Edelweiss II, the quest for **dark matter particles**

J.-J. Bigot/CEA/DAPNIA

320-g germanium bolometer and NTD (neutron transmutation doped) thermal sensor for the EDELWEISS II project.

To detect the elusive particles that may well form a major part of the hidden mass of the Universe, ultra-sensitive detectors must be used, located so as to shield them from other sources of radiation. It is not sufficient, however, to detect just one component, such as ionization, induced by the few interactions anticipated. The aim is to detect a second quantity, such as the heat or light generated. The sensitivity the EDELWEISS II experiment sets out to achieve thus stands at around one interaction per year, per kilogram of detector.

Uncovered as early as the 1930s by US astrophysics genius Fritz Zwicky, the puzzle of **dark matter** in the Universe has taken on, over the past few years, a more pressing character, as cosmological measurements became more and more precise. Indeed, observations of the **cosmological background** at 2.7 **kelvins**, of large **galactic** structures, together with investigation of **supernova** explosions – those of the so-called SN1a type providing good "standard candles," shining with the brightness of an entire galaxy as they die – reveal a highly disconcerting Universe (see Box A, ***The standard cosmological model***). In this picture, the normal matter we are made of, so-called **baryonic matter**, only accounts for 4.5% of the Universe's energy content. The rest would seem to consist of two components, one being very weakly interacting matter, "dark matter," the other being a mysterious "**dark energy**" that accelerates, rather than slow down as expected, the expansion of our Universe (see Figure).

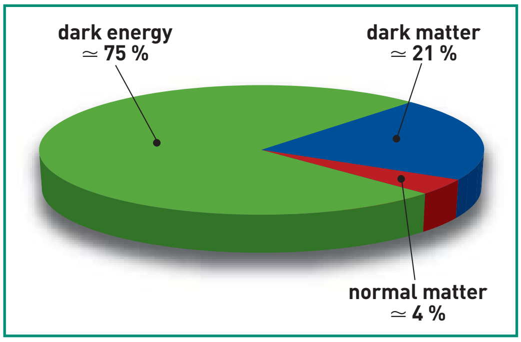


Figure.
How the Universe's energy content is distributed.

The puzzle of "dark matter"

The trouble is neither of these two majority constituents has yet been directly identified. Physicists thus find themselves in the disconcerting, and somewhat uncomfortable, position of a steward who could only account for 5% of his master's estate. Physicists do have one available candidate for the "dark matter" in the Universe, in the form of the mirror world of **supersymmetric** matter, which is predicted by a great number of theories that would allow unification of **gravitation** with the other interactions (see Box B, ***Fundamental interactions and elementary particles***), however this has not as yet been directly evidenced.
On the border between France and Switzerland, **CERN**'s Large Hadron Collider (LHC) should allow the exploration to begin, of that mirror world of supersymmetry, by the end of 2007. However, in order to play their part as a major constituent of the Universe, supersymmetric particles must have one stable representative that would have survived right down to our times, some 14 billion years after the **Big Bang**. The acronym WIMPs – for "weakly interacting massive particles" – is used to refer to such extremely weakly interacting particles, which have yet to be observed.
In their endeavor to find evidence for WIMPs, many international teams have taken on the issue of the direct detection, in the controlled environment of the laboratory, of the very tiny number of interactions between WIMPs and normal matter. Led by one of the world's foremost teams to be involved in this quest, the EDELWEISS experiment entered on 31 March 2006 its second phase, EDELWEISS II, which is currently recording its first data.


J.-J. Bigot/CEA/DAPNIA

Welding operation to fix the gold and aluminum wires onto a bolometer in the cryogenic detector for the EDELWEISS II experiment.

A multiplicity of challenges

The challenges facing the EDELWEISS experiment are many, and diverse. Indeed, it is known that, to make it possible for a solution to be found to the puzzle of "dark matter," interactions of WIMPs with normal matter must be extremely rare, rarer still than those of the elusive **neutrino**, which may pass right through the Earth billions of times without undergoing an interaction. Initial experiments, such as e.g. the Heidelberg–Moscow experiment, in the 1980s and 1990s, used materials exhibiting high **radioactive** purity, such as germanium, developing, over two decades, increasingly stringent techniques for the selection of materials, and shielding them from **cosmic rays** in underground laboratories. This radioactive purification strategy, however, fell down when confronted with two major issues: on the one hand, it was becoming increasingly difficult to purify all the materials involved in the experiment, certain sources of radioactive noise, such as the **decay** products from radon, or the **cosmogenesis** of radioactive elements such as **tritium** by cosmic radiation, proving stubbornly resistant to purification efforts. On the other hand, the strategy deployed by that initial generation of experiments further suffered from one major limitation. Even if it were possible to purify materials sufficiently to access the very low rate of interaction – probably less than one hundredth of an interaction per kilogram per day – predicted by the theories of supersymmetry, how then could one make sure that such residual interactions were indeed due to interactions with WIMPs, rather than to some poorly controlled or unforeseen radioactive background? How, then, in such conditions, could these experiments prove the existence of WIMPs?
At the same time as two other **cryogenic** experiments, CDMS (Cryogenic Dark Matter Search), in the United States, and CRESST (Cryogenic Rare Event Search with Superconducting Thermometers), bringing together German and British teams, at the **Gran Sasso Laboratory** (Italy), the EDELWEISS team thus embarked, in the early 1990s, on development of detectors that would allow discriminating between the rare WIMP interactions, and the radioactive background. To that end, it would be necessary to detect not just one component resulting from the interaction, such as **ionization**, rather this had to be combined with measurement of another quantity, such as heat or light generated in the interaction, while verifying that knowledge of these two quantities did allow the signal so eagerly sought for to be discriminated from ambient radioactivity. The energy distribution, into heat, which is very easily generated, and light and ionization, which involve processes more costly in terms of energy, does indeed allow discrimination of WIMP interactions. Contrary to the **photons** and **electrons** from normal radioactivity, WIMPs must travel at very low velocities compared to that of light, namely about one thousandth of the latter. This results in light and heat being generated in distinctly smaller amounts

in a WIMP interaction, for a given interaction energy, than with gamma or electron emissions from radioactivity.

One hundredth of a degree above absolute zero

The problem is that measuring the heat released during the interaction calls for extremely low temperatures, to restrict thermal noise fluctuations to a level allowing the energy from the interaction to be measured. It is thus necessary to cool the detectors to just one hundredth of a degree above absolute zero (i.e. to 0.01 kelvin), a temperature 30,000 times cooler than normal ambient temperature. For the initial phase of the experiment, EDELWEISS I, which in 2002 was the first experiment to embark on exploration of the theories of supersymmetry, it was CEA's Condensed Matter, Atoms and Molecules Research Department (DRECAM: Département de recherche sur l'état condensé, les atomes et les molécules) that built the **cryostat**, having a useful capacity of 1 liter, which allowed such

X.-F. Navick/CEA/DAPNIA

Detail view of the assembled detector stages for the EDELWEISS experiment, in the Modane Underground Laboratory.

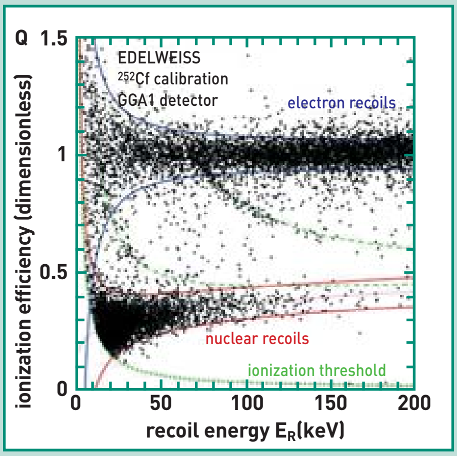
temperatures to be reached. For the second phase of the experiment, which should make it possible to improve sensitivity by a factor close to 100, useful capacity stands at about 100 liters. This ambitious cryogenic suite, employing pulse tubes designed by the CEA/Grenoble Low Temperatures Department, to cut down as far as possible on use of external cryogenic fluids, was constructed by the **CNRS** Very-Low-Temperatures Research Center in Grenoble (France), in collaboration with DRECAM and the Research on the Fundamental Laws of the Universe Department (DAPNIA), at Saclay. This cryostat may be fully remotely controlled, this being an essential consideration for an experiment sited in an underground location, relatively hard to access, and intended to collect data in virtually continuous manner over a number of years. At such very low temperatures, the characteristics may be detected with excellent accuracy, of a WIMP interaction, though it only involves a rise in temperature of one to a few millionths of a degree, and a few hundred electrons or so. The ratio of these two quantities, ionization and heat released during the interaction, allows very precise discrimination, and rejection, of interactions related to the radioactive background, as distinct from the very rare ones involving WIMP-induced **nuclear recoils** (see Figure in Box).

J.-J. Bigot/CEA/DAPNIA

Positioning one of the ten 12-bolometer stages used in the EDELWEISS II experiment.

A highly discriminating measurement

As may be seen from the Figure, the discrimination effected by EDELWEISS II, between nuclear recoils, induced by **WIMPs** (weakly interacting massive particles) and **neutrons**, and **electron** recoils, due to the **radioactive** background, is outstanding. For a given energy, as indicated along the x-axis, nuclear recoil **ionization** efficiency (indicated on the y-axis) will vary by a factor depending on energy, and ranging between 3 and 4 at typical WIMP interaction energies (a few tens of **keV**). While in fact, intervening between the two populations of nuclear and electron recoils, a small population of intermediate events may be observed, a large fraction corresponding to **inelastic** nuclear **interactions**, whereby the nuclear recoil is associated to a low-energy **gamma** emission. The quality of the radioactive background rejection effected by these detectors is impressive: when one notes that, when subjected to 100,000 gamma interactions, not a single one of these is attributed to a nuclear recoil.



These measurements involve very-low-noise amplifiers, the preamplification stage of which is positioned on a low-temperature stage (cooled by pulse tube to a temperature of about 30 **kelvins**), to reduce electronic noise in the ionization measurement. Charge measurement exhibits noise that is lower than the keV mark for each channel (full width), while measurement of the energy deposited in the form of heat allows for even more precise measurement of energy, the best detectors produced for EDELWEISS exhibiting a resolution of 250 eV (full width), this being more precise, by over one order of magnitude, than conventional germanium detectors. Such highly precise calorimetric measurements are made possible by use of germanium thermal sensors, doped in very homogeneous fashion with neutrons (NTD, for "neutron transmutation doped"), or thin-film sensors, based on a amorphous niobium–silicon mix, both types of sensors being used in the metal–insulator transition.

B Fundamental interactions and elementary particles

The **standard model** of particle physics is the reference theoretical framework describing all known **elementary particles** (see Table 1) and the fundamental **interactions** these particles are involved in (see Table 2). The basic constituents of matter, known as **fermions**, are partitioned into two main categories, as determined by their participation in the fundamental interactions, or forces (the **gravitational**, **electromagnetic**, **weak**, and **strong** forces), which are mediated by **vector bosons**, the fundamental particles which carry out the transmission of the forces of nature[1] (see Table 2). Whether a particle belongs to the category of fermions, or to that of bosons depends on its **spin** (i.e. its intrinsic angular moment, or internal rotation moment), depending on whether it exhibits half-integer spin (fermions) or integer spin (**bosons**).
At the same time, to every constituent of matter is associated its **antiparticle**, a particle having the same *mass*, but the opposite *charge*. The **positron** is thus the positively charged antiparticle of the **electron**, which exhibits a negative charge.

Leptons and quarks

Fermions include, on the one hand, **leptons**, which may travel freely and do not participate in the *strong interaction*, which ensures the cohesion of atomic **nuclei** (it is consequently termed a *nuclear* interaction), and, on the other hand, **quarks**, which participate in all interactions but are not individually observed, enmeshed and confined as they are within **hadrons**, the particles susceptible to strong interaction, of which they are the constituents.[2]
In the lepton category, **charged leptons** participate in the *electromagnetic interaction* (which ensures the cohesion of **atoms** and **molecules**, and in the *weak interaction* (which underlies **decay** processes, in particular **β radioactivity**). Neutral leptons, or neutrinos, for their part, participate in the weak interaction only. Exhibiting very low mass, there is one type of neutrino for each type of charged lepton.
Independently from their involvement in interactions, the basic constituents of matter are classified into three *generations*, or *families*, of particles. From one family to the next, quarks and leptons having the same charges only differ by their mass, each family being heavier than the preceding one.
The **electron**, up quark (symbolized *u*) and down quark (symbol *d*), which belong to the first generation, are the lightest massive particles, and are stable. These are the sole constituents of **normal matter**, so-called **baryonic** matter (a baryon is an assembly of quarks), which is made up of **protons** and **neutrons**, this however only accounting for 4% of the Universe's energy content!
Particles in the other two families are heavier, and are unstable, except for neutrinos, which on the other hand exhibit non-zero mass, but are stable.
These latter particles may only be observed or detected in the final states resulting from collisions effected in **accelerators**, or in **cosmic radiation**, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.
According to **quantum mechanics**, for an interaction to take place between particles of normal matter, at least one elementary particle, a boson, must be emitted, absorbed, or exchanged. The **photon** is the **intermediate** (or **vector**) boson for the electromagnetic interaction, the **W^+**, **W^-** and **Z** are the intermediate bosons for the weak interaction, and **gluons** are those of the strong interaction, acting at quark level.
As to the **graviton**, the putative vector for the gravitational interaction, it has not so far been empirically discovered. The **gravitational force**, which acts on all fermions in proportion to their mass, is not included in the standard model, due in particular to the fact that quantum field theory, when applied to gravitation, does not yield a viable scheme, as it stands. While gravitational effects are negligible in particle physics measurements, they become predominant on astronomical scales.

Interaction ranges

Quarks and charged leptons exchange photons. The photon having no electric charge, these particles conserve their electric charge after the exchange. Since the photon's mass is zero, the electromagnetic interaction has an infinite range. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.
In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: **charged-current weak interaction**, for which the interaction vectors are the W^+ and W^-; and **neutral-current weak interaction**, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (about 80 GeV/c^2 for $W^\pm$, 91 GeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (*flavor*). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.
Only those quarks that have a color charge[1] exchange gluons, these in turn being bearers of a color charge. Thus,

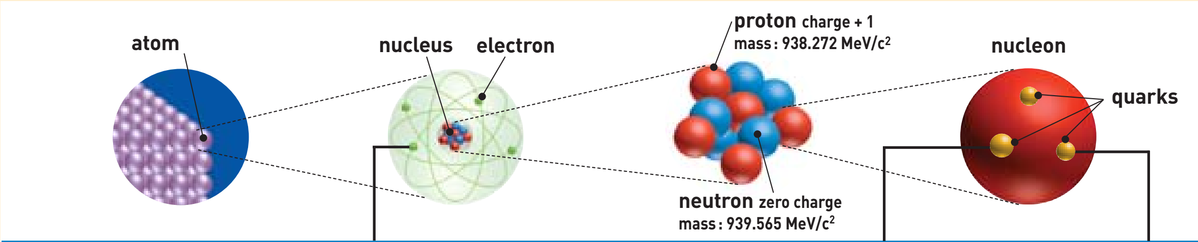
(1) The participation of basic constituents in fundamental interactions is governed by their *interaction charges* (electric charge, color charge), or "conserved quantum numbers." *Color charge*, a quantum number that determines participation in strong interactions, may take one of three values: "red," "green," or "blue" (these colors bearing no relation to visible colors). Every quark bears one of these color charges, every antiquark one of the three anticolor charges. Gluons are endowed with double color–anticolor charges (eight combinations being possible).

(2) To take e.g. **nucleons**: the proton holds two up quarks and one down quark, the neutron two down quarks and one up quark. A **meson** is made up of just two quarks (one quark and one antiquark).

when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact together, which greatly complicates theoretical treatment of this interaction. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The quest for unification

The theoretical framework for the standard model is quantum field theory, which allows a quantitative description to be made of the fundamental interac-



		leptons able to move freely		quarks assembled into triplets, or quark–antiquark pairs, to form the many subatomic particles	
Fermions Normal matter is made up of particles from this group.	First family	**electron (e)** responsible for electricity and chemical reactions charge: - 1 mass : 0.511 MeV/c²	**electron neutrino** (ν_e) has no electric charge, and interacts very seldom with the ambient medium.	**down (*d*)** electric charge: - 1/3 the proton holds one, the neutron two mass : 4 – 8 MeV/c²	**up (*u*)** electric charge: + 2/3 the proton holds two, the neutron one mass : 1.5 – 4 MeV/c²
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	Second family	**muon (μ)** a more massive companion to the electron. mass : 105.658 MeV/c²	**muon neutrino** (ν_μ) properties similar to those of the electron neutrino.	**strange (*s*)** a heavier companion to "up" mass : 80 – 130 MeV/c²	**charmé (*c*)** a heavier companion to "down" mass : 1.15 – 1.35 GeV/c²
	Third family	**tau particle (τ)** heavier still. masse : 1,776.99 ± 0.29 MeV/c²	**tau neutrino (ν_τ)** properties similar to those of the electron neutrino.	**beauty (*b*)** tau particle. mass : 4.1 – 4.4 GeV/c²	**top (*t*)** heaviest in the family (observed in 1995) mass : 171.4 ± 2.1 GeV/c²
Vector bosons Fundamental particles carrying out transmission of natural forces.		**photon** elementary grain of light, vector for the electromagnetic force	**gluon** bearer of the strong force between quarks	**W±, Z⁰** bearers of the weak force, responsible for some forms of radioactive decay (W+, W-, Z0)	
Higgs boson?		responsible for "electroweak symmetry breaking"			

Tableau 1.
Table showing the twelve elementary constituents for which the standard model describes the interactions involved. The three charged leptons (electron e-, muon, μ^-, tau particle τ^-) are subject to electromagnetic and weak interactions, neutrinos (ν_e, ν_μ, ν_τ) are only affected by weak interaction, and the six quarks (up, charm, top – or *u*, *c*, *t* – bearing a charge of 2/3; and down, strange, bottom – *d*, *s*, *b* – bearing a charge of – 1/3) are subject to all three interactions. Every elementary constituent has its antiparticle, having the same mass, and algebraic quantum numbers (such as electric charge) of the opposite sign.

B Fundamental interactions and elementary particles (cont'd)

tions between elementary particles, while respecting the principles of *special relativity*, as those of quantum mechanics. According to the latter theory, if one seeks to observe a microscopic structure at high temporal and spatial resolution, this entails transferring to it an amount of energy–momentum, the greater, the higher the resolution being sought. However, according to the theory of relativity, such an energy–momentum transfer is liable to undergo transformation, yielding particles not present in the initial state: fermions may be generated, or annihilated, in particle–antiparticle pairs, while bosons may be so in any arbitrary number.

All processes involving one and the same fundamental interaction are interrelated. The quantum field theory approach, in which properties of **symmetry** play a fundamental part, seeks to describe all of the processes relating to each fundamental interaction, within overarching theoretical constructions.

The strong and electromagnetic interactions are formalized, respectively, in the theories of **quantum chromodynamics**, and **quantum electrodynamics**. The weak interaction, for its part, is not subject to a separate description, being described jointly with the electromagnetic interaction, in the unified formalism of **electroweak theory**. Theories of the *grand unification* of all fundamental interactions do exist, however they remain as yet lacking any experimental validation.

All the predictions of the standard model have been corroborated by experiment, except for just one, to wit, the existence of the **Higgs boson(s)**, which particle (particles?), it is hoped, will be discovered with LHC. The **Higgs mechanism** is thought to be responsible for the mass exhibited by elementary particles, the eponymous boson making it possible for zero-mass fermions interacting with it to be endowed with mass. This would allow the unification, at high energies, of the weak and electromagnetic interactions within the electroweak theory, while effectively accounting for the **breaking** of this **electroweak symmetry** at low energies, taking the form of two interactions, which may be seen as distinct at that energy level (see *The electroweak interaction from one accelerator to the next: the LHC roadmap and the yardstick of LEP measurements*, p. 23).

Going beyond, or completing the standard model?

The standard model features a set of parameters (such as the masses of elementary particles, or the intensities of fundamental forces) which are "anchored" in experimental findings. It is, in any event, a theory that is liable to be improved, or further elaborated, or even surpassed and left behind. It does not account in any way for the classification of the constituents of matter into three generations of particles, whereas it is precisely the existence of these three generations which makes it possible to account for **CP** (charge–parity) **invariance violation** (meaning that a physical process involving the weak interaction is not equivalent to its own mirror image), a violation that is in all likelihood the source of the matter–**antimatter** imbalance, running in favor of the former, in the primordial Universe. The model neither allows quantum treatment of gravitation, nor does it fully account for the fundamental property of *confinement*, which prevents quarks from propagating freely outside hadrons.

To go beyond, or to complete the standard model, research workers are mainly exploring two avenues:

– **supersymmetry** (widely known as SUSY) would associate, to every particle (whether a boson or a fermion) in the standard model, a partner from the other series, respectively a fermion or a boson. Supersymmetric partners would, at first blush, be highly massive, the lightest of them being a particle interacting very weakly only. This would be an ideal candidate to account for the **hidden matter** (or **dark matter**) in the Universe, accounting as it does for some 21% of the Universe's energy content, the remainder (close to 75%) consisting in a **dark energy**, the nature of which likewise remains to be determined. These WIMPs (acronym for "weakly interacting massive particles") are actively being sought (see *EDELWEISS II, the quest for dark matter particles*);

– the **substructure** path assumes there could be a new level of elementarity, underlying the particles in the standard model (or some of them). This would lead to a veritable blossoming of new, composite particles, analogous to hadrons, but exhibiting masses two to three thousand times heavier.

It should be noted that, whereas supersymmetry theories yield predictions that agree with the precision measurements carried out at LEP, the theories propounding substructures (or their simpler variants, at any rate) fail to do so. As for the more complex variants, these are encountering difficulties at the theoretical level.

fundamental interaction	associated particles (messengers)	actions
gravitation	graviton?	having an infinite range responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic interaction	photon	having an infinite range responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak interaction	W^+, W^-, Z^0	responsible for β^- and β^+ radioactivity, reactions involving particles as neutrinos
strong interaction	gluons (there are 8 gluons)	ensures the cohesion of the atomic nucleus

Tableau 2.
Fundamental interactions, their vectors, and effects.

Currently, the three cryogenic experiments, CDMS, EDELWEISS, and CRESST, are leading the field of international competition. All three, however, are coming up against the challenge from radioactivity depositing onto detector surfaces. Major research and development efforts have been carried out, to secure the ability to identify, and reject, such occurrences.

Countering and identifying surface radioactivity

Such surface radioactivity presents a potential hazard to the search for WIMPs, for two very distinct reasons. On the one hand, the response of ionization detectors is often weaker for interactions occurring on the surface of the detector. Such interactions may then, in a small proportion of cases, mimic WIMP interactions, which are also less ionizing than natural radioactivity. And, on the other hand, decay products from radon, such as e.g. polonium, **adsorbed** onto materials around the detectors, may also appear as WIMPs, exhibiting as they do comparable energy and mass. Each of the three major current experiments is developing, therefore, a specific method to identify interactions close to the detector surface. While the CDMS-II experiment, which has already been in its second phase for two years, using some 10 kilograms of germanium and silicon detectors, is employing detectors featuring **superconducting** sensors exhibiting very fast responses, CRESST has been using a light reflector featuring plastic **scintillator** panels, positioned around its detectors, enabling it to reject a large proportion of background events. EDELWEISS II, on the other hand, is carrying forward deployment of thin-film sensors, developed at the CNRS Nuclear **Spectrometry** and **Mass Spectrometry** Center (CSNSM), at Orsay, exhibiting a response pattern that is highly distinctive, according to whether the interaction is located in the sensor's immediate vicinity, or on the contrary within the detector volume.

Towards the EURECA experiment

The sensitivity experiments like EDELWEISS II are setting out to achieve stands at about one WIMP interaction per year, per detector kilogram. Physicists, however, are already designing the next stage, which would allow a further advance by a factor close to 100, in terms of sensitivity, in order to test a major part of the supersymmetry models, while affording a good chance of identifying WIMPs, and characterizing them precisely. This future experiment, EURECA, is bringing together the expertise, in Europe, of the groups involved in the CRESST and EDELWEISS experiments, but also the CERN Cryogenics Laboratory, together with a dozen leading laboratories in the field of cryogenics and cryoelectronics, joining in a European network, VeLoTIC. EURECA's goal is indeed ambitious, since the experiment is planning to deploy about a thousand detectors, here again at a temperature of one hundredth of a degree absolute, exhibiting performances, in terms of identification of the radioactive background, that will enable it to achieve the fantastic sensitivity, for a WIMP signal of just about ten interactions per year, per tonne of detector.

The neutron background

To attain such a sensitivity, the quality of the cryogenic detectors needs must be complemented by virtually absolute control of the background noise from **neu-**

CDMS Collaboration

The refrigerator and cryostat for the CDMS experiment, installed at the Soudan Mine (Minnesota).

trons, and – as far as feasible – from the materials' natural radioactivity. To that end, all of the world-leading experiments are now making use of underground experimental sites, which suppress cosmic radiation by a factor of 100,000 to several million. Thus, at ground level, some one hundred particles per second pass through our body, and that background is far too high to allow evidence to be gained of a WIMP signal as weak as that predicted by supersymmetry theories. The EDELWEISS experiment can thus draw on the asset of the **Modane Underground Laboratory**, lying under more than 1,650 m of bedrock, which suppresses cosmic radiation by a factor of about 2 million, and ranks, along with **SNO** (Sudbury Neutrino Observatory), in Canada, as currently one of the best underground sites. However, even in such laboratories, the struggle to curb radioactivity remains paramount. Indeed, the surrounding rocks contain, as do all materials in the Earth, traces of uranium, and various radioactive elements. These elements, whether through uranium fission or **alpha**–n reactions, generate fast neutrons which, even though they occur in extremely small numbers, present a major hazard to WIMP detection experiments. Indeed, these neutrons, although much lighter than WIMPs, induce nuclear recoils that are very hard, if not impossible, to distinguish from WIMP interactions.

To counter this neutron background, an experiment such as EDELWEISS II has used polyethylene passive shielding, some 60 centimeters thick, curbing by a factor of over 10,000 the flux of fast neutrons emanating from the surrounding rocks. Similar shields are employed by the CDMS and CRESST experiments, and, for EURECA, the requirement will be for shielding from one to several meters thick, employing **hydrogen**ated materials, which are highly effective in moderating the energy of fast neutrons, by slowing them down. Two other fast neutron sources, however, further threaten WIMP detection experiments, if due care is not taken. One the one hand, there are neutrons induced by residual cosmic **muons**, which have managed to come through the mountain. Exhibiting an average energy some 300 times larger than the energy of cosmic rays found at ground level, these cosmic-radiation-induced muons quite frequently cause nuclear interactions, which generate in turn considerable numbers of very fast neutrons, with energies ranging from a few **MeV** to several tens of MeV. For experiments such as EDELWEISS II, and even more so for EURECA, it becomes a requisite to detect such muons, even though their number be extremely small, in order to identify, and reject, interactions that coincide with their passage. EDELWEISS II is thus almost entirely covered with plastic scintillator panels, made by two laboratories in Karlsruhe (Germany), which allow the identification, with a high degree of confidence, of a muon passing through the scintillator shield surrounding the experiment. Better still, in some 75% of cases, the muon will pass through a sufficient thickness in two plastic scintillator layers, allowing in such instances the incoming particle to be identified with near-complete certainty.

A second neutron source may equally act to limit the experiment's sensitivity. This consists in neutrons generated – even though this occurs in but a small proportion of cases – by high-energy gamma rays from the **uranium** and **thorium** decay chains, these elements being present in the form of traces in the shielding material. This neutron background is a peculiarly formidable issue, insofar as it is practically impossible to gain any protection from it, barring seeking to eliminate all traces of radioactive elements from the vicinity of the detectors, which hardly seems realistic, for an experiment of this type. The strategy to counter this background then consists in achieving a detector structure that is as compact as possible. In such cases, indeed, a large proportion of the events will involve two or more interactions, the interaction length for a neutron in a material such as germanium being a few centimeters. The Italian CUORICINO cryogenic experiment, investigating double beta decay at the **Gran Sasso Laboratory**, has thus produced a highly compact detector structure, where detector mass accounts for 80% of total cooled mass. In such conditions of compactness, neutrons may, for a large proportion of them, be identified from their multiple interactions, whereas WIMPs, for their part, have no chance of interacting twice, owing to their very low rate of interaction.

It is thus apparent that the challenges posed by WIMP detection are many and diverse, requiring that physicists adjust constantly, even as they achieve greater sensitivities, revealing unforeseen backgrounds. The detectors employed in an experiment such as EDELWEISS II have allowed, in the course of a few years, advances to be made, in terms of experimental sensitivity, by a factor of more than 1,000. Looking beyond EDELWEISS II, an experiment such as EURECA, of necessity European or worldwide in scale, will doubtless make it possible to finally pin down the nature of the "dark matter" in the Universe.

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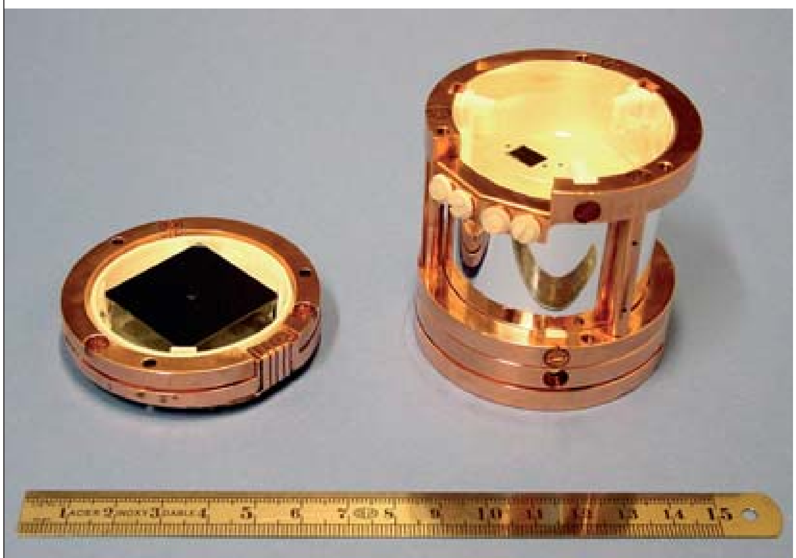


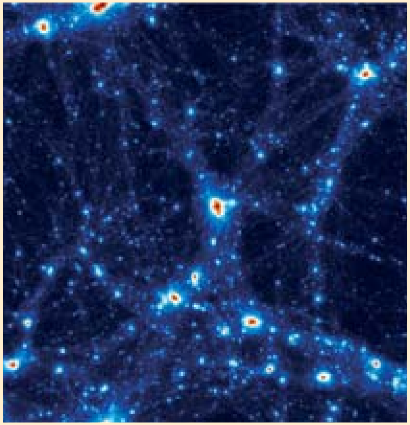
CRESST Collaboration

Prototype detector module for the CRESST II experiment.

A The standard cosmological model

The **standard cosmological model**, i.e. the currently agreed representation of the Universe, is based on a theory of **gravitation**, Einstein's **general relativity**. This model takes into account a degree of expansion of the Universe, as evidenced by the observations made by US astronomer E. P. Hubble, showing that **galaxies** are receding from one another at a rate that increases with distance.
The model's basic assumptions are that the Universe is *homogeneous*, i.e. that it exhibits throughout identical properties (at a cosmological scale, at any rate), and *isotropic*, i.e. its appearance remains unchanged, in whichever direction it is viewed.
Three parameters characterize the evolution of the Universe, in this model: **Hubble's constant**, first, which characterizes its rate of expansion; **mass density** (the ratio of its own density over a *critical density*); and the **cosmological constant**. Introduced by Einstein in the guise of a force acting against gravitation, in order to account for a stable Universe, this constant rather corresponds to the manifestation of the action of *dark energy*, in an expanding Universe. [1]

If mass density is less than, or equal to, 1, that expansion will carry on indefinitely. The latest observations would appear to support a density of matter equal to 1, this implying a "flat" Universe (i.e. one where the sum of the angles in a triangle is precisely equal to 180°).
The current standard cosmological model involved a radius of the observable Universe of some 45 billion light-years, with an age of around 13.7 billion years, as counted from an initial "singularity" (primordial explosion) known as the **Big Bang**, followed, some 300,000 years later, by an uncoupling of matter and radiation, leading to a stage of **inflation**.
The model further makes it possible to account for the **cosmological background** (diffuse radiation), at a temperature of 2.7 K, and for the fluctuations in radiation/density leading, very early on, to the formation of the initial "seed" structures for the galaxies.



D. Aubert/CEA-C. Pichon (IAP)

Numerical simulation of a universe during formation, carried out in the context of the Horizon Project, bringing together, around a program targeted at the investigation of galaxy formation, the numerical simulation activities of a number of French teams, including the DAPNIA team (CEA). Its aim is to gain an understanding of the physical mechanisms leading to the structure and distribution of the galaxies around us – and particularly our own, the Milky Way.

(1) Interpretation of measurements from the WMAP (Wilkinson Microwave Anisotropy Probe) space probe, and from SDSS (Sloan Digital Sky Survey) leads to a value close to 71 (km/s)/Mpc ± 0.03 for Hubble's constant, however surprises as to the value of this parameter remain a possibility, should the disconcerting composition of the Universe, whereby 95% of the Universe is made up of dark matter and dark energy, in fact turn out not to be correct.

D Spectroscopy and spectrometry

Spectrometric methods are subdivided, as a whole, into two main categories, radiation spectrometry – itself comprising absorption spectrometry, emission spectrometry, Raman scattering spectrometry, and nuclear magnetic resonance spectrometry – and mass spectrometry.

Radiation spectroscopy and spectrometry[1] cover a ensemble of analytical methods allowing the composition and structure of matter to be ascertained, based on investigation of the spectra yielded by the interaction between atoms and molecules, and various types of electromagnetic radiation, emitted, absorbed, or scattered by the former.

Depending on their energy, photons interact selectively with the various electron shells, or levels, making up the electronic structure of the atom, or molecule. The electrons involved are *core electrons* (close to the atom's nucleus), for X-rays,[2] *peripheral electrons* (furthest from the nucleus, and involved in chemical bonds) for light absorbed, or emitted, in the near ultraviolet and visible region. In the infrared radiation region, it is the leap from one *molecular vibration* level to another that is involved, the switch from one molecular *rotation* level to another for microwave radiation, and atomic nucleus spin for NMR.

Absorption spectrometry

Those spectroscopy methods that rely on absorption make use of the Beer–Lambert law, setting out the proportional relation between the intensity of light absorbed, and the amount of absorbing matter:

$$A = \log (I_0/I) = \varepsilon\, l\, C,$$

where A stands for the absorbance of the medium traversed, I_0 for incident light intensity, I for transmitted light intensity, ε is the characteristic molar extinction coefficient, for a given wavelength, for the substance investigated – expressed in L mol^{-1} cm^{-1} – while l stands for the thickness passed through, expressed in centimeters, and C is the concentration, in moles per liter.

By measuring the medium's absorbance, for a given wavelength, the concentration of a substance, in a sample, may thus be determined.

In an absorption spectrum, as recorded by means of a spectrometer, *absorption peaks* correspond to the wavelengths the medium is able to absorb. Just as the spectrum from the Sun's light is obtained by making it pass through a prism, which breaks it up, spectrometers analyze the spectral distribution of the whole range of electromagnetic radiations, separating them out according to wavelength, by means of a reflection diffraction grating. Spectra exhibit peaks, each one corresponding to a specific wavelength.

Depending of the type of sample to be analyzed, and the performance level being sought, in the laboratory, absorption spectrometry is used either on molecules in liquid or gaseous phase, or on atomic vapor, obtained through thermal breakdown of liquid or solid samples.

Molecular absorption spectroscopy, in the UV–visible region, affords simplicity of use, however it is only applicable to samples of moderate complexity, since, owing to the width of *molecular absorption bands*, absorption spectra, as a rule, do not allow specific discrimination of every constituent, in a complex mixture.

In infrared (IR) spectrometry, absorption is the outcome of molecular vibration and rotation processes. Infrared absorption spectra thus allow the nature of chemical bonds to be determined, that make up a molecule, by ascertaining the bond's elasticity constant (influencing vibration frequency, as for a spring), thus confirming structural hypotheses.

As the number of atoms increases, the spectrum rapidly exhibits growing complexity, and interpretation becomes highly problematical, especially for organic compounds.

Atomic absorption spectrometry, in this respect, brings higher performance, since absorption by atoms yields very narrow absorption lines. Very precise measurements are thus feasible, even when the sample consists in a complex assembly of chemical elements. Atomic absorption is a reference technique for the analysis of trace elements in a wide variety of samples, in particular for biological samples.

Emission spectrometry

Atoms or molecules brought to an excited state may deexcite by emitting radiation, known as *emission radiation*. When the excitation is caused by selective absorption, by the atoms or molecules to be analyzed, of electromagnetic radiation, this represents a fluorescence emission (or a phosphorescence emission, depending on the electron excitation state involved).

As with absorption, fluorescence may be applied, in the UV–visible radiation region, to molecules, or atoms. X-ray fluorescence spectrometry, on the other hand, refers to the X radiation emitted by atoms excited by absorption of X-radiation. Fluorescence techniques are more complex to implement than is the case for absorption techniques, since they entail that the particle subjected to analysis be selectively excited by a monochromatic radiation. On the other hand, since the radiation emitted is likewise specific to the particle, fluorescence spectrometry involves a double selectivity, resulting in very low background noise, thus making it peculiarly well suited for the measurement of very low concentrations.

Emission of radiation may also occur when atoms are thermally excited, in an environment brought to high temperatures. Emission spectroscopy is based on the fact that atoms, or molecules excited to high energy levels deexcite to lower levels, by emitting radiation (emission, or luminescence). This differs from fluorescence spectrometry in that excitation is not applied selectively, rather it involves indiscriminately all of the particles making up the medium. Emission lines thus correspond to radiation directly emitted by a body brought to a high temperature, and the emission spectrum allows the detection, and quantification, of all atoms present in the emission source.

Raman spectrometry

Interactions between matter and electromagnetic radiation also give rise to scattering processes, such as elastic scattering, and inelastic scattering. Scattering may occur when the interface between

(1) The term "spectrometry," initially used only to refer to recording and measurement techniques, has tended to become synonymous with "spectroscopy," as the eye was supplanted, for observation purposes, by other receptors and instruments, while the visible region now only formed one special region, in analytical terms.

(2) It should be noted, at the same time, that X-ray crystallography is not deemed to be a spectroscopy method, in the strict sense of the term.

D (cont'd)

two media is encountered, or as a medium is passed through. This process, in most cases, is an "elastic" one, in other words it takes place with no change in frequency for the radiation forming the beam involved. Elastic scattering of solar radiation by the atmosphere is, for instance, responsible for the blueness of the sky, observed when the eye is not directed towards the Sun (*Tyndall effect*). Indeed, scattered intensity is all the greater, the shorter the radiation wavelength, which, in the case of the solar spectrum, corresponds to the color blue.
As regards spectrometry, the main use of scattering concerns *Raman spectrometry*. This involves the inelastic scattering of incident radiation by the molecules making up the sample. The difference between scattered radiation frequency, and incident radiation frequency allows the identification of the chemical bonds involved. Raman spectrometry is a technique that is widely used for structural analysis, to complement infrared spectrometry, and mass spectrometry.

Nuclear magnetic resonance spectrometry

The principle of nuclear magnetic resonance (NMR) is based on the fact that an atom has a *magnetic moment*, just like a spinning charge acting as a tiny magnet, governed by quantum mechanics, aligning in a magnetic field as the needle of a compass in the Earth's magnetic field. The principle of NMR consists in inducing, and detecting, the transition, for the nuclear magnetic moment, from the lowest energy level to the highest energy level, through absorption of electromagnetic radiation of a wavelength lying in the radiofrequency region: when the energy of the photon precisely matches the energy difference between the two levels, absorption occurs. Nuclei having numbers of protons, and neutrons that are both even exhibit zero spin. Carbon 12 and oxygen 16 atoms, which are very widespread in nature, thus have zero spin. On the other hand, hydrogen only has one single proton, and its nuclear magnetic moment equals 1/2: it may thus take on two possible energy states, corresponding to the two orientation states of its spin, relative to the magnetic field. Measuring the resonance frequency in the electromagnetic field allowing transition from one of these energy states to the other enables the molecules to be analyzed. This frequency is fixed, however the various nuclei in a molecule do not all resonate at the same frequency, since their magnetic environment is modified by their chemical (electronic) environment.
Many NMR spectra exhibit more peaks than there are protons in the nucleus, owing to the interactions between protons and their neighbors. Two nuclei may interact within the molecule, though they are separated by several chemical bonds: this is known as interatomic coupling. This interaction endows the NMR spectrum with a fine structure.

C. Dupont/CEA

Spectromètre de masse d'ions secondaires utilisé au CEA pour réaliser des mesures isotopiques rapides sur un échantillon par exemple prélevé sur une installation aux activités nucléaires suspectes.

Mass spectrometry

Mass spectrometry is a highly sensitive *detection* and *identification* technique, allowing determination of molecular structures, and thus of a sample's composition. This is not, strictly speaking, a form of spectrometry, since it is not concerned with discrete energy levels. What is its principle? A compound introduced into the device is vaporized, and subsequently ionized by an electron bombardment source (at 70 eV). The ion thus obtained, termed a molecular ion, allows the compound's molar mass to be determined. Breaking chemical bonds within the compound may yield characteristic fragment ions. These are then sorted according to their mass/charge ratio in an *analyzer*, through application of a magnetic and/or electric field, then collected by a *detector*, which amplifies the signal associated to the ions, which arrive with varying delays. A data processing system converts the information from the detector into a mass spectrum, readout of which, by comparing it with reference spectra, allows the identity details of the molecule to be drawn up. Through use of a high-resolution mass spectrometer, the exact mass of the compound may be determined, together with isotope percentages for each constituent atom.
Choice of ionization method is directly related to the nature of the sample, and the type of analysis. If mass spectrometry has gradually adapted to meet the growing demands from chemists, and biologists (separation of increasingly complex, highly polarized mixtures, determination of ever higher molecular masses on samples of ever more constricted sizes), this is essentially due to advances in *ionization techniques*, these including secondary ion mass spectrometry (SIMS), chemical ionization, thermospray ionization, and fast atom bombardment (FAB) sources, further comprising, from the 1980s, matrix-assisted laser desorption ionization (MALDI), and electrospray ionization (ESI), together with advances in *detection techniques*, from time-of-flight (TOF) measurement to "ion traps" (ITs), through quadrupoles (MS or Q).
In proteomics, for instance, only MALDI, ESI and SELDI (surface-enhanced laser desorption ionization) are employed.
Ion mobility spectrometry (IMS) is a chemical analysis technique in the gaseous phase, which consists in subjecting a gas to an electric field. Ionized molecules acquire a velocity that is characteristic for the ion, since this depends on mass, and charge. Arrival of the ions on one of the plates generating the field results in a current, which is recorded. The length of time after which a peak occurs can be related to the nature of the ion causing it.
Scientists often make use of a coupling of devices each belonging to one of the two main families of analytical techniques (see Box E, *What is chromatography?*), e.g. of a chromatograph with a mass spectrometer (or an electron-capture detector [ECD]), particularly for the investigation of trace complex mixtures.

B Fundamental interactions and elementary particles

The **standard model** of particle physics is the reference theoretical framework describing all known **elementary particles** (see Table 1) and the fundamental **interactions** these particles are involved in (see Table 2). The basic constituents of matter, known as **fermions**, are partitioned into two main categories, as determined by their partcipation in the fundamental interactions, or forces (the **gravitational**, **electromagnetic**, **weak**, and **strong** forces), which are mediated by **vector bosons**, the fundamental particles which carry out the transmission of the forces of nature[1] (see Table 2). Whether a particle belongs to the category of fermions, or to that of bosons depends on its **spin** (i.e. its intrinsic angular moment, or internal rotation moment), depending on whether it exhibits half-integer spin (fermions) or integer spin (**bosons**).
At the same time, to every constituent of matter is associated its **antiparticle**, a particle having the same *mass*, but the opposite *charge*. The **positron** is thus the positively charged antiparticle of the **electron**, which exhibits a negative charge.

Leptons and quarks

Fermions include, on the one hand, **leptons**, which may travel freely and do not participate in the *strong interaction*, which ensures the cohesion of atomic **nuclei** (it is consequently termed a *nuclear* interaction), and, on the other hand, **quarks**, which participate in all interactions but are not individually observed, enmeshed and confined as they are within **hadrons**, the particles susceptible to strong interaction, of which they are the constituents.[2]
In the lepton category, **charged leptons** participate in the *electromagnetic interaction* (which ensures the cohesion of **atoms** and **molecules**, and in the *weak interaction* (which underlies **decay** processes, in particular **β radioactivity**).
Neutral leptons, or neutrinos, for their part, participate in the weak interaction only. Exhibiting very low mass, there is one type of neutrino for each type of charged lepton.
Independently from their involvement in interactions, the basic constituents of matter are classified into three *generations*, or *families*, of particles. From one family to the next, quarks and leptons having the same charges only differ by their mass, each family being heavier than the preceding one.
The **electron**, up quark (symbolized *u*) and down quark (symbol *d*), which belong to the first generation, are the lightest massive particles, and are stable. These are the sole constituents of **normal matter**, so-called **baryonic** matter (a baryon is an assembly of quarks), which is made up of **protons** and **neutrons**, this however only accounting for 4% of the Universe's energy content !
Particles in the other two families are heavier, and are unstable, except for neutrinos, which on the other hand exhibit non-zero mass, but are stable.
These latter particles may only be observed or detected in the final states resulting from collisions effected in **accelerators**, or in **cosmic radiation**, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.
According to **quantum mechanics**, for an interaction to take place between particles of normal matter, at least one elementary particle, a boson, must be emitted, absorbed, or exchanged. The **photon** is the **intermediate** (or **vector**) boson for the electromagnetic interaction, the **W^+**, **W^-** and **Z** are the intermediate bosons for the weak interaction, and **gluons** are those of the strong interaction, acting at quark level.
As to the **graviton**, the putative vector for the gravitational interaction, it has not so far been empirically discovered.
The **gravitational force**, which acts on all fermions in proportion to their mass, is not included in the standard model, due in particular to the fact that quantum field theory, when applied to gravitation, does not yield a viable scheme, as it stands. While gravitational effects are negligible in particle physics measurements, they become predominant on astronomical scales.

Interaction ranges

Quarks and charged leptons exchange photons. The photon having no electric charge, these particles conserve their electric charge after the exchange. Since the photon's mass is zero, the electromagnetic interaction has an infinite range. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.
In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: **charged-current weak interaction**, for which the interaction vectors are the W^+ and W^-; and **neutral-current weak interaction**, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (about 80 GeV/c^2 for $W^\pm$, 91 GeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (*flavor*). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.
Only those quarks that have a color charge[1] exchange gluons, these in turn being bearers of a color charge. Thus,

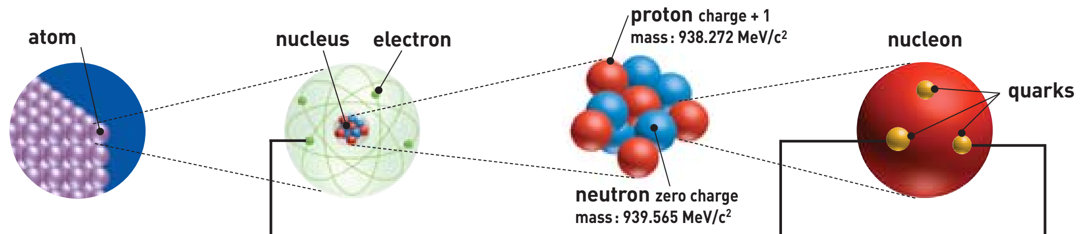
(1) The participation of basic constituents in fundamental interactions is governed by their *interaction charges* (electric charge, color charge), or "conserved quantum numbers." *Color charge*, a quantum number that determines participation in strong interactions, may take one of three values: "red," "green," or "blue" (these colors bearing no relation to visible colors). Every quark bears one of these color charges, every antiquark one of the three anticolor charges. Gluons are endowed with double color–anticolor charges (eight combinations being possible).

(2) To take e.g. **nucleons**: the proton holds two up quarks and one down quark, the neutron two down quarks and one up quark. A **meson** is made up of just two quarks (one quark and one antiquark).

when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact together, which greatly complicates theoretical treatment of this interaction. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The quest for unification

The theoretical framework for the standard model is quantum field theory, which allows a quantitative description to be made of the fundamental interac-



		leptons able to move freely		**quarks** assembled into triplets, or quark–antiquark pairs, to form the many subatomic particles	
Fermions Normal matter is made up of particles from this group.	First family	**electron (e)** responsible for electricity and chemical reactions charge:- 1 mass : 0.511 MeV/c^2	**electron neutrino** (ν_e) has no electric charge, and interacts very seldom with the ambient medium.	**down (*d*)** electric charge: - 1/3 the proton holds one, the neutron two mass : 4 – 8 MeV/c^2	**up (*u*)** electric charge: + 2/3 the proton holds two, the neutron one mass : 1.5 – 4 MeV/c^2
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	Second family	**muon (μ)** a more massive companion to the electron. mass : 105.658 MeV/c^2	**muon neutrino** (ν_μ) properties similar to those of the electron neutrino.	**strange (*s*)** a heavier companion to "up" mass : 80 – 130 MeV/c^2	**charmé (*c*)** a heavier companion to "down" mass : 1.15 – 1.35 GeV/c^2
	Third family	**tau particle (τ)** heavier still. masse : 1,776.99 ± 0.29 MeV/c^2	**tau neutrino (ν_τ)** properties similar to those of the electron neutrino.	**beauty (*b*)** tau particle. mass : 4.1 – 4.4 GeV/c^2	**top (*t*)** heaviest in the family (observed in 1995) mass : 171.4 ± 2.1 GeV/c^2
Vector bosons Fundamental particles carrying out transmission of natural forces.		**photon** elementary grain of light, vector for the electromagnetic force	**gluon** bearer of the strong force between quarks	**$W^{\pm}$, Z^0** bearers of the weak force, responsible for some forms of radioactive decay (W^+, W^-, Z^0)	
Higgs boson?		responsible for "electroweak symmetry breaking"			

Tableau 1.
Table showing the twelve elementary constituents for which the standard model describes the interactions involved. The three charged leptons (electron e-, muon, μ^-, tau particle τ^-) are subject to electromagnetic and weak interactions, neutrinos (ν_e, ν_μ, ν_τ) are only affected by weak interaction, and the six quarks (up, charm, top – or *u*, *c*, *t* – bearing a charge of 2/3; and down, strange, bottom – *d*, *s*, *b* – bearing a charge of – 1/3) are subject to all three interactions. Every elementary constituent has its antiparticle, having the same mass, and algebraic quantum numbers (such as electric charge) of the opposite sign.

B (cont'd)

tions between elementary particles, while respecting the principles of *special relativity*, as those of quantum mechanics. According to the latter theory, if one seeks to observe a microscopic structure at high temporal and spatial resolution, this entails transferring to it an amount of energy–momentum, the greater, the higher the resolution being sought. However, according to the theory of relativity, such an energy–momentum transfer is liable to undergo transformation, yielding particles not present in the initial state: fermions may be generated, or annihilated, in particle–antiparticle pairs, while bosons may be so in any arbitrary number.

All processes involving one and the same fundamental interaction are interrelated. The quantum field theory approach, in which properties of **symmetry** play a fundamental part, seeks to describe all of the processes relating to each fundamental interaction, within overarching theoretical constructions.

The strong and electromagnetic interactions are formalized, respectively, in the theories of **quantum chromodynamics**, and **quantum electrodynamics**. The weak interaction, for its part, is not subject to a separate description, being described jointly with the electromagnetic interaction, in the unified formalism of **electroweak theory**. Theories of the *grand unification* of all fundamental interactions do exist, however they remain as yet lacking any experimental validation.

All the predictions of the standard model have been corroborated by experiment, except for just one, to wit, the existence of the **Higgs boson(s)**, which particle (particles?), it is hoped, will be discovered with LHC. The **Higgs mechanism** is thought to be responsible for the mass exhibited by elementary particles, the eponymous boson making it possible for zero-mass fermions interacting with it to be endowed with mass. This would allow the unification, at high energies, of the weak and electromagnetic interactions within the electroweak theory, while effectively accounting for the **breaking** of this **electroweak symmetry** at low energies, taking the form of two interactions, which may be seen as distinct at that energy level (see *The electroweak interaction from one accelerator to the next: the LHC roadmap and the yardstick of LEP measurements*, p. 23).

Going beyond, or completing the standard model?

The standard model features a set of parameters (such as the masses of elementary particles, or the intensities of fundamental forces) which are "anchored" in experimental findings. It is, in any event, a theory that is liable to be improved, or further elaborated, or even surpassed and left behind. It does not account in any way for the classification of the constituents of matter into three generations of particles, whereas it is precisely the existence of these three generations which makes it possible to account for **CP** (charge–parity) **invariance violation** (meaning that a physical process involving the weak interaction is not equivalent to its own mirror image), a violation that is in all likelihood the source of the matter–**antimatter** imbalance, running in favor of the former, in the primordial Universe. The model neither allows quantum treatment of gravitation, nor does it fully account for the fundamental property of *confinement*, which prevents quarks from propagating freely outside hadrons.

To go beyond, or to complete the standard model, research workers are mainly exploring two avenues:

– **supersymmetry** (widely known as SUSY) would associate, to every particle (whether a boson or a fermion) in the standard model, a partner from the other series, respectively a fermion or a boson. Supersymmetric partners would, at first blush, be highly massive, the lightest of them being a particle interacting very weakly only. This would be an ideal candidate to account for the **hidden matter** (or **dark matter**) in the Universe, accounting as it does for some 21% of the Universe's energy content, the remainder (close to 75%) consisting in a **dark energy**, the nature of which likewise remains to be determined. These WIMPs (acronym for "weakly interacting massive particles") are actively being sought (see *EDELWEISS II, the quest for dark matter particles*);

– the **substructure** path assumes there could be a new level of elementarity, underlying the particles in the standard model (or some of them). This would lead to a veritable blossoming of new, composite particles, analogous to hadrons, but exhibiting masses two to three thousand times heavier.

It should be noted that, whereas supersymmetry theories yield predictions that agree with the precision measurements carried out at LEP, the theories propounding substructures (or their simpler variants, at any rate) fail to do so. As for the more complex variants, these are encountering difficulties at the theoretical level.

fundamental interaction	associated particles (messengers)	actions
gravitation	graviton?	having an infinite range responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic interaction	photon	having an infinite range responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak interaction	W^+, W^-, Z^0	responsible for β^- and β^+ radioactivity, reactions involving particles as neutrinos
strong interaction	gluons (there are 8 gluons)	ensures the cohesion of the atomic nucleus

Tableau 2.
Fundamental interactions, their vectors, and effects.

E What is chromatography?

Chromatography, together with the various forms of spectroscopy and spectrometry (see Box D, *Spectroscopy and spectrometry*), represent the two major basic analytical techniques, the former serving for the separation, the latter for the identification of the constituents of a substance.

Chromatography (from the Greek *khrôma*, "color," and *graphein*, "to write"), allows the *separation* of the constituents of a mixture in a homogeneous liquid or gaseous phase, as blotting paper might spread out in concentric rings a liquid poured onto it.

A chromatograph comprises a sample injection device, a *column*, a detector, and a recording and analysis system. Its principle is based on the equilibrium of compound concentrations, between two phases coming into contact: the *stationary phase*, in the column, and the *mobile phase*, which moves across it. Separation relies on the differential displacement of constituents inside the column, passing through in times that are proportional to their size, or depending on their structure, or affinity for the stationary phase (polarity...). As they reach the far end of the column, a *detector* measures, on a continuous basis, the quantities of each constituent.

The most common form of chromatography is gas chromatography, carried out on gaseous samples, or samples that may be vaporized without incurring breakdown. The mobile phase is a gas (helium, nitrogen, argon, or hydrogen), constantly sweeping through the column, which is placed in a thermostat oven. Detectors allow the selective analysis and identification of highly complex mixtures.

If the stationary phase is a nonvolatile, or not highly volatile liquid, exhibiting solvent properties for the compounds to be separated, the process is termed gas–liquid chromatography, or *partition chromatography*. If the stationary phase is an adsorbent solid (silica, alumina, zeolites, or polymers), this is gas–solid chromatography. Within this same family, of adsorption chromatography processes, liquid–solid chromatography is characterized by its stationary phase, this being a polar solid.

In high-performance liquid chromatography (HPLC), the sample must be wholly soluble in the mobile phase (elution solvent). The latter must be kept at high pressure (hence the alternative name of *high-pressure* liquid chromatography), to ensure a constant flow rate inside the column, and preclude any loss of head. HPLC involves solute–mobile phase–stationary phase exchange mechanisms, based on partition or adsorption coefficients, depending on the nature of the phases in contact.[1]

A chromatographic analysis yields a chromatogram, this being a graphical representation of the evolution of a parameter (intensity of the detector signal), related to instantaneous solute concentration, as function of time. This exhibits *peaks*, rising above the *baseline*, which obtains in the absence of any compounds (see Figure).

(1) There are two further types of liquid chromatography, *ion chromatography*, and *exclusion chromatography*.

N.B: This Box reproduces a number of excerpts from a presentation by Pascale Richardin, head of the Datation Group at the Research and Restoration Center of the French National Museums Administration (Musées de France), taken from the pages dealing with analytical methods, as posted on the site : ttp://www.culture.gouv.fr/culture/conservation/fr/biblioth/biblioth.htm

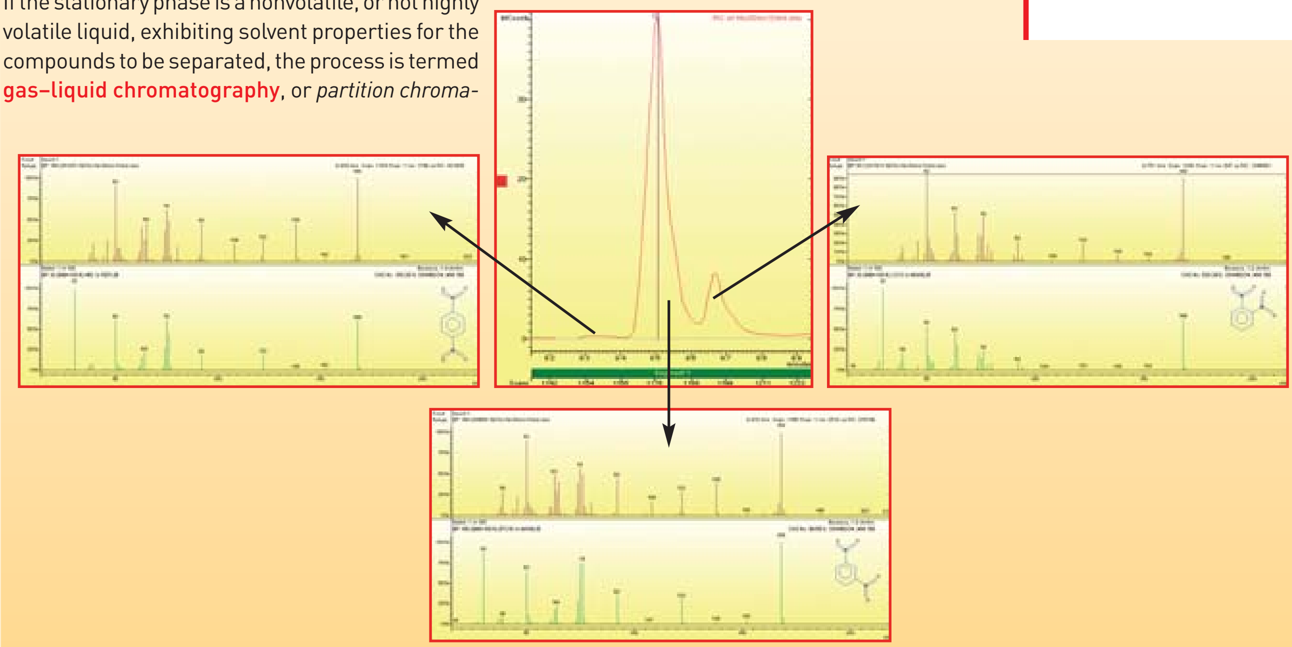


Figure.
An example of the combined use of mass spectrometry and chromatography: the separation of isomers ("sister molecules") of an explosive molecule (dinitrobenzene [DNB]), after solid-phase microextraction sampling, by gas chromatography, and their detection by mass spectrometry (SPME–GC–MS).