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Institut d'Estudis Catalans, Barcelona

The High-Energy Physics Institute of Barcelona (IFAE)*

The science of high-energy physics

The High-Energy Physics Institute of Barcelona (Catalan acronym: IFAE) was created in 1991 by the Generalitat (the Regional Government of Catalonia) with the goal of consolidating and promoting high-energy physics research in Catalonia, particularly on the experimental front. The IFAE is a consortium between the Generalitat and the Autonomous University of Barcelona (UAB). The Institute also has an agreement with the University of Barcelona (UB) that allows personnel of this university working in high-energy physics to conduct research in the IFAE. Thus this institute is made up of its own personnel, and associated members from the UAB and the UB.

Since its creation the IFAE has maintained a broad program of research, both in theoretical and experimental high-energy particle physics. Following the international trend, this program has recently incorporated studies on cosmology and high-energy astrophysics. The IFAE also promotes applied lines of research that take advantage of the technological infrastructure and know-how needed to carry out experiments in high-energy physics, namely detector development for use in medicine, and information technologies, particularly those related to data-intensive applications.

High-energy particle physics and astrophysics (ground or satellite-based) are often called «big-science». The name is unfortunate, for science is neither big nor small. What is indeed «big» is the amount of resources, material and human, needed to carry out experiments in these fields.

Experiments in high energy particle physics are generally performed in high-energy particle accelerators, enormous machines that no single country (except the US, Germany and Japan) can build alone. European countries have pooled their resources (since 1952) to build and operate accelerators in Europe, namely at the international laboratory CERN which is located in Geneva, Switzerland. The accelerators, as their name implies, accelerate elementary particles (protons, electrons and others) to very high energies to subsequently make them collide with each other or with the nuclei (protons and neutrons) of a target material. By studying these collisions, researchers aim to elucidate the structure of matter at the elementary level and the laws that describe the interactions between elementary components. This study requires very large and complex apparatus generically called particle detectors. Typically, teams from various institutions collaborate in the design and construction of these detectors, which are then used at the accelerator site for data collection. Once the data are recorded, these teams work together on their analyses and on the publication of results.

High-energy astrophysics is the study of the energetic particles in the cosmos. Experiments in this field take place at very different locations, such us the top of mountains near telescope sites, the ice deep below the South Pole, or in artificial satellites. Their scope is somewhat broader than that of those carried out at accelerators, and often focuses on the physics of the sources that produce these particles, such as active galactic nuclei, supernova remnants and other galactic or extra-galactic objects. These experiments require appropriate detectors, whether ground-based or on board satellites, which are built with very similar technologies to those at accelerators. Again, several teams from various institutions collaborate in the building of the detectors and in data analyses.

It is clear, therefore, that a significant contribution to high-energy projects requires a team of individuals who can contribute to all the phases of an experiment: detector design, detector construction, data collection and data analysis. Of these phases, only the latter is entirely carried out by physicists. The others are performed by highly specialized personnel made up of physicists and experienced engineers and technicians. Such a team is very difficult, if not impossible, to put together in a typical university department in Spain. At universities where personnel categories are often obsolete for modern research needs. Likewise, the material infrastructure needed to build large detectors also calls for installations and working methods which are not common in Spanish universities. The creation of the IFAE has been fundamental to meet the above challenges.

Some history

Research in theoretical particle physics has been done at the UAB since its creation in 1971, and since even earlier at UB. Between1961 and 1968 this field underwent strong development in Spain, partly because of the country membership of CERN. This development undoubtedly suffered after Spain

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left this international organization in 1968; however, the subsequent creation of the «Grupo Interuniversitario de Física Teórica» (GIFT) helped considerably, both in consolidating what was developed and in further advancing the field. The GIFT organized periodic schools of high international standards and gave grants to young physicists to spend postdoctoral time abroad. At the same time, many positions in universities were filled with theoretical physicists. Consequently, by international standards, theoretical particle physics had, and still has, a good scientific level in Spain.

Experimental particle physics, on the other hand, did not have time to develop during Spain's membership of CERN and practically disappeared when Spain left the organization. Only very small groups, at the «Junta de Energía Nuclear» (now CIEMAT) in Madrid and at the «Instituto de Física Corpuscular» (IFIC, joint center CSIC-University of Valencia), maintained some activity, mainly in data analysis. Experimental particle physics was almost non-existent in universities; however, in the early seventies this situation started to change. The experimental group at the CIEMAT, in particular, made a considerable effort to establish international collaborations that paved the way for Spain to rejoin CERN in 1982.

The decision to rejoin was accompanied by a plan to develop high-energy physics in Spain. The so-called «Plan Movilizador de la Física de Altas Energías» was drawn up in 1984 by the «Comisión Interministerial de Ciencia y Tecnología» (CICYT). This plan was in fact a precursor of the «Plan Nacional de Investigación Científica y Desarrollo Tecnológico» (National Plan for Scientific Research and Technological Development) in which it was integrated when the latter was launched in 1987. The «Plan Movilizador» proposed the creation of new experimental groups in several universities in Spain. The Ministry of Education contributed to the start-up of three new groups by creating three positions that were offered to experienced Spanish physicists working outside Spain.

The UAB decided to host one of these groups which became operational in 1985. Scholarships were also given to recent graduates to go abroad to complete their doctoral degree in experimental high-energy physics. The group at the UAB soon joined an experiment which was being prepared for the LEP (Large Electron Positron collider) accelerator at CERN, which was then under construction. This experiment, named ALEPH, brought about the development of the group. The ALEPH experiment began data collection in 1989, immediately after the start of the LEP accelerator, and soon after several individuals completed their doctoral degrees at the *UAB* on subjects studied in the experiment. By 1991 the group had become established in ALEPH and the number of people working in the group, including doctoral students, grew to about 15. It became clear, however, for the reasons explained at the beginning of this article, that in order reach a critical mass of permanent personnel and to fully establish itself in the international context the group needed another organizational structure.

In 1991, the President of the Generalitat, accompanied by two ministers of his government, visited CERN; a visit which spurred the decision to create the IFAE. As mentioned in the Foundational Act it was the existence of the experimental high energy physics group at the UAB and of theoretical groups in Catalunya, the desire to strengthen research in High Energy Physics, particularly on the experimental side, and the desire to collaborate in the effort of the Spanish Government to develop the field, that led the authorities to create the IFAE.

The structure of the IFAE

The goal of the Institute, as stated in its Charter, is to carry out research and to contribute to the development of both theoretical and experimental high-energy physics in Catalonia. Legally, it was created as a consortium between the Education Department of the Generalitat and the UAB. As a consortium, the IFAE is an independent organization governed by its own statutes. The Institute also holds the status of a «University Institute» associated to the UAB, thus allowing its personnel to participate in the educational program of the university at the doctoral level.

The Institute is governed by a Board and by a Director. The general research lines, the hiring of personnel, the annual budget and the creation or suppression of Divisions are among the responsibilities of the Governing Board, which also appoints the Director from a list of candidates nominated by the Rector of the UAB. The Director is responsible for the execution of the decisions of this Board. The Coordinators of the Divisions are nominated by the Director and are appointed by the Board.

The Institute is staffed by personnel directly hired by the Institute itself and by personnel who belong to the two parts of the consortium (UAB and Generalitat). The latter work in the field of high-energy physics and are incorporated, on a voluntary basis, as associate personnel. The Institute has an agreement with the UB by which the members of this university working in the field of high-energy physics can also become associate personnel of the Institute.

The IFAE is structured into two Divisions: Theoretical and Experimental. At present the former has about 20 faculty members, 5 to 10 postdoctoral fellows and 15 graduates, roughly half from UAB and half from UB. All the members of the Theoretical Division are associated personnel, and thus are not directly hired by the Institute. The Experimental Division is composed of 8 senior physicists (3 faculty members of UAB and 5 hired directly by the IFAE), 2 senior engineers hired by the IFAE, between 5 and 10 postdoctoral fellows and visiting scientists, about 15 graduates and between 5 and 10 technicians and other support personnel.

Scientific program

Research in the Theoretical Division covers a broad spectrum of high-energy theoretical physics, which ranges from phenomenology of the Standard Model to Cosmology. Indeed the main avenues of theoretical research include:

a) Effective field theories, heavy quark physics and low energy QCD
b) Electro-weak phenomenology and Higgs physics
c) Lattice gauge theories
d) Formal aspects of field theory and field theory at finite temperature
e) Quantum computation
f) Supersymmetry
g) Astroparticle physics
h) Quantum field theory in curved space-time and cosmology.

No further description of these topics, which are at the forefront of research in physics, is given here because of space limitations.

The theoretical groups at the UAB and UB are involved in various European Networks and international collaborations. Many researchers from abroad come on short-term visits each year, and many seminars are organized, typically 50 per year, at each university. Scientific production is also extensive, about 40 articles are published annually in International Journals.

The experimental division is involved in several international experiments, which are only described briefly here.

The first large project at the IFAE, now nearing its completion, was the ALEPH experiment at the LEP accelerator. The LEP *(already defined on page 3)* was the «flag-ship» accelerator of CERN from its inauguration on the 14^{th} July 1989 to its shut-down on 2^{nd} November 2000. In the LEP accelerator, electrons and positrons are accelerated to very high energies (around 90 GeV total center of mass energy in the first phase of LEP from 1989 to 1995, and up to 209 GeV shortly before its shut-down) and then made to collide head on. Analysis of these collisions has shown that the so-called Electro-Weak Theory, developed over the last 25 years from an impressive number of experimental measurements to explain the properties of weak and electromagnetic interactions, works precisely and consistently up to the highest energies attained in LEP. The measurements taken by ALEPH (and by the other 3 experiments carried out at LEP) have exceeded the foreseen precision and have tested the Electro-Weak Theory up to the per mil level. This is an impressive legacy that will remain valid for many years. Some of the more precise measurements of strong interactions, which are described by a theory called QCD (Quantum Chromo Dynamics), as well as of many other properties of elementary particles, have also been performed at ALEPH. The Electro-Weak Theory and the QCD theory constitute the so-called Standard Model of fundamental interactions. The LEP accelerator will be remembered for establishing the Standard Model as a true theory, and for proving that it can explain results with great precision.

The IFAE (and its precursor group at UAB) made substantial contributions to ALEPH. On the technical side, the Institute built a sub-detector to measure the luminosity of the LEP accelerator at the ALEPH interaction point (luminosity is a measure of the number of electron-positron collisions taking place at the center of the detector), denominated BCAL. It also conceived and configured a system of computers (workstations) which processed the large amount of data produced by the detector (the system was called FALCON). There were two versions of BCAL, one for the first phase of LEP (from 1989 to 1995) and one, called BCAL++, for the second phase. A photograph of BCAL++ is shown in Figure 1. The IFAE also contributed to the analysis of the ALEPH data, in particular to the precision measurements of the parameters of the Electro-Weak Theory, including the masses of the Z and W bosons, and to measurements of properties of the tau lepton and of the strong interaction. A total of 20 doctoral theses have been presented in Barcelona on different aspects of the ALEPH experiment and two more will be presented shortly, thereby ending our involvement in this experiment.

In preparation for the future CERN major accelerator, the LHC (Large Hadron Collider), the IFAE is now participating in the ATLAS experiment. At the LHC, protons will be accelerated to energies of 7 TeV and made to collide with each other, giving a center of mass energy of 14 TeV, the highest energy ever achieved in a controlled way (cosmic ray particles can be even more energetic). The motivation to do experiments at these very high energies comes from the fact

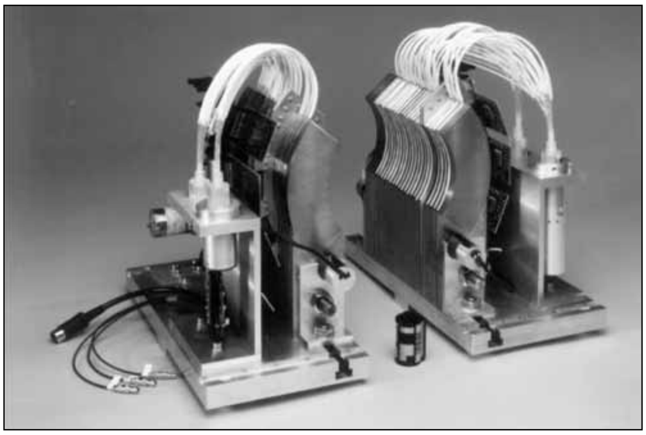

Fig. 1. Photograph of two of the four modules of the BCAL++ subdetector. The modules are mounted on each side of the LEP accelerator beam pipe. They are made of alternating layers of Tungsten and plastic scintillator. When electrons and positrons enter the front face of the Tungsten they interact and produce a «cascade» of secondary particles, consisting of electrons, positrons and photons. The charge particles of the cascade, the secondary electrons and positrons, produce light when passing through the plastic scintillators. The light is collected by scintillating fibers that are bundled and inserted into photo-multiplier devices that convert the flashes of light into electronic pulses. The total charge of the pulse is proportional to the energy of the original particle. At the maximum of the cascade there is a plane of silicon pads. The silicon layer, 300 microns thick, is polarized in such a way that the passage of charged particles also produces a small current which is collected on the surface of the silicon, and electronically amplified and treated to be transmitted, together with the signal from the photo-devices, to other electronic modules located over 30 meters away, outside the detector area. The optical fibers, the cylindrical case housing the photo-devices and the silicon electronics are visible in the photograph. The detector was conceived, designed and built at the IFAE.

that, despite its great success, the Standard Model, has not been fully tested, and, moreover, cannot be a final theory. There are too many parameters, and unexplained relations that point in several possible directions «beyond the Standard Model». It is expected that at the LHC energy scale, new phenomena will be detected and will clarify the direction towards a more complete theory. After many considerations, an international consensus to build the LHC has emerged. There will be two major general-purpose experiments at the LHC, ATLAS and CMS, and two more specific, but also very large experiments, ALICE and LHC-B.

Since 1993 the IFAE has been heavily involved in R&D, design, prototyping and construction of one of the ATLAS sub-detectors called the Hadronic Calorimeter (also known as the Tile Calorimeter, or TileCal, for short). This sub-detector aims to measure the energy deposited by the particles generically called hadrons, produced in the proton-proton interactions of the LHC. The detector consists of three «barrels», each made of 64 modules. One of these barrels, that is a set of 64 modules, is partially produced and completely assembled at the IFAE. Twenty four research institutions worldwide collaborate in the building of TileCal. After their assembly at the IFAE, and, after a first verification of their performance, the modules (Figure 2) are sent to CERN for final assembly of the ATLAS detector. So far more than 90 % of the modules, each weighing about 12 tons, have been completed and shipped to CERN. In addition to the production of the modules, the IFAE is also involved in computational aspects related to the on-line selection of the appropriate proton-proton interactions, and in the preparation of the physics analysis of the ATLAS data.

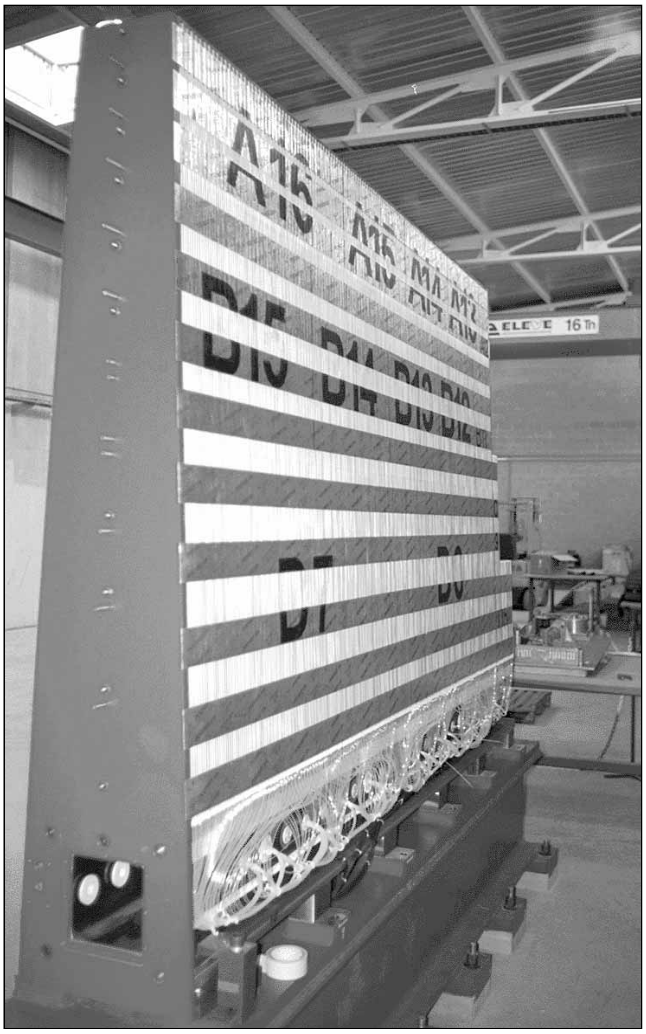

Fig. 2 Photograph of one of the TileCal modules assembled at the IFAE being prepared for shipment to the CERN laboratory in Geneva, Switzerland. The module, with a weight of about 12 tons, is also a calorimeter made of many small plates («tiles») of iron interspersed with plastic scintillator. The light generated in the scintillator is collected by scintillating optical fibers, grouped in a way which is convenient for the later analysis of the energy deposition in the modules. The square cavity with the end visible on the lower left-hand corner houses a long structure where the photo-devices and all the corresponding electronics (not shown in the photograph) are located.

A third project underway at the IFAE is the MAGIC experiment (the acronym of Major Atmospheric Gamma Imaging Cherenkov Telescope), which will study high-energy cosmic gamma rays. The aim is to study the sources of gamma rays in the until now unexplored energy range between 20 and 200 GeV. The «detector» of this experiment is an imaging Cherenkov telescope that consists of a «reflector» made of an array of almost 1000 square mirrors (each measuring 0.5mx0.5m) which make up a 17-m diameter parabolic reflecting surface. The mirrors reflect the Cherenkov light created by the cascade of particles produced by the incoming gamma ray when it hits the upper layers of the atmosphere above the telescope. The light is reflected towards a camera located at the focal point of the parabolic surface. The first version of the camera is being made of an array of conventional photo-multiplier tubes, which, in future versions, will be changed to other photo-devices of high quantum efficiency with red-extended sensitivity.

Figure 3 shows a photomontage of what the telescope will look like once installed at the site in the Roque de los Muchachos on the Island of La Palma, in the Canary Islands. The IFAE is responsible for the design and assembly of the cam-

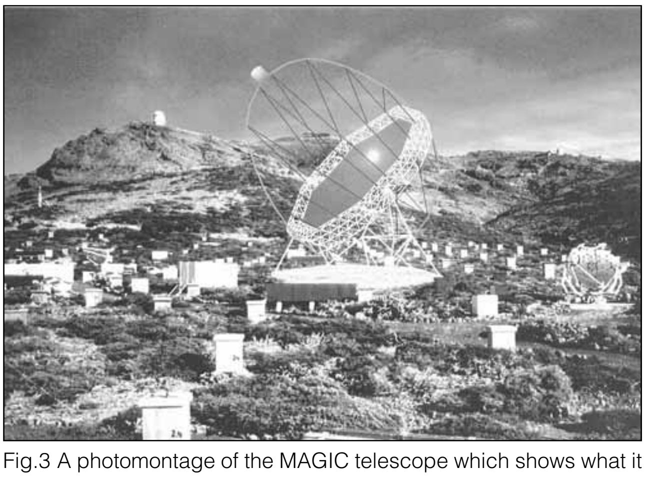

Fig.3 A photomontage of the MAGIC telescope which shows what it will look like once mounted at its location in the Roque de los Muchachos, 2400 meters above sea level on the Island of La Palma. One can see the parabolic shape of the reflector and the camera, which hangs over the reflector at its focal point. The rest of the figure is a photograph of the site. The small telescope visible on the right of the photograph is at present recording data and can be considered as a prototype of the much larger MAGIC.

era, together with all the corresponding electronics contained in a cylinder of about 1.5m diameter and 70 cm height. The Institute is also taking the responsibility of constructing the building that houses the control room and all the equipment of the telescope. The experiment is now underway and its set-up is scheduled for the winter of 2001-2002. (The construction can be followed through a WebCam at http://161.72.7.34/view/view.shtml).

As mentioned in the introduction, a new line of research in applied physics, namely in the application of high-energy physics instrumentation for use in medicine, is also being promoted. In this context, a project has been launched in the development of a digital X-ray detector, able to produce a radiological image of quality similar to that of conventional film but with slightly better contrast and a considerably reduced X-ray dose. The detector consists of a high-density semiconductor directly coupled to a pixelated chip, which has been specifically developed for this application. This project, in which the IFAE is the coordinating institute of an international collaboration consisting of six laboratories, has been submitted for funding to the European Union and has been approved.

The projects described here are those being carried out at present. However, as in any research institution, new ideas are continually under discussion and, given the appropriate circumstances, could become future research lines.

Conclusions

The creation of the IFAE almost ten years ago has had a great impact on research in experimental high-energy physics in Catalonia, in that it has allowed a research team entirely based in Barcelona to fully participate, as an equal partner to other European groups, in a forefront field of research. This is not a minor accomplishment, since experimental sciences, in the modern sense of the word, have never been part of the intellectual or academic tradition in Spain, and physics in particular, which is in many respects the prototypical experimental science, has not been an exception. The impact has not been due to the amount of financial resources used, but rather to other qualitative aspects. In particular, it has been possible to hire scientific personnel at the highest level outside the rather inflexible structures of the more traditional academic and research institutions. Moreover, it has also been possible to make rational short– and mid-term plans for a research program. These aspects are crucial for any scientific research, including the field of high-energy physics.