist of very many isolated solutions living off the shore of the supersymmetric connected valleys. Many of these solutions actually have different values for the vacuum energy and perhaps may thus decay from one to the other. In particular bubbles may form within one configuration, bubbles that contain in them a lower energy configuration. Some researchers would like to see the universe itself, or the bubbles that form in it, as eternal tourists who will end up visiting many of these metastable states. Some suspect that many of these metastable states are stable. Some would encourage brave sailors to take to sea again, as they did in the 80s,

and chart this unknown geography, some are trying to make this endeavor quantitative by counting vacua which have a given property, such as a given cosmological constant. This subject is still in its infancy. Many hopes and opinions are currently being expressed, but it would be nice if this issue would turn out to fall within the realm of soluble problems. In that case abstracts of papers in the near future could look something like:

*I am reporting that the calculation of the mass ratio between the tau lepton and the electron to be  $3417 \pm 8$ . This calculation was done in the sole ground state of M theory. This vacuum was identified after all non perturbative effects were carefully considered and shown to remove all other candidate vacua.*

or:

*We have shown that the probability of finding a universe, in which the muon to electron mass ratio is  $203 \pm 2$  and the mass ratio of the Z and W particles is  $1.13385 \pm 0.00026$ , is  $0.05 \pm 0.01\%$ . Do you feel lucky today?*

The challenges to string theory on the experimental side have been to reproduce the standard model. This has not been done to this day. Many new ideas and insights have been added. Bounds have been shifted several times, one has felt being very near to obtaining the desired model, each new approach seemed to bring one nearer to that goal, but obtaining one completely worked-out example, which is the standard model, remains a challenge for string theorists. Another important issue is that of the value of the cosmological constant. It is usually stated that the small value of the cosmological constant is a major problem. These arguments are centered around some version of a low-energy effective-field theory. That theory could be valid below a few tens of electron volt thus describing only aspects of electromagnetism or it could be at a TeV scale describing both the electroweak interactions. The argument goes on to say that the vacuum energy of such an effective theory should be, on dimen-

sional arguments grounds, proportional to the scale of the cutoff, (the cutoff is set at that energy beyond which the ingredients of the physics start to change) that is eVs or TeVs in the above examples. In either case, the value of this vacuum energy, which is the source of the cosmological constant, is larger by an astonishing number than the known bounds on the value of the cosmological constant. The argument is not correct as stated, it is not only the cutoff that contributes to the cosmological constant, all scales do actually contribute to the vacuum energy and if a cutoff should be invoked, it is the highest one, such as the Planck scale, that should be chosen. Moreover, this argument does not take into account the possibility that the fundamental theory has a certain symmetry which could be the guardian of a vanishingly small value of the cosmological constant. Such a symmetry exists, it is called scale invariance, and it has shown to be a guardian in several settings. Scale invariance is associated with the absence of a scale in the theory. There are many classical systems which have this symmetry and there are also quantum systems which retain it. In a finite, scale-invariant theory not only does the vacuum energy get contributions from all scales, they actually add up to give rise to a vanishing vacuum energy. This remains the case even when the symmetry is spontaneously broken. Being a consequence of a symmetry, the vacuum energy contribution to the cosmological constant vanishes also in the appropriate effective theory. What does string theory have to say about that? String theory could well be a finite theory; it is not scale invariant, as it contains a string scale, but if that scale would be spontaneously generated perhaps one would be nearer to understanding the value of the cosmological constant. If that scale is indeed not elementary, one would be searching for the stuff the strings themselves are made of. Such searches originating from other motivations are underway, some go by the name of Matrix Model. Particle physics as we know it is described by the standard model evolving in an expanding universe. The methods used to study string theory are best developed for supersymmetric strings, and for strings propagating on a time-independent background; nature is explicitly neither. What then are the successes of string theory?

### Successes: Black Holes, Holography and all that...

A major success described above was to obtain a theory of gravity well defined to several orders in perturbation theory; in addition, no obvious danger signals were detected as far as the higher orders in perturbation theory are concerned, non-perturbative effects being yet to be definitely understood. This issue involves the short distance structure of string theory. String theory is supposed to be a consistent completion of General Relativity (GR). General Relativity suffers from several problems at low energies. String theory, which according to a correspondence principle, is supposed to reproduce GR in some long distance limit, will thus have inherited all the debts and problems of GR in this merger. If it does solve them it will need to do it with a "twist" offering a different point of view. That perspective could have been adopted in GR but was not. This has occurred in several circumstances. One outstanding problem in GR is to deal with the singularities that classical gravity is known to have. These include black holes, big bangs and big crunches as well as other types of singularities. String theory can offer a new perspective on several of these issues. Let us start with black holes. The first mystery of black holes is that they seem to possess thermodynamical properties such as temperature and entropy. This is true for charged black holes as well as for uncharged Schwarzschild ones. In the presence and under the protection of a very large degree of supersymmetry, string theory tools have enabled one to provide a detailed microscopical accounting of the entropy of some black holes. More precisely it was shown in these special cases that the number of states of a black hole

is identical to the number of states of essentially a gauge theory. It was possible to count the microscopic number in the gauge theory case and the resulting number of states was exactly that predicted for black holes! These are mostly higher dimensional very cold black holes. This has not yet been fully accomplished for uncharged black holes. Black holes have several more non-conventional properties. The above mentioned entropy of a mass  $M$  black hole is much smaller, for many types of black holes, than that of a non-gravitating system of particles which have the same energy,  $M$ . In fact one may suspect that such black holes dominate by far the high energy spectrum of any gravitating system. The Schwarzschild radius of these black holes actually increases with their mass. In general one associates large energies with short distances; in the case of black holes large energies are related also to large distances. A meticulous separation of long and short distances is a corner stone of the renormalization group approach. This is not evident in the case of gravity. One possible implication of this behavior is that in gravitational systems the amount of information stored in a spatial volume is proportional to the boundary's surface area rather than to the bulk volume. String theory provides explicit and concrete realizations of this amazing behaviour. A system of strings moving in particular ten dimensional space-times (of the anti-deSitter type) are equivalent to special highly symmetric supersymmetric non-abelian gauge theories living in four dimensions and experiencing no gravitational forces. Moreover modifying the backgrounds on which the strings propagate by adding defects to them, one finds that strings propagating on certain backgrounds are equivalent to gauge theories in which color is confined. String theory methods are used to perform difficult calculations in hadronic physics. String theory, which was born out of hadronic physics, has returned to pay back its original debt! In addition, remarkable structures have been uncovered in supersymmetric gauge theories using string theory methods. Attempts have been made to confront strings with other singularities. Why should strings respond to singularities in any other way than particles do? A Talmudic story helps explain the manner in which extended objects modify problems associated with point particles. During a seminar, the following question came up: Assume a pigeon (a very valuable animal at the time) is found somewhere, to whom does it belong? The rule is, finders-keepers, as long as the pigeon is found further away, than some determined distance, from the entrance to an owned pigeon-hole. A student raised his hand and asked: "The pigeon is, after all, an extended object, what if one of its legs is nearer than the prescribed distance to the pigeon-hole but the other leg is further away?" The student was ejected from his place of study for raising the question! Strings definitely turn out to soften some harsh singularities which are time independent (called time-like singularities). Strings are also found to punch through singularities which form at particular times such as a big crunch. The analysis of such systems is still at very early stages. However, I would like to note a very interesting, common feature up to the present of all attempts to study, using string theory methods, universes that are spatially closed. In these cases the compact universe is found to be immersed in one way or another in a non-compact universe. The study of strings near these singularities could well be essential to appreciate their properties at short distances. A key ingredient driving some researchers is a new panoramic vista opening up to them. For some it is the precise calculations of experimentally measurable quantities, for others it is the Magic.

### Magic

The universe as viewed with string probes is full of magic ambiguities and symmetries unheard of before. In fact most mathematical concepts used to describe the universe are veiled under symmetry.

There are cases for which each of the following concepts becomes ambiguous: distance, the number of dimensions, topology, singularity structure, the property of being commutative or not being commutative. Let us somewhat elaborate on the magic.

- **Distance-** The simplest example is that of a universe in which one of the dimensions is extended along a circle of radius  $R$ . It turns out that an experimentalist using strings as her probes will not be able to determine if the universe is indeed best described by one of its dimensions being a circle of radius  $R$  (in the appropriate string scale) or by being a circle of radius  $1/R$ . For point particles moving on a circle of radius  $R$ , the energy spectrum has large gaps when  $R$  is small, and very small gaps when the value of  $R$  is large. For strings, which are extended objects, the spectrum consists of an additional part, that of the strings wrapping around the circle. A point particle can't wrap around the circle. This part of the spectrum is narrowly gapped for small values of  $R$  and widely gapped for large values of  $R$ ; this is because the energy required to wrap a string, which has its tension, around the circle, is proportional to the length of the wrapped string. For an experimentalist, who can use point particles as probes, the distinction is clear, but not so for one using string probes. This is but the tip of the iceberg of an infinite set of ambiguities. Some geometries, judged to be different by point probes, are thus identified by extended probes.

- **Dimensions-** One could at least expect that the value describing the number of space-time dimensions to be unique. It turns out not to be the case. Ambiguities in calling the "correct" number of space-time dimensions come in several varieties. In string theory there are examples of a string moving in certain ten dimensional space-times which measures exactly the same physics as that measured by a certain point-particle gauge theory in four dimensions. Each system is made out of totally different elementary constituents, one system is defined to exist in ten dimensions, the other in four and yet both reproduce the same observables, the same physics. Another example consists of a strongly coupled string theory in ten dimensions whose low energy physics is reproduced by an eleven-dimensional supergravity theory. This is true for large systems. For small, string scale, systems, more magic is manifested. A string in some cases can't distinguish if it is moving on a three dimensional sphere or a one dimensional circle. So much for non-ambiguous dimensions.

- **Topology-** Objects that can be deformed into each other without using excessive violence (such as tearing) are considered to have the same topology. The surface of a perfect sphere is the same, topologically, as that of the surface of a squashed sphere, but different, topologically, from that of a bagel/torus. Well, once again that is always true only as far as point-particle probes are concerned. In string theory there are examples in which the string probes can describe the same set of possible observations as reflecting motions on objects with different topologies. In addition in string theory there are cases where one may smoothly connect two objects of different topology in defiance of the definition given above for different topologies. Topology can thus be ambiguous.

- **Singularities-** A crucial problem of General Relativity is the existence of singularities. Bohr has shown how such singularities are resolved in electrodynamics by quantum mechanics. In GR one is familiar with singularities which are stationary (time-like) such as the singularity of a charged black hole and those which form or disappear at a given instant such as the big bang and the big crunch(space-like). What happens in string theory to black holes, big crunches or big bangs? A good question. Consider first the

motion of a particle on a circle of some radius and the motion of the string on a segment of some length. The circle is smooth, the segment has edges. For a point-particle probe the first is smooth and the second is singular. In some cases, viewed by stringy probes, both are actually equivalent, i.e. both are smooth. The string resolves the singularity. Moreover there are black holes for which a string probe cannot distinguish between the black hole's horizon and its singularity. There are many other cases in string theory where time-like singularities are resolved. The situation in the case of space-like singularities is more involved and is currently under study. Some singularities are in the eyes of the beholder.

- **Commutativity-** The laws of quantum mechanics can be enforced by declaring that coordinates do not commute with their conjugate momenta. It is however taken for granted that the different spatial coordinates do commute with each other and thus in particular can be measured simultaneously. The validity of this assumption is actually also subject to experimental verification. A geometry can be defined even when coordinates do not all commute with each other. This is called non-commutative geometry. There are cases when strings moving on a commutative manifold would report the same observations as strings moving on a non-commutative manifold.

It seems many certainties can become ambiguities, when observed by string probes. Stated differently, string theory has an incredible amount of symmetry. This may indicate that the space-time that one is familiar with is in some sense suited only for a "low" energy description. At this stage each of these pieces of magic seems to originate from a different source. The hard-wired mind seeks a unified picture for all this tapestry. This review may reflect ambiguous feelings; challenges, success and magic each have their share. All in all, string theory has been an amazingly exciting field, vibrating with new results and ideas, as bits and pieces of the fabric of space time are uncovered and our idea of what they really are shifts.

### The human effort and closing remarks

One may estimate that about 10,000 human years have been dedicated up to now to the study of string theory. This is a global effort. It tells an amazing story of scientific research. In the mid eighties a regime/leadership change occurred. The scientific leaders who had nursed the standard model, have been replaced by a younger generation of string theorists. Some of those leaders complained that the field had been kidnapped from them. Mathematical methods of a new type were both applied and invented, many pieces of a vast puzzle were uncovered and a large number of consistency checks were used to put parts of the puzzle together tentatively. As in any human endeavor alternative paths are suggested and criticism is offered. I have incorporated in this article some of the serious challenges string theory faces. There are additional complaints, complaints that the new style leaves too many gaps in what is actually rigorously proven, complaints that a clean field-theory description is needed and lacking. Research has been democratized and globalized to a quite unprecedented extent. This has mainly been achieved by making research results available simultaneously to most of the researchers by posting them on the web daily. There are some drawbacks inherent in this evolution. Research attitudes have been largely standardized and the ranges of different points of view have been significantly focused/narrowed. The outside pressures to quantify scientific production better have found an easily accessible statistical database. In particular, it is leading to the assignation of a somewhat excessive weight to the citation count in a variety of science policy decisions. The impact of this is yet to stabilize. All that said, one should notice that phe-

nomenologists and experimentalists do turn to string theory and its spin-offs in search of a stimulus for ideas on how to detect possible deviations from the standard model. The problems string theory faces are difficult; one approach is to accept this and to plunge time and again into the dark regions of ignorance using string theory as an available guide, hoping that it will be more resourceful than its practitioners are. Another approach is to break away from the comfort of physics as we formulate it today and replace some of its working axioms by new ones, such as holography, the anthropic principle or eventually perhaps something else. It seems that the question of the exact nature of the basic constituents of matter will remain with us for still quite some time. My favorite picture is that it will turn out that asking if the basic constituents are point-like, or are one-, two- or three-dimensional branes, is like asking whether matter is made of earth or air. A theory including the symmetries of gravity will have different phases, some best described by stringy excitations, some by point particles, some by the various branes, and perhaps the most symmetrical phase will be much simpler. Several of these will offer the conventional space-time picture, others will offer something new. String theory, either as a source of inspiration, or as a very dynamic research effort that attracts criticism, leaves few people indifferent.

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### About the author

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# Particle physics from the Earth and from the sky: Part II

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This second part deals mostly with the results and prospects of non-accelerator physics [1], although several of the themes have a counterpart at accelerators. We will underline recent developments and give a concise report on ongoing projects, their main goals and their present status.

### Neutrinos

All reviews of neutrino physics [2] recognize that in this domain the time is truly revolutionary. The proof that neutrinos have non-zero masses has been given by the observation and measurement of oscillations\* between neutrino species. This effect provides the differences between masses squared,  $\Delta m^2$ . Other processes and techniques are needed to measure their absolute values.

Let us recall that Nature is flooding us with huge fluxes of solar electron neutrinos: this amount to  $\sim 6 \cdot 10^{10}/\text{cm}^2/\text{s}$ , mostly in the 0-0.42 MeV energy range corresponding to the p-p solar process, but with a tiny fraction, in particular from the  ${}^8\text{B}$  process, extending up to 15 MeV. Nature also provides us with atmospheric neutrinos: these are secondaries from cosmic interactions, giving about twice as many muon neutrinos as electron neutrinos, with useful energies between  $\sim$ hundred MeV and several GeV. Neutrinos coming from the Earth's radioactivity (roughly equivalent to 10000 GigaW) are about 6 millions /s/cm<sup>2</sup>, but are usually drowned in the flux coming from local reactors. We are immersed in a bath of fossil neutrinos ( $\sim 300/\text{cm}^3$ ), at a temperature of  $\sim 1.95^\circ\text{K}$ , undetectable directly. Finally we receive neutrinos in the MeV range that originate from Supernova explosions and possible other cosmic sources.

Concerning man-made sources, electron antineutrinos of energies around 4 MeV are produced isotropically from nuclear

\* Neutrino oscillations are a quantum mechanical effect. One can identify a particle by the way it is produced or interacts. For instance the positive-pion decay results in a positive muon and a muon neutrino. But one also knows its identity from the knowledge of its mass. Usually these two identifications are the same for each particle. However we already saw in Part I that the quarks are "a bit confused about their identity". For neutrinos the situation is more dramatic: the state that we call for instance muon neutrino is not the same as the particle mass state. The muon neutrino should actually be considered as composed of two states of slightly different masses. These states may be thought of as waves which, for a given energy, have different periodicities and oscillate in and out of phase with each other as they travel along. In one phase the pair interacts as a muon neutrino; but when shifted by 90 degrees it makes a tau neutrino. In between, one would see some fraction of each kind.

One can compare neutrino oscillations to the beats of two neighbouring musical notes. Another analogy would be with the rotation of the plane of polarization of light when passing through some optically active materials. The light is composed of right-hand circular and left-hand circular polarized photons, who travel at slightly different speeds in such media. For neutrinos, however, the oscillations happen even when they travel in empty space.

reactors (a standard nuclear plant produces  $5 \cdot 10^{20}$  antineutrinos/s). Accelerators produce directional beams of muon (anti)neutrinos from the decay of focused pions and kaons, with energies between a few hundred Mev and  $\sim 100$  Gev.

In the range of energies considered here the neutrino (antineutrino)-nucleon cross-section is proportional to the neutrino energy and amounts to  $0.68 (0.34) \cdot 10^{-38} \text{ cm}^2$  at 1 GeV, a tiny value which explains how demanding is neutrino physics. Neutrinos interact with quarks either by a Neutral Current (i.e. the exchange of a virtual  $Z^0$ , the neutrino keeping its identity) or by a Charged Current (i.e. the exchange of a W, in which case the neutrino is turned into the corresponding charged lepton).

**Mass differences and neutrino oscillations**

Numerically the oscillation rate goes like  $\sin^2 2\theta \sin^2(\pi d/L)$  where  $\theta$  is the mixing angle ( $\theta=45$  degrees corresponds to a full oscillation),  $d$  the distance of flight and  $L$  the oscillation length which is proportional to  $E/\Delta m^2$ . The oscillation length for a neutrino energy  $E=1 \text{ GeV}$  and a mass squared difference  $\Delta m^2=3 \cdot 10^{-3} \text{ eV}^2/c^4$  is about 800 km. From this numerical value it is easy to obtain the oscillation length for any given situation.

**The key oscillation neutrino experiments**

Starting with the radio-chemical method, the chlorine HOMES-TAKE experiment in the mid sixties, and the gallium GALLEX and SAGE experiments, in which neutrino interactions transform a few atoms of the target into another element, which has then to be extracted, reported a deficit of solar electron neutrinos relative to the expectations of the Standard Solar Model (SSM) [3]. This deficit amounts to 30 to 60%.

The water Cerenkov experiments Kamiokande and especially SuperKamiokande (SK), whose main results appeared in 1998, have measured a deficit of atmospheric  $\nu_\mu$  produced near the antipode of the detector, some 12800 km away, and have shown that the zenith angle dependence of this deficit (i.e. its dependence on the distance  $d$  to the source) is well reproduced by an oscillation effect, in which the  $\nu_\mu$  becomes a  $\nu_\tau$  when passing through the Earth. Very recently the first minimum of the oscillation pattern has been observed by SK. Experiments under preparation (OPERA, ICARUS in Gran Sasso, fed by a beam from CERN) will complete the proof by observing directly the  $\nu_\tau$  interaction.

The major results of the last two years [4] are due to:

- the Sudbury Neutrino Observatory (SNO), a 1 kton heavy water experiment in Canada, measuring charged and neutral current events and sensitive to  $\nu_e$  from the former, and to all active flavours from the latter. SNO demonstrated that the missing solar  $\nu_e$  have indeed turned into another active species and thus confirmed numerically the validity of the SSM
- K2K, a long baseline oscillation experiment of accelerator-produced  $\nu_\mu$  of 1-2GeV from KEK to SK, 250 km away, that confirmed the atmospheric oscillation observed in SK
- KAMLAND, a terrestrial experiment in Japan, measuring the electron-antineutrino flux from all reactors located within a few hundred km, which confirmed the solar neutrino oscillation and allowed the choice of the so-called Large Mixing Angle solution from competing solutions (figure 1).

Our knowledge of oscillations is thus quite strengthened and several new experiments are underway. The main open question is to know whether there exists a fourth neutrino, of sterile nature, i.e. not coupled to the  $Z^0$  and thus unnoticed at LEP. This was suggested by the LSND experiment at Los Alamos (in which  $\nu_\mu$  from pion decay would turn into  $\nu_e$ , suggesting a "large"  $\Delta m^2$  scale of  $1\text{eV}^2$  and very small mixing), but is strongly disfavoured by the other results. The MiniBoone experiment in Fermilab will settle the matter in the coming years.

**The results**

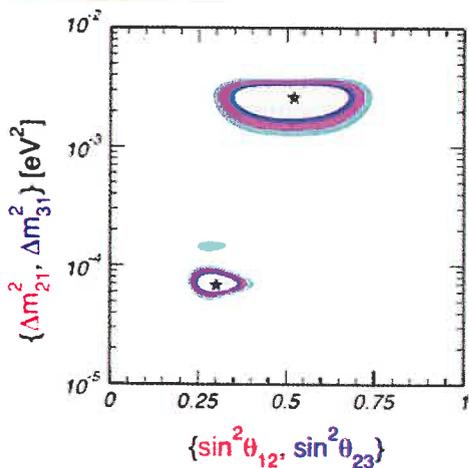
The neutrino mixing matrix, giving the relation between flavour and mass eigenstates, can be written as shown by figure 2 and presents a simple structure in which the various effects are factorized. Figure 1 and 2 give also the numerical value of the measured parameters, the two mass differences and the two mixing angles, which turn out to be maximal in the atmospheric case but not quite so in the solar one.

The big unknown is presently the magnitude of the third mixing angle  $\theta_{13}$ . Its numerical value will tell whether the ultimate stage of neutrino physics, the measurement of CP violation in this sector, i.e. a difference of behaviour between the left-handed neutrino and the right-handed antineutrino parameterized by the phase  $\delta$ , is accessible or not. To obtain  $\theta_{13}$  one needs to measure the  $\nu_e \leftrightarrow \nu_\mu$  oscillation. The reactor experiment CHOOZ has set a limit on its value,  $\sin \theta_{13} < 0.16$  (90%CL). The next answer will likely come from an oscillation experiment involving a  $\nu_\mu$  beam obtained from an accelerator and a long baseline, as the T2K project in Japan, which could start in 2008, and the US NUMI project. Other possibilities of  $\theta_{13}$  measurements are also under consideration, such as those involving experimentation close to a nuclear reactor. Further in the future quite ambitious projects could involve very high intensity neutrino beams or "beta-beams" [5] as well as huge new detectors, like a megaton water Cerenkov *à la* SK.

**Absolute values of the masses**

Oscillations only give access to the mass differences between neutrino mass eigenstates. But one also wants to know their absolute values and to determine the properties of the neutrino mass spectrum. Is it degenerate, i.e. are the three masses close to each other, around some common value, or is it hierarchical, as the spectrum of charged leptons? Is it normal, i.e. with the masses ordered as those of the corresponding charged leptons, or inverted?

To reach the absolute values two different methods are used [6]. The first exploits the  $\beta$ -decay of tritium, through a careful study of the end point of the emitted electron spectrum (the Kurie plot), giving access to the electron neutrino mass  $m_{\nu_e}$ . The second is a search for neutrinoless double beta decay  $0\nu\beta\beta$  (figure 3). In this



▲ Fig. 1: Present status of mass difference measurements and mixing angles from atmospheric (top) and solar (bottom) neutrino oscillations (from M. Maltoni, hep-ph/0401042).

features

process, whose existence is not yet proven, the energies of the two electrons sum up to the energy available in the decay. Its observation, to be possible, requires an extreme level of radiological purity of the detector.

Considering the former method, the upper limit on  $m\nu_e$ , obtained from the Mainz and Troitsk experiments, is presently 2.2 eV. In future the large KATRIN spectrometer in Karlsruhe should reduce this to 0.2 eV.

The observation of the  $0\nu\beta\beta$  process would imply that the neutrino is of the Majorana type. This means that the particle is its own antiparticle, as the graph of figure 3 requires, which is not the case if the neutrino carries a conserved lepton number, opposite for the antineutrino. The NEMO3 experiment, starting in the Frejus underground laboratory, looks for a signal by observing up to 10 kilograms of  $0\nu\beta\beta$  decay isotopes (for instance  $^{100}\text{Mo}$ , whose signal would be at  $\sim 3$  MeV) and performing an accurate tracking and energy measurement of the two potential electrons. It should in particular settle the open question of a possible signal as claimed by the Heidelberg-Moscow germanium experiment in the Gran Sasso laboratory (the best value of the effective neutrino mass would be 0.39 eV). Later, more ambitious experiments may still gain a good order of magnitude and become sensitive to the neutrino masses, at least in the case of an inverted hierarchy.

### Cosmology and neutrinos

Most interesting news concerning neutrinos have been coming from cosmology. Concerning the power spectrum of the Cosmic Microwave Background (CMB) [7], to which we will return later, the presence of relativistic neutrinos tends to suppress the growth of fluctuations at small angular scales. A combination of the results of the satellite programme WMAP (Wilkinson Microwave Anisotropy Probe) and of the galactic survey 2dFGRS (Two degree Field Galaxy General Survey) seems to indicate that the sum of the masses of the three species  $\Sigma m\nu_i$  is smaller than 0.71 eV. This limit implies that the heaviest of these masses is in the mass range  $0.03 \leq m_3 \leq 0.24$  eV (95% CL). The upper limit corresponds to the degenerate case, the lower one to the lowest bound of the atmospheric mass difference. However several authors call for some caution in extracting such numerical values, given the methodology used and the need to resort to complementary information.

### What can we learn from these studies?

What can we expect from the knowledge of the parameters, masses and mixing angles, which govern neutrino physics?

One would like to know whether neutrinos are Dirac or Majorana particles, and from which energy scale their masses originate. Is it from the typical SUSY scale of the order of a TeV? Presently one prefers an origin of the mass linked to a much higher scale, via the so-called “seesaw” mechanism (figure 4), implying the existence

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}}_{\text{atmospheric } \nu \text{ (SK)}} \times \underbrace{\begin{pmatrix} -1 & 0 & e^{-i\alpha} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\alpha} \sin \theta_{13} & 0 & -1 \end{pmatrix}}_{\text{reactor and accelerator } \nu \text{ (Chooz)}} \times \underbrace{\begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu + \text{KamLAND (LMA)}}$$

▲ Fig. 2: The factorized neutrino mixing matrix. The atmospheric part reflects the full mixing observed,  $\theta=45^\circ$ . On the contrary in the solar sector, mixing is large but incomplete. We know from Chooz result that  $\theta_{13}$  is small. Its actual size will tell whether the phase  $\delta_{CP}$  is accessible.

at that scale of a heavy right-handed (RH) neutrino, as allowed by Grand Unification. This is another good reason to consider seriously the possibility of Supersymmetric Grand Unification (SGU) that was presented in the first part of this review. This faith clearly calls for a still more sensitive exploration of proton stability. Indeed GU, by unifying leptons and quarks, naturally leads to proton decay, with however a tiny probability of occurrence, given the huge “loan” of energy required to “jump” from 1 to  $10^{16}$  GeV. Some versions of SGU expect that the proton lifetime is within an order of magnitude above the present lower limit ( $4.3 \cdot 10^{33}$  years for the mode  $e^+\pi^0$ ,  $1.9 \cdot 10^{33}$  years for the mode antineutrino  $-K^+$ , preferred by SUSY). If giant detectors are conceived for future neutrino experiments, it is imperative as well to consider seriously their ability to detect proton decay.

The results obtained on neutrino properties should guide us in the quest of a theory of flavour. The present experimental results we have discussed already fill a full churchyard of models. But still ignored is whether the neutrino world is an “anarchical” one, in which the parameters have been drawn from a hat at random, or a “hierarchical” one, governed by an underlying law. Knowledge of the value of  $\theta_{13}$  should contribute to the answer.

A further question is whether that information will tell us something about our “genealogy”, namely matter-antimatter asymmetry, also called baryogenesis [8]? Remarkably, there seems to exist a viable scheme of leptogenesis [9] that finds its origin in the properties and out-of-equilibrium decays of right-handed neutrinos at very high mass scale, and which explains the existing baryon asymmetry, for masses of the usual neutrinos in the range  $10^{-3}$  to 0.1 eV, as observed.

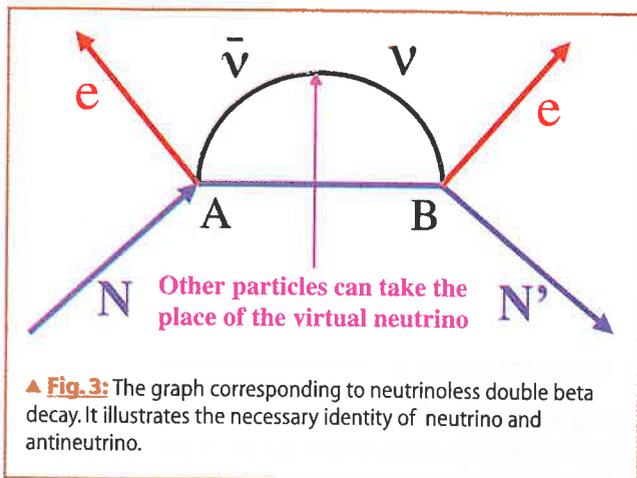
### Astroparticle physics

Astroparticle physics is a vast and rapidly expanding domain, concerning now all types of incident particles and whose goal is to obtain information not only on their properties, but even more on the cosmological objects or events from which they originate. We will focus here on the first aspect.

The known cosmic projectiles, except for neutrinos, are bound to interact in the atmosphere. One can thus either detect them directly at very high altitude (balloon or satellite, with a modest detection area, typically  $1\text{m}^2$ ) or on the ground, through their interaction products. Matter being “transparent” to neutrinos up to huge energies (the Earth becomes opaque above 100 TeV if the cross-section is SM-like), the search for cosmic neutrinos involves gigantic detectors well shielded from ordinary cosmic rays, deep under rock, water or ice.

A still open enigma concerns ultra high energy cosmic rays (UHECR) [10], beyond the Greisen-Kuzmin-Zatsepin (GKZ) cut-off, i.e. particles which seem to have escaped absorption by scattering on the CMB background. Even their existence has to be demonstrated, since the present available experimental results (from Fly’s Eye in Utah and AGASA in Japan) cannot settle the issue. The AUGER programme (with its first site of  $3000\text{ km}^2$  in Argentina), as a result of its two independent and concurrent techniques to detect an atmospheric shower (a fluorescence measurement with telescopes of the Fly’s Eye type, plus an array of ground detectors), should bring the answer and, if they exist, perhaps tell something of their nature.

Gamma Astronomy [11] studies incoming photons, detected either above the atmosphere in balloons and satellites, or on the ground, by large mirrors focusing the Cerenkov light of their shower onto a fine-grained array of photodetectors. Its main objective at present is to fill the gap between low energies (a few GeV, the domain of satellites, EGRET in the past, GLAST in the future) and



▲ **Fig. 3:** The graph corresponding to neutrinoless double beta decay. It illustrates the necessary identity of neutrino and antineutrino.

high (a few hundred GeV, the threshold of ground detectors up to now). This region can in particular give information about the distribution of the CMB background with which the photons interact. But these detectors are able to tackle several other subjects and search for relic cold dark matter candidates (Weakly Interacting Massive Particles or WIMPs) through their annihilation products, as next discussed. Preliminary results from HESS, a stereo-imaging Cerenkov telescope in Namibia, and the recent start of the 17 meter diameter MAGIC in La Palma (Canarias) are the highlights of the field.

The search for high energy cosmic neutrinos is made either by telescopes measuring both atmospheric fluorescence and Cerenkov light (AUGER, presently in its initial phase, looking at the atmosphere from the ground, EUSO – Extreme Universe Space Observatory, under study for the International Space Station, which would look at a huge volume of atmosphere from far above), or by sub-ice (AMANDA, in operation, ICECUBE, in progress, at the South Pole) and submarine (ANTARES and NESTOR in the Mediterranean sea) Cerenkov experiments. Neutrino astrophysics [12] is certainly a fascinating possibility. Neutrinos, free from absorption, should be able to map the topology of the far Universe in its high energy manifestations. However, given the low probability of interaction of neutrinos, even with  $\text{km}^3$  sized detectors and in the most favourable conceivable physics scenarios, the rates expected at very high energy are always marginal. No detection of high energy neutrinos (i.e. non solar) of extra-terrestrial origin has been reported so far.

Finally the search for gravitational waves [13] (GW) is also in an exciting phase. Besides studies concerning pulsars which are “natural laboratories” for GW, both the cryogenic bar detectors, operating in coincidence (EXPLORER, AURIGA, NAUTILUS,...) and the large interferometers, presently being commissioned, LIGO, with its two sites in the US, VIRGO, near Pisa, TAMA, in Japan, could open a new method of exploration of the universe. Even further in the future the space interferometer LISA could give access to gravitational waves of much lower frequencies.

### Dark matter

Unless one finds a convincing explanation in terms of a deviation from Newton's law at great distance [14], it is presently admitted that a substantial part of the matter of the Universe is “dark”, i.e. invisible and felt only through its gravitational effect. Moreover most of it must be “cold”, i.e. non-relativistic at the time relevant for galaxy formation. The cold dark matter contribution to the content of the universe has been accurately determined by WMAP to be  $(29 \pm 4\%)$ .

Concerning its baryonic part  $(4.4 \pm 0.4\%)$ , of which only a tenth

corresponds to visible stars), the possibility that it could be mostly due to dark objects like “failed stars” is now excluded. Gas and dust may be the answer.

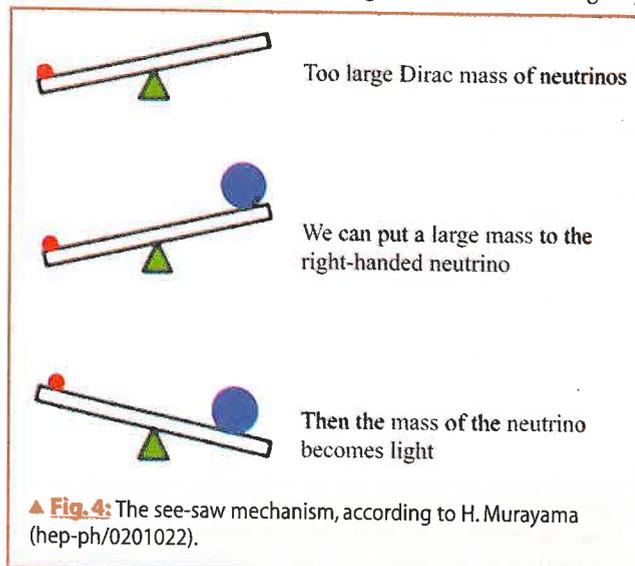
For non baryonic dark matter, for which the search is in full swing, the axion [15] and the neutralino (the highest supersymmetric particle) are still the favoured candidates, although newcomers have appeared, for instance in the frame of theories with extra-dimensions of space.

In the direct search for neutralinos and more generally for WIMPs [16], fossil Weakly Interacting Particles, one looks for the tiny recoil energy that a nucleus struck by the projectile leaves in a detector. This has to be well shielded from cosmic radiation and sensitive to one, or rather several, manifestations of this energy deposit, namely ionization, light or heat.

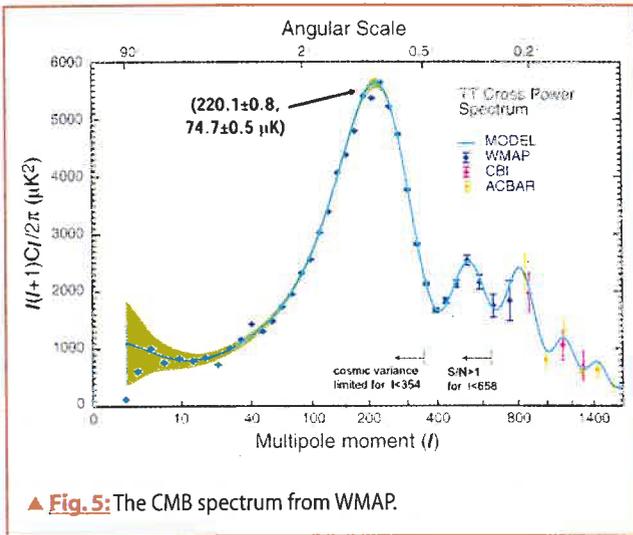
The DAMA experiment at LNGS (Gran Sasso National Laboratory), exploiting about 100 kg of NaI crystals, continues to give, with more data having been taken, a result that suggests a seasonal variation of its counting rate, for a very low threshold, as could be expected from a halo of fossil neutralinos of about sixty proton masses and the seasonal variation of the Earth's velocity relative to the halo. An unidentified systematic effect is not excluded and it will be important to obtain independent confirmation of this observation. Neither the Cryogenic Dark Matter Search (CDMS) nor the EDELWEISS experiment in Frejus (which utilize both ionization and phonons as discrimination methods) confirm it, and at first sight they seem to exclude the mass and cross-section regions corresponding to the DAMA effect. However this conclusion has to be considered with caution, given in particular the potential role of spin-dependent interactions of WIMPs with nuclei.

One can hope to gain up to three orders of magnitude in the sensitivity with future experiments. Besides the cross-section of the WIMP-nucleon interaction, one needs assumptions about the local density and the velocity distribution of WIMPs in the halo which is supposed to exist in and around our galaxy. Comparing the expected sensitivities to the predicted values of the cross-section in various SUSY incarnations, the conclusion is that, even if one limits oneself to the rather constrained case of Supergravity (SUGRA), these types of search, although they can bring eventually positive evidence, are unable to falsify the theory in the absence of signal.

A similar conclusion can be drawn concerning the indirect search methods in which one tries to identify an excess of positrons or gamma rays (monochromatic or as a continuum) due to the annihilation of fossils WIMPs, a signal that a Karlsruhe group



▲ **Fig. 4:** The see-saw mechanism, according to H. Murayama (hep-ph/0201022).



▲ Fig. 5: The CMB spectrum from WMAP.

claims to have observed. The players in the game, following after the balloon experiment HEAT and EGRET on the Compton Gamma Ray Observatory satellite, are the satellite-borne spectrometer PAMELA, the Antimatter Spectrometer AMS, which after its initial shuttle flight should be installed on the ISS, the Gamma Astronomy detectors quoted above and, perhaps, the neutrino detectors.

**Cosmic Microwave Background Radiation (CMBR)**

In the inflation model of the Universe the CMBR spectrum [7] is the result, observed at the decoupling time (namely 380000 years after the Big Bang, the time at which the Universe became transparent to photons) of Gaussian, nearly scale-invariant (an amplitude independent of the wavelength), quantum fluctuations of space-time produced during the inflation period. These fluctuations led to gravitational ones, which induced sound waves in the fluid of electrons, protons and photons. Any region where the density of protons and electrons is higher than average (i.e. a region of compression in a sound wave) is also a region where the density of photons is higher. After decoupling, such a region will appear as hotter than average.

A striking result from the year 2003 is the measurement by the satellite WMAP of the power spectrum of the microwave background (figure 5) with a much better accuracy than previous programmes such as the balloon experiments (ARCHEOPS, BOOMERANG and MAXIMA) and the ground experiment DASI at the South Pole. It covers angular scales extending from ~90 degrees (multipole  $l \sim 3.5$ ) to ~0.25 degree (multipole ~750). WMAP measures also the spectrum of the correlation between polarization and temperature. From the position (in multipole) and the respective heights of the observed peaks and troughs a large number of parameters of the Universe have been extracted with an impressive accuracy. The flatness of the Universe seems to be proven without ambiguity. As for the fraction of dark energy [17] (of matter)  $\Omega_\Lambda$  ( $\Omega_m$ ), WMAP alone gives the range 0.5 - 0.8 (0.58 - 0.14) ( $\pm 2\sigma$ ). It also finds most interesting evidence for an early reionization period, probably due to the effect of the first cosmological objects and leading to further rescattering of photons. The only potential anomaly reported could be a lack of power at large angular scale (the smallest multipoles), but in this particular region the so-called cosmic variance (the unavoidable uncertainty due to the fact that we only observe one copy of the Universe) is large and the conclusions are not very significant.

One can therefore say that WMAP has confirmed two of the three major predictions of inflation: the flatness of the universe, linked to

the superluminal, i.e. faster than light, expansion of space, and the existence of density perturbations corresponding to a quasi scale-invariant spectrum (inflation actually predicts a slight deviation from invariance which still needs experimental confirmation). The third prediction, the existence of gravitational waves originating from inflation, is out of reach of the interferometers, even including the futuristic space project LISA. Relevant information can, however, still come from the programmes able to measure the CMBR polarization, in particular DASI, WMAP itself and, later on, PLANCK.

On the other hand the various models of inflation on the market are still rather unconstrained by the present data and the nature of the inflation, i.e. the scalar field whose energy density is supposed to have caused the inflation, stays as a deep mystery.

**About the author**

Daniel Treille is a senior physicist at CERN and a former spokesman of the DELPHI experiment.

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# Action now – no more talk!

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Scientific and technological development is fundamental for a competitive knowledge society. General and specialised scientific or technological knowledge is increasingly called upon in professional and daily life, in public debates, decision making and legislation. All citizens need a basic understanding of mathematics, science (hereon defined as natural science, ie. physics) and technology. If Europe is to maintain, let alone to improve, its position in the world, and to meet the Lisbon targets, we need a strategic research and education policy.

The globalization of the economy includes both opportunities and challenges for R&D based companies. And globalisation is already happening! All R&D based companies are globally oriented. Clear evidence of globalization can be found if one looks at the share of global GDP growth from 1995 to 2002. Asia, excluding Japan alone, had a share of 43%, USA 20%, EU 14%, Japan 2% and ROW 21%. This presents a challenge for the European companies.

## The goal for Europe

“The Union has today set itself a new strategic goal for the next decade: to become the most competitive and dynamic economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion.” Presidency conclusions, Lisbon European Council, 23-24 March, 2000.

This was the goal set out by the European Commission in March 2000. The science community is a central player in achieving that goal to become the most knowledge-based economy and society in the world.

But how are we doing in Europe? Are we moving towards the goals?

If we look at how old Europe is doing in a larger perspective, there is a need for structural changes in tax, labour market, agriculture and immigration. If one looks at the European electorate, we see the contours of the growing demographic challenges ahead. One in five is retired, one in five is on public support, one in four is employed by public sector and 35 % is employed by private sector. The demographic outlook tells us than there are going to be fewer hands to support an increasingly ageing population. In Europe we are also weak in high-tech value-added products. The high-tech share of total exports in Denmark is 14% (EU average 21%), whereas in the USA it is 28% and in Japan 25%.

How do we compare in other respects with competing parts of the world. If one looks at Asia, which has 50% of world population, there is a young population, with a desire to succeed and a strong personal drive among individuals. In the USA, there is a more happy marriage between technology, money, individual drive and aspiration than in Europe and where immigrants are seen overall as an asset.

## Business R&D and the link to universities

Business R&D and innovation are linked to economic growth and productivity gains. Competition is growing and many countries aim to increase innovative capabilities (see table 1). To support this,

the national authorities must make room for public investment as well as improved framework conditions for private R&D and innovation spending.

▼ **Table 1:** The level of R&D investments

Country/region	R&D intensity	R&D target	Target date
Austria	1.88%	2.5% of GDP	2005
Canada	1.93%	Top 5 in OECD	2010
EU	1.88%	3.0%	2010
Germany	2.53%	3.0%	2010
Hungary	0.81%	OECD avg.	2006
Korea	2.68%	5% of gov't spend	2002
Norway	1.46%	OECD avg.	2005
Spain	0.96%	1.29% of GDP	2003

Source: OECD

There are good reasons to encourage industry-science partnerships. The formal partnerships through joint laboratories, spin-offs and licensing are well known. But also the informal partnerships through mobility of researchers, co-publications & conferences, flow of graduates to industry, and research contracts are all a part of the increasing vital co-operation between universities and industry.

The routes to commercialisation of basic research can be pursued through three different paths. The entrepreneurial route with spin-offs/spin-outs, the patenting route through licensing of technology and the co-operative route through joint and collaborative research.

However the essential condition to obtain the European goal of becoming the most competitive and dynamic knowledge-based economy in the world is that we have the right number of human resources in science, engineering and technology. It is here that the EU member states have a challenge in the coming years.

## Shortage of science skills

The EU states have called for an increase in the proportion of European GDP invested in research from 1.9% to 3%. This is called the Barcelona goal. In terms of human resources, it is estimated that an extra 0.5 million researchers (or 1.2 million research-related personnel) are needed to meet that goal between now and 2010 in addition to the current number of researchers (see table 2 and figure 1). This is on top of the required replacement of the ageing workforce in research.

▼ **Table 2:** Number of graduates in Mathematics, Science and Technology and Number of Researchers and Engineers.

Region	Graduates (2000)	Researchers and Engineers (1999)
EU (15)	555 647	919 796
USA	369 391	1 219 407
Japan	236 670	658 910

Source: RTD, Third European Report on S&T Indicators

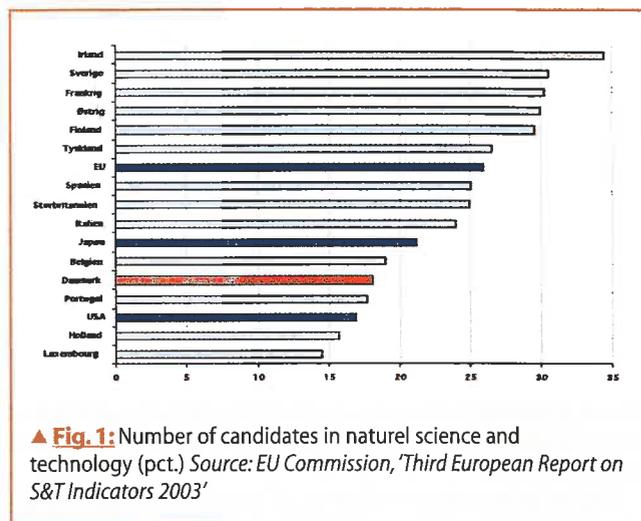
Data Source: Eurostate Education Statistics

Note: The number of graduates does not include data for Greece (not available); The number includes graduates in science, mathematics, computing and engineering.

The question is thus: Will Europe experience a serious shortage of science-related personnel and a serious lack of skills in science over the next 10 years?

The trends in the choice of education of the younger generations does not support the need for more qualified researchers in science. On the contrary, it justifies why action is needed now. We know that the numbers of students who choose to study science has been decreasing over the last decade. Also the (negative) change of attitude of students towards science is a big problem.

On the other hand, the requirements of the European economy for more science-trained personnel is rapidly increasing.



▲ Fig. 1: Number of candidates in natural science and technology (pct.) Source: EU Commission, 'Third European Report on S&T Indicators 2003'

**Science for all**

There is a need not only to continue to encourage children and young people to take a greater interest in science and mathematics but also to ensure that those already in scientific and research careers find their careers, prospects and rewards sufficiently satisfactory to keep them there. In this context, gender balance must be encouraged.

We must also continue to underline the importance of increasing recruitment to scientific and technological disciplines, including a general renewal of pedagogy and closer links to working life and industry throughout the whole educational and training system. This will contribute to the construction of the European research area.

▼ Table 3: Estimates of percentages of student who no longer consider a career in science to be a personal prospect at different stages of the educational system.

Age	Percentage Stating Research in MST is not a Career Option	Decrease in interest as compared to input at that level
9	20%	20%
12	50%	37.5%
16	75%	50%
18	90%	60%
22	95%	50%
26	98%	60%

Up to the age of 18, the percentages considering careers in science and research-related careers are indistinguishable at this level of accuracy. The Table is a compilation from numerous studies on student interest in and attitudes towards science. In this table science is defined as the systematic study of the nature and behaviour of the material and physical universe, together with mathematics, the social and economic sciences and some branches of the humanities.

Source: The European Commission

But the food chain to a career in scientific research is weak. When one examines table 3, it shows that students leak out of the pipeline that leads to a scientific career at any of the six age marks. It happens at every transition: from middle to high school, from high school to University and from a first degree to graduate school. Students who lose interest in pursuing science and engineering studies and potential careers at a specific educational time point may do so either because they decide that another field interests them more than science or because they decide to opt out of the educational requirements of a scientific career. Either way, this is a problem that needs to be solved in order to ensure the human resources required in science.

**Outlook on the future**

The goal of the European Union and its members states must be to have a world-class science community, not only for the better understanding of our world and the laws of nature, but because Europe should also be a place where good ideas and inventions turn naturally into innovation. This requires a long-term research strategy.

We need more strategic and prioritized higher investment in research—both basic research and applied research. The goal is to create excellent research centres and innovative environments to attract entrepreneurs.

The essential condition for this includes higher investments in university education and more PhD- and post-doctoral positions. This can not be done without better education in science and technology in primary and secondary school to ensure the food chain to higher education in science and technology.

At the same time, the quantity and the quality of R&D spending in the private sector have to be increased, which requires the appropriate fiscal and regulatory framework—such as a Community patent or a community science curriculum—to be put in place. And last but not least we have to turn “brain drain” into “brain gain” by attracting more non-EU researchers.

This is the way to achieve the Lisbon goal: to become the most competitive and dynamic economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion. And the EPS must consider how best to play its part in meeting this challenge.

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... Europe should also be a place where good ideas and inventions turn naturally into innovation.

# Photoelectrons measuring the phase of light

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Ultrashort, visible laser pulses have gained immense importance in the past decade. The new technology based mainly on Ti:sapphire lasers has achieved several breakthroughs in respect of increasing the magnification of by far the best temporal magnifying glass mankind has ever had. With this tool even those extremely fast processes can be resolved in time that would normally appear as smeared out just like the images taken with a camera with insufficient shutter speed. These advanced light sources have not only revolutionised femtochemistry by affording an insight into ultrafast chemical processes, earning Ahmed H. Zewail the Nobel Prize for Chemistry in 1999, but have also allowed a huge further step to be made by the production of isolated attosecond ( $1 \text{ as} = 10^{-18} \text{ s}$ ) pulses in 2001 [1]. Interaction of femtosecond pulses with gases results in X-ray generation which, under certain circumstances, can give rise to a single X-ray burst as short as 250 as – an order of magnitude shorter than could have been dreamed of five years ago. Apart from the unprecedented temporal resolution that they provide, these laser-driven X-ray sources afford promise of compact, coherent X-ray diagnostic tools that are so much desired by the medical industry.

Several further intriguing questions are raised, such as, what happens when the length of such a visible pulse (the current state-of-the-art is around 3.5 fs) becomes comparable to the oscillation cycle (2.7 fs at the typical wavelength of 800 nm of Ti:sapphire lasers). Does the momentary amplitude of the oscillations (the envelope of the pulse – see upper part of Figure 1) remain a crucial parameter in determining the interaction of these pulses with matter or has one rather to take the evolution of the actual electromagnetic waveform into account? Intuition, simulations and, most recently, experiments have all indicated that the latter is the case, for example, when one assesses the photoelectron yield from a metal surface induced by controlled, few-cycle optical waveforms, as we

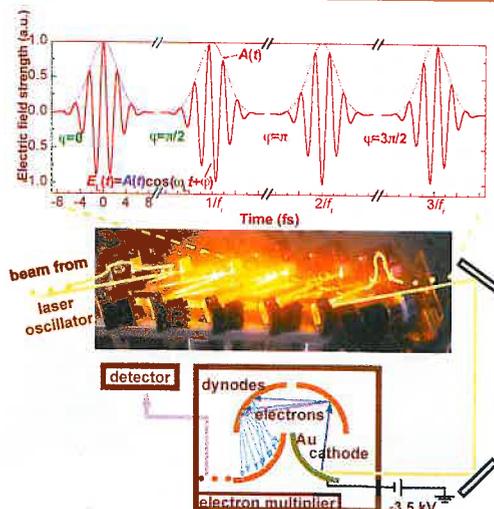
have recently shown [2]. If this is true, the standard approach to light-matter interactions aiming only at control over the evolution of the temporal amplitude envelope of such laser pulses has become out-of-date.

Even though there is a wide spectrum of technologies that allow almost arbitrary shaping of the envelope of laser pulses, the control of the actual waveform within the envelope remained a challenge until 2000. It then became possible to gain access to this last final parameter of light in such a way that the end result was a train of ultrashort laser pulses in which the relative phase between the carrier wave and the envelope of the pulse (the carrier-envelope phase, CEP) shifts from one pulse to the next by a known, controlled and stabilised amount (as depicted in the upper part of Figure 1) [3]. Even though this did not imply that the actual carrier-envelope phase value of an individual pulse could be measured, it was a true revolution in another sense. Namely, when one looks at such a phase-stabilised pulse train in the frequency domain one finds that it is composed of a comb of equidistant frequencies with a fixed and stable offset from zero frequency, i.e. a truly unprecedented reference in the visible and near-infrared optical domains [4]. This optical frequency ruler can then be used for metrological applications in a domain that was only accessible before with a dozen synchronised oscillators typically filling an industrial-scale facility. The improvement was immense and this branch of research has been intensively pursued since then. The measuring accuracy has improved by several orders of magnitude thanks solely to this technology. In this way such exciting aspects as, for example, the measurement of the much-debated time drift of fundamental constants have been put within reach. Apart from this most important spin-off of carrier-envelope phase stabilisation, it has opened a new era in the investigation of light-matter interactions.

In 2003 several optically induced phenomena were shown to depend on the carrier-envelope phase. One of them is of particular interest, since it allows unambiguous measurement of the phase of low-energy laser pulses. It is based on the well-known photoelectric effect, the research history of which spans from the late nineteenth century until the present and in which eminent physicists have played a prominent role.

In 1886–1888 Hertz and Hallwachs observed the emission of electrons from a metal surface when light of sufficiently high frequency impinges on it. This process is known as the photoelectric effect. The so-called “light electricity” was explained by Einstein in 1905, for which he received the Nobel prize in 1921. The photon

► **Fig. 1:** A train of chirped laser pulses with a central wavelength of 750 nm, produced by a special Ti:sapphire oscillator with a repetition rate  $f_r=24 \text{ MHz}$ , is compressed by 12 reflections off specially coated (chirped) mirrors (middle part of figure) after which the pulses attain a duration of 4 fs. The pulse train has also been carrier-envelope phase stabilised (in a setup not shown in the figure). This results in a waveform evolution similar to that depicted in the upper part of the figure; i.e. every  $n^{\text{th}}$  laser pulse has the same electromagnetic waveform (in the figure,  $n=4$  for the sake of simplicity; in the experiment  $n=24$  was realised). The pulse train interacts with a gold surface that emits electrons in a multi-photon process. These are then amplified in a multiplier tube, the output signal of which clearly shows a frequency component at  $f_r/n$ , this being a clear indication that the emission process is directly sensitive to the actual optical waveform, not just to the amplitude envelope. By means of simulation results the measurement can be calibrated so that we can tell at an arbitrary time the shape of the waveforms interacting with the surface.



approach of Einstein allowed the early experiments to be explained: the photoelectric effect takes place when the photon energy exceeds the threshold for freeing the electrons from the metal. If it occurs, the number of electrons emitted depends on the light power (i.e. the number of photons) and its polarisation. In addition to these parameters, we have found that the photoelectric effect (photoelectron emission from a gold surface) also depends on the phase of the light (or, more precisely, the carrier-envelope phase) in the case of few-optical-cycle laser pulses.

The mathematical expression for the electric field of a short light pulse ( $E_1(t)$  in Figure 1) includes its temporal amplitude evolution ( $A(t)$ ), central carrier frequency ( $\omega_1$ ) and the carrier-envelope phase ( $\varphi$ ). It has not been possible to measure the last parameter, the phase, until now, but the photoelectric effect has allowed us to access this quantity, with the indispensable help of colleagues from the National Institute of Advanced Industrial Science, Japan, and Max-Planck-Institut für Quantenoptik, Germany [2]. By utilising the fact that the carrier-envelope phase evolves in the pulse train periodically with a fixed frequency, we have presented experimental proof of the phase sensitivity of photoelectron emission from a metal cathode by demonstrating that the output signal of the multiplier has the same periodic variation (see Figure 1). The known theoretical prediction of the maximum of the photocurrent

as a function of the carrier-envelope phase [5] served as an absolute calibration for carrier-envelope phase determination in the experiment. This finding, provided by a compact, solid-state detector, opens the door for the experimental characterisation of the complete waveform of light pulses and the optimisation of a huge variety of nonlinear experiments in optics on femtosecond and attosecond time scales.

This paper is a summary of an article published in NJP (see ref. [2]).

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- [2] P. Dombi *et al.*, *New J. Phys.* **6**, 39 (2004).
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# Physics in daily life: Drag 'n' Roll

L.J.F. Hermans, *Leiden University, The Netherlands*

Whether we ride our bike or drive our car: there is resistance to be overcome, even on a flat road; that much we know. But when it comes to the details, it's not that trivial. Both components of the resistance—rolling resistance and drag—deserve a closer look. Let us first remember the main cause of the rolling resistance. It's not friction in the ball bearings, provided they are well greased and in good shape. It's the tires, getting deformed by the road. In a way, that may be surprising: the deformation seems elastic, it's not permanent. But there is a catch here: the forces for compression are not compensated for by those for expansion of the rubber (there is some hysteresis, if you wish). The net work done shows up as heat.

The corresponding rolling resistance is, to a reasonable approximation, independent of speed (which will become obvious below). It is proportional to the weight of the car, and is therefore written:  $F_{roll} = C_r mg$ , with  $C_r$  the appropriate coefficient. Now we can make an educated guess as to the value of  $C_r$ . Could it be 0,1? No way: this would mean that it would take a slope of 10% to get our car moving.

We know from experience that a 1% slope would be a better guess.



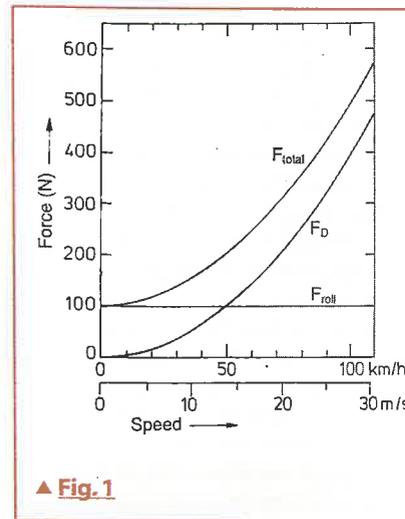
Right! For most tires inflated to the recommended pressure,  $C_r = 0,01$  is a standard value. By the way: for bicycle tires, with pressures about twice as high,  $C_r$  can get as low as 0,005.

The conclusion is that, for a 1000 kg car, the rolling resistance is about 100N.

What about the drag? In view of the Reynolds numbers involved ( $Re \approx 10^6$ ) forget about Stokes. Instead, we should expect the drag  $F_D$  to be proportional to  $1/2 \rho v^2$ , as already suggested by Bernoulli's law. On a vehicle with frontal area  $A$ , one can write  $F_D = C_D A \cdot 1/2 \rho v^2$ . Now,  $C_D$  is a complicated function of speed, but for the relevant  $v$ -range we may take  $C_D$  constant. For most cars, the value is between 0,3 and 0,4.

The total resistance is now shown in the figure, for a mid-size model car ( $m=1000$  kg,  $C_r = 0,01$ ,  $C_D = 0,4$  and  $A=2$  m<sup>2</sup>). It is funny to realize that the vertical scale immediately tells us the energy consumption. Since 1 N is also 1 J/m, we find at 100 km/h approximately 500 kJ/km for this car. Assuming an engine efficiency of 20%, this corresponds to about 7 liters of gasoline per 100 km. At still higher speeds, the figure suggests a dramatic increase in the fuel consumption. Fortunately, it's not that bad, since the engine efficiency goes up, compensating part of the increase.

What about the engine power? Since  $P = F \cdot v$ , we find at 100 km/h about 15 kW is needed. That's a moderate value. But note that, at high speed where drag is dominant, the power increases almost as  $v^3$ ! Should we want to drive at 200 km/h, the engine would have to deliver the 8-fold power, or 120 kW. That's no longer moderate, I would say, and I'm sure the police would agree....



▲ Fig. 1

# Increasing the membership of national physical societies

Peter Melville

Director, International & Business, Institute of Physics, UK and member of the EPS Executive Committee

In the EPS there are two big physical societies – the German Physical Society (DPG) with 47k members and the Institute of Physics (IoP) with 37k members. Together their members account for more than 75% of the members of the physical societies within EPS and together they provide 50% of the total EPS income. This imbalance causes some friction within EPS. In addition, IoP and DPG have been very successful in increasing their membership. The IoP has increased its membership from 17k in 1993 to 37k in 2003. The DPG has been even more successful and with 47k members is the largest national physical society in the world. It would help EPS greatly if other physical societies were able to increase their membership. This would also help strengthen these national societies and strengthen physics in Europe.

The EPS lists for 2003 show 11 member societies with over 1000 members: after DPG (45 018) and IoP (36 498) come the Netherlands (3618), French (2386), Russian (2300), Polish (1877), Ukrainian (1550), Swiss (1196), Italian (1100), Finnish (1015) and Norwegian (1006) Physical Societies. EPS has 2295 Individual Ordinary Members, all but 151 of whom are members of national societies that are members of EPS. There is a big drop from 36 498 for the IoP to the next largest society, the Netherlands Physical Society with 3618. However, the Netherlands is a relatively small country with a population of 16 million compared with 60 million in France, where the French Physical Society, the next largest, has 2386 members. To take account of this, it is quite instructive to divide the membership by the population of the country, as is shown in the first column of Table 1.

UK & Ireland	570/241	Sweden	91/85	Portugal	25/23
Germany	546/206	Austria	91/69	Belarus	24/22
Iceland	258/258	Hungary	84/12	Macedonia	24/24
Netherlands	228/159	Czech Rep.	67/60	Italy	19/19
Norway	221/170	Slovakia	55/43	Spain	19/16
Finland	196/182	Poland	49/30	Russia	16/14
Switzerland	163/153	Lithuania	43/31	Albania	15/11
USA	145	France	40/31	Bulgaria	13/ 8
Estonia	136/98	Israel	38/22	Yugoslavia	12/12
Denmark	129/95	Belgium	35/34	Romania	11/11
Croatia	124/113	Ukraine	32/32	Greece	6/11
Slovenia	103/98	Latvia	32/28	Turkey	0.7/0.7
		Armenia	30/30		

▲ **Table 1:** Membership / 'effective membership' per million of population

This gives an indication of how well the physical societies are doing. (IoP covers UK and Ireland). The American Physical Society (APS) is included for comparison; this has a significant membership outside the USA and if one include only those within USA the membership per million of population is closer to 110. Likewise the IoP has some 8000 members outside Britain and Ire-

land, and if account is taken of this it pushes it below Germany; 2600 members of the DPG live outside Germany. The second column shows the 'effective membership' per million of population. The 'effective membership' is used to calculate the EPS subscription and takes into account a lower fee payable for students, teachers, etc. Both the IoP and the DPG have large numbers of student members. The Icelandic Physical Society with 76 members in a population 294k heads this second column.

Not too much attention should be paid to the exact position in this table; the situation is different in each country. However, it does present some interesting impressions. All the physical societies in column 1 are doing well; this includes the Nordic physical societies, Netherlands and Switzerland and, surprisingly, Estonia, Croatia and Slovenia. It is understandable that the numbers are lower in most of Central and Eastern Europe because of the difficult economic situations that apply. However, the numbers for France, Italy and Spain are disappointing particularly in view of the high standards of physics performed.

Both the IoP and DPG have paid a lot of attention to recruiting and retaining members. The IoP has conducted a number of membership surveys; consistently the results show that the most important reasons for being a member are:

- identity with the physics community – this sense of belonging should not be underestimated as an important motivating force;
- professional qualifications CPhys (Chartered Physicist), MInstP, FInstP (Member/Fellow of the Institute of Physics) – however, this is a peculiarly British phenomenon and experience with the EurPhys has shown that this is not readily transferable elsewhere;
- a good membership magazine in the form of *Physics World*.

Surveys have also been conducted of young members who have resigned their membership. The most frequent reason is given is that their careers have moved to far from physics and IoP is no longer relevant. However, the IoP does have a large number of members in industry and engineering and has started Groups in Physics in Finance, Physics and Law, etc. to attract to a wider range of physics graduates.

IoP places great emphasis on recruiting students through networks of members in universities, greatly reduced student rates, strong links with student physical societies and activities for students. Initially students were offered free membership for the first year of their course, but this has been changes to a small lump sum to cover whole course. This is backed up with activities (and reduced subscriptions) for young members when they have graduated helps ensure a growing membership for the future. The average age of members is 31. Over an age of about 30 members tend to be very loyal to the IoP. The IoP also has a network of industry representatives at major employers of physicists and this combined with company visits to meet physicists, activities aimed at physicist working in business and industry together with a Business Partner network (companies that join the Institute corporately) ensures that the IoP covers physicists outside universities. Nearly two thirds of the members in employment (ie excluding students and retired) work outside academe. Another important activity is in targeting physicists, particularly influential physicists, who are not members and attracting them into membership.

- The DPG has found that powerful reasons for membership are:
- a good membership magazine in German – *Physik Journal*;
  - bursaries from the Heraeus Stiftung, which enables young physicists to attend the very popular Spring meetings organized by the DPG and attended by more than 5000 participants;
  - a strong network within the universities encouraging membership.

Like the IoP the DPG has been very active in encouraging student membership, offering a book prize for the best high school students in physics and free membership for the first year of study.

Not all the activities that the IoP and DPG have been engaged in in increasing membership will be transferable to other physical societies, but some of the ideas may prove useful. ■

#### About the author

Peter Melville is a member of the EPS Executive Committee and has chaired the Interdivisional Group on Applied Physics and Physics and Industry. He led the Institute of Physics recruitment campaign in 1998-2000, achieving a 50% increase in membership from 22 000 to 33 000 in two years.

## UN declares 2005 International Year of Physics

Following months of intensive lobbying effort, notably by M. Ducloy and C. Rossel, the United Nations General Assembly has adopted the resolution A/58/L.62 declaring 2005 as the International Year of Physics. The EPS, IUPAP, and other physical societies around the world have already declared 2005 as the World year of Physics. United Nations sponsorship will be another step ensuring the success of this initiative.

Below is the text of UN press release GA/10243:

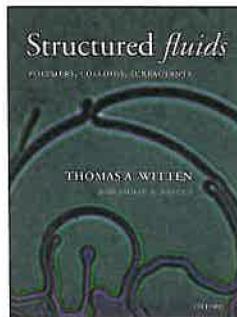
By the terms of another resolution adopted today, contained in document A/58/L.62, the Assembly declared the year 2005 the International Year of Physics, and invited the United Nations Educational, Scientific and Cultural Organization (UNESCO) to organize activities celebrating the Year, collaborating with physics societies and groups throughout the world, including in the developing countries.

Introducing the text, Lebohang K. Moleko (Lesotho) said that, in 1905, Albert Einstein had published several scientific articles that had profoundly influenced understanding of the universe. He had introduced utterly revolutionary ideas on fundamental questions, including the existence of atoms, the nature of light and the concepts of space, energy and matter. The aim of the International Year went beyond the mere celebration of one of the greatest minds in physics in the twentieth century. The Year would provide an opportunity for the largest possible audiences to acknowledge the progress and importance of the great field of science.

The Year should also be the occasion to begin prospective debates on the great need for scientific research in the twenty-first century, he said. The debates would also have to relate to social issues, which accompanied the practice of science, in general, and of physics, in particular. The ethical responsibilities for physicists were enormous. The Year would allow all practitioners, especially women, to more actively participate in its advancement. Countries around the world were preparing special events to celebrate the Year under the sponsorship of UNESCO. The launching of the Year would take place at UNESCO headquarters in Paris from 13 to 15 January 2005.

For more information, please see:  
<http://www.un.org/Depts/dhl/resguide/r58.htm> ■

## BOOK REVIEWS

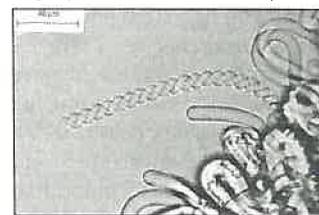


### Structured fluids: Polymers, Colloids, Surfactants

T. Witten (with P. Pincus)  
Oxford University Press, 2004  
216 pages

Around 1900 the spectacular success of X-ray crystallography created an obsession with the single crystal, pure and perfect. Solid state physicists pursued it avidly. Meanwhile metallurgists insisted on the practical importance of *mesoscopic* structure – grains, dislocations, precipitates, cracks... Today's materials physics strikes a balance, with due regard for structure on every scale.

It has taken a little longer for us to recognise and categorise mesoscopic structure in fluids. It governs the behaviour of egg white, toothpaste, jellies, ice cream... Their flow properties are highly nonlinear and may include a yield stress, at which they



Can of worms? A drop of concentrated surfactant in water can give rise to growing micron-sized worms, which sometimes develop a twist.

change smoothly from solid to liquid. They are not simply fluid, instead they are *soft*. Soft condensed matter, in the person of de Gennes, has received the accolade of a Nobel Prize, but it remains something of a can of worms. A can of wormlike objects is indeed one of its prime objects of study!

Tom Witten has written a splendid introduction to the subject, with three strong themes indicated by the subtitle.

Others are largely excluded (liquid crystals? foams?) in the interests of coherence, but there are eclectic digressions that enliven the presentation, nevertheless. The style is that of the Chicago school, deep yet discursive, with an emphasis on economical arguments that lead to scaling relations and rough estimates. The text is elegantly laid out and well complemented by illustrations.

Perhaps for a discourse upon structure there would have been good cause to use more and better pictures. It is curious that book production lags so far behind the average Powerpoint conference talk in this respect. Only occasionally does a figure portray the compelling beauty of the subject. The very last one is the best: a twisted wormlike surfactant structure, as observed by Mark Buchanan. It occurs spontaneously in a simple system, yet it is reminiscent of biological structures. Coincidence? Similar principles of self-organisation? Such analogies are fascinating and will grow in number as physics builds a partnership with biology on the meso and nano scales. Our bodies are full of structured fluids. We will all surely want to understand them better. ■

Denis Weaire, Trinity College Dublin

... deep yet  
discursive, with  
an emphasis  
on economical  
arguments

## Atomic physics – An exploration through problems and solutions

Dmitry Budker, Derek Kimball and David Demille  
Oxford University Press, February 2004  
320 pages

I had mixed feelings before reading this book. On one hand the contents list indicated a interesting assemblage including up to the minute topics such as geonium, parity non-conservation in anti-atoms, geometric phase, searches for permanent electric dipole moments, laser cooling, magneto-optical traps, Bose-Einstein condensation, stochastic cooling, and optical frequency combs. These are not normally found together in a text book in this subject area and at this level. On the other hand the title mentions 'problems and solutions' and my heart sank at the prospect of reading through the terse, sparingly explanatory text such titles usually imply. I need not have worried. The book was an interesting and even gripping read.

In order, the chapters deal with atomic structure; atoms in external fields; the interaction of light with atoms; the effect of external fields; atomic collisions; cold atoms; problems involving molecules; and experimental methods. The final chapter is entitled 'Miscellaneous Topics.' The choice of cgs units may worry some people.

Each chapter comprises self-contained sections each of which begins by posing a problem. Although the background to each is well covered, a thorough knowledge of quantum mechanics, electromagnetic theory and optics at undergraduate level is assumed. Often hints are provided concerning starting point and method, in which all necessary concepts are fully and carefully explained. For example, the section on geonium, gives the relationship between kinetic and canonical momentum and magnetic vector potential (for which the appropriate expression is also provided). Most of the problems are carefully structured, students being guided through solutions to 'precursor' problems leading to the final solution. At this point, presumably, students would be expected to arrive at the solution themselves. But only the best could do this for all the problems. The temptation to skip straight to the solution is very strong. Most readers, like myself, would feel driven by the authors' readable style to continue here. This is not a criticism. Each section has a comfortable 'tutorial' style and would make a good basis for a tutorial.

The authors appear to have given much thought to their choice of topics. There is an underlying unity and often the results of earlier problems are identified as relevant to the solution of the current problem. Consequently there is comprehensive cross-referencing. Necessary theoretical background material, e.g. rotation matrices, irreducible tensors and the density matrix are conveniently placed together in appendices. Again these topics are adequately covered although it would have been useful to include some background on coherent states—a concept used in the text but one which much of the intended readership would not have met. A comprehensive set

of references to the literature is provided. The quality of editing is excellent: I only came across five typographical errors. A slight quibble concerns the authors' use of  $\hbar$ . In the preface they say they '...set  $\hbar = 1$  where it is convenient to do so...' but have not been consistent in applying this rule.

Notwithstanding this, the authors have succeeded in writing a readable and interesting book covering many areas of atomic physics which are the subject of current research, as well as more standard areas (but why did they not include something on stopped light?). They have accomplished this at a level appropriate to the intended readership—advanced undergraduates, graduate students and researchers. Any library purchasing this book for its physics section will find that it will be well used. ■

*Ian C Malcolm, Edinburgh, Scotland.*

### Books available for review

**Alternative Logics. Do Sciences Need Them?**  
P. Weingartner, Springer, 2004

**Asymptotic Giant Branch Stars**  
H. J. Habing, H. Olofsson, Springer, 2004

**Atomic And Molecular Spectroscopy. Basic Aspects and Practical Applications (Fourth Edition)**  
S. Svanberg, Springer, 2004 (1991)

**Beyond Measure. Modern Physics, Philosophy and the Meaning of Quantum Theory**  
J. Baggott, Oxford, 2004

**Cosmology and Particle Astrophysics**  
L. Bergström, A. Goobar, Springer, 2004

**Fundamentals of Applied Dynamics**  
R. A. Tenenbaum, Springer, 2004

**Gauge Theories in Particle Physics. Volume II : QCD and the Electroweak Theory. 3rd Edition**  
I.J.R. Aitchison, A.J.G. Hey, IOP Publishing (Graduate Student Series in Physics), 2004

**Laser Diode Microsystems**  
H. Zappe, Springer, 2004

**Modelling Complex Systems**  
N. Boccara, Springer, 2004

**Nanoelectronics and Nanosystems. from Transistors to Molecular and Quantum Devices**  
K. Gosser, P. Glösekötter, J. Dienstuhl, Springer, 2004

**New Directions in Statistical Physics. Econophysics, Bioinformatics, and Pattern Recognition**  
L. T. Wille, Springer (Complexity), 2004

If you are interested in reviewing books, please send us your name, and contact co-ordinates, along with the your field(s) of specialisation to:

Book Reviews, EPS Secretariat  
BP 2136, 68060 Mulhouse Cedex, France

Each section has a comfortable 'tutorial' style and would make a good basis for a tutorial.



## Mapping Physics Students in Europe

The High Level Group on Increasing Human Resources for Science and Technology was set up in May 2003 by Philippe Busquin, Commissioner for Research. The group was chaired by Professor José Mariano Gago, former Portuguese minister of science and technology. Its aim is to identify specific actions and policy measures to increasing the number of research personnel and science and technology professionals in Europe, in line with the 3% "Barcelona declaration".

The EPS President Martin Huber was invited to attend the High Level Group on Human Resources for Science and to present the views of the European physics community. While there is a definite impression in the physics community that the number of students is declining, no comprehensive study was available. From this lack of hard data was born the "Mapping of Physics Students in Europe" (MAPS) study, prepared by the EPS.

MAPS covers a 5 year period 1997-2002, and tracks the flow of students entering into a degree course in physics, and those studying through a PhD level. The study compares throughput of students in physics with students in economics and biology. An indication of employment opportunities for physics graduates is also provided. MAPS covers 40 European countries, and provides a brief description of each of the university systems.

The full report is available at [www.eps.org](http://www.eps.org). ■

## Obituary: Dr Venkataraman Chandrasekharan

*M. Chergui (Lausanne), M.-M. Thiéry (Paris), B. Silvi (Paris)*

Dr Venkataraman Chandrasekharan, Directeur de Recherches au CNRS, passed away on September 5<sup>th</sup>, 2003 at the age of 78. His students and colleagues regret the loss of a great scientist and a multifaceted, warm and demonstrative person.

Chandra (as we called him) was a pure product of the Southern Indian school of Physics that counted prestigious names such as S. Chandrasekhar, R.S. Krishnan and C.V. Raman.

His thesis was on light scattering of diamond and quartz. After completing it, he left for the United States and worked in Eugene, Oregon. At the beginning of the 1960's, he met Boris Vodar who offered him a position at the CNRS Laboratoire des Hautes Pres-

sions in Bellevue, near Paris (later to become Laboratoire des Interactions Moléculaires et des Hautes Pressions). Two years later he became a staff scientist at the CNRS, and later on Directeur de Recherches.

His scientific activity knew no boundaries and he worked on scattering spectroscopies (Raman, Rayleigh), as well as IR, Raman and Vacuum-ultraviolet spectroscopy of gas phase and condensed phase molecular systems, with a penchant for theoretical aspects. He was also a pioneer of computer simulations of dynamical properties of molecular crystals and solids. He stayed with the CNRS until he retired in 1991.

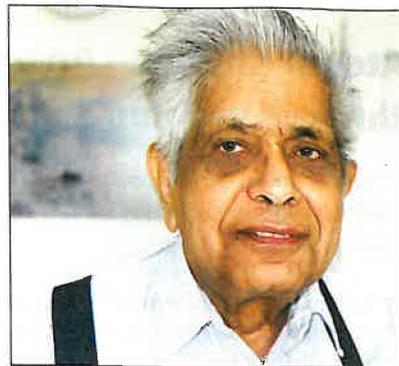
For anyone who met him, Chandra had all the traits of a genius. A vast scientific culture with an incredible physical insight, a wealth of ideas, and an acute curiosity for physical problems, matched with an intellectually rigorous and demanding character. As is often the case with such brilliant, high calibre individuals, he also had a complex personality: temperamental, sincere, sometimes tormented, with a deep love of life and an incredible sense of humour. When asked why he had settled in France, he would reply that it was because of French cuisine.

Chandra had all the traits of a genius. A vast scientific culture with an incredible physical insight...

He once gave a talk, and at the moment he finished it, an alarm clock, which was in his bag, went off. He stopped it and told the audience "that was to wake you up", alluding to the Institute Head, who tended to sleep at seminars. This anecdote shows Chandra's special dislike of authority (be it political, religious or otherwise), and he never hesitated to provoke the scientific establishment of CNRS by his statements and criticisms.

Nothing expresses better his contemplation of life and of what lies beyond, than the poem we reproduce below, which he wrote when he retired from CNRS. It was read at his cremation. May his soul rest in Peace. ■

*Let me but live my life from year to year  
With forward face and unreluctant soul  
Not hurrying to, nor turning from the goal,  
Nor mourning for the things that disappear  
In the dim past, nor holding back in fear  
From what the future veils, but with a whole  
And happy heart, that pays its toll  
To youth and age, and travels on with cheer,  
So let the way be up the hill or down  
O'er rough or smooth, the journey will be joy,  
Still seeking what I sought when but a boy  
New friendship, high endeavour and a crown  
My heart will keep the courage of the quest  
And hope the road's last turn will be the best.*



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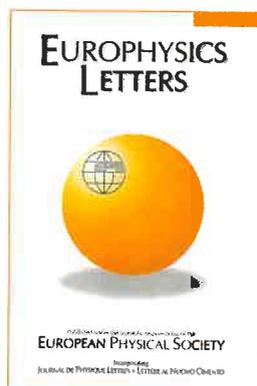
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