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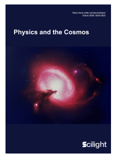

Review

The Rise of Astroparticle Physics

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Abstract: Astroparticle is a relatively young but broad field of physics. It links particle and nuclear physics, astrophysics and cosmology, in a fruitful cross-fertilisation both of theoretical ideas and experimental techniques. The latter have been transferred, with adaptation, from accelerator-based experiments, such as charged-particles tracking, gamma-ray detectors, calorimeters, cryogenic techniques. The most diverse observatories have been developed, on the Earth's surface and deep underground, beneath the Oceans and the ice of South Pole, on high-altitude mountain plateaus, and in space, on dedicated satellites and on the International Space Station. In this article the rise of astroparticle physics will be described, on a number of examples, including elements concerning the origin of the name and on the scientific policy actions that guided the process at both community and government levels.

Keywords: cosmic rays; gamma rays; neutrino telescopes; underground laboratories; nuclear astrophysics; neutrino oscillations

1. Introduction

The histories of the names tell us much about the concepts they represent, and we shall start with that of "astroparticle" in Section 2. The earliest astroparticles, not originally called so, are the cosmic rays, the study of which initiated subnuclear physics and are now messengers of the very high energy astrophysics, discussed in Section 3. In Sections 4 and 5 we shall see how deep sea and deep ice neutrino observatories and underground laboratories were developed. Two examples at the birth of X-ray and gamma-ray astronomy are given in Section 6. In Section 7 we shall see how, in a somewhat unexpected way, underground laboratories contribute to nuclear astrophysics. Finally, in Section 8, the most relevant scientific policy actions in the creation of the discipline are discussed.

2. Birth of a Word

Astroparticle Physics lies at the intersection of particle physics, astrophysics, and cosmology. For centuries, astronomers have studied the Universe using electromagnetic messengers: initially visible light, then more components of the spectrum, from X-rays to microwaves. Elementary particle physics initially developed studying cosmic rays, high energy protons and nucleons, till the mid-1950s when proton accelerators reached multi-GeV energies. Later still, the exploration of the Cosmos with γ rays required techniques developed by particle physics at accelerators, to be transferred and adapted to the observation of the sky, from the surface of the Earth, from balloons and space missions. A similar situation holds for non-electromagnetic messengers, such as charged cosmic rays (protons, nuclei and electrons), neutrinos and, more recently, gravitational waves. Clearly, different messengers bring us different pieces of information from the Cosmos, in particular on violent phenomena, like, for example gamma ray bursts or binary black holes merging, but also unique data on particle physics. Indeed, astroparticles are the only ones that can teach us of subnuclear physics at energies larger—indeed much larger—than those reachable with accelerators. Just to give some examples, astroparticle physics studies the physics of the early universe, baryogenesis, dark matter, dark energy, neutrinos from the Sun and from supernovae, black holes and neutron stars, etc. It should be recalled, on this context, that the only measured evidence we have of physics beyond the standard model are neutrino oscillations discovered in atmospheric neutrinos and the neutrino flavour conversion in matter (called MSW effect) discovered in solar neutrinos. For one of the fundamental forces of nature, gravity, we do not have a quantum theory, but only its macroscopic approximation called general relativity. Since gravity is by far the weakest interaction at the present temperature of the Universe, quantum effects are completely negligible. However, extremely high energies phenomena, such as occurring in the black holes, might teach us something. The discipline includes also the study of extremely rare processes, which may be indirect messengers, once more, of extreme high energies.

In short, astroparticle physics seeks to understand the smallest components of matter and their role in shaping the largest structures and phenomena in the universe.

In a scientific meeting, the term "astroparticle physics" appears for the first time in 1987 as the "First International School on Astroparticle Physics" [1], held at the Ettore Majorana Foundation and Centre for Scientific Culture at Erice. It ran for three weeks, from 5 to 25 January, under the leadership of Antonino Zichichi. The poster of the School stated:

Recent progress in particle physics, cosmology and astrophysics has given birth to a discipline that encompasses them all. These embryonic developments are not often covered in an interdisciplinary way. The purpose of this school is to cover this gap.

The School was attended by about on one hundred participants, teachers and students, with lectures ranging from surveys of the status, experimental and theoretical, of particle physics and of the cosmological models, to the formation and evolution of cosmic large scale structures, including hypothetical ones, such as cosmic strings, to the violent phenomena in the Universe, to the primordial abundances of the light elements.

The immediate predecessor of the term "astroparticle physics" was "particle astrophysics", which in turn mirrored the term "nuclear astrophysics".

As a matter of fact, the necessity of nuclear physics to understand how the stars shine and evolve was immediately evident since the first years of the non-relativistic quantum nuclear theories, with Enrico Fermi, Hans Bethe, George Gamow and others. However, after this "prehistory", the birth of "nuclear astrophysics" can be traced back to 1957, the year of two founding articles: the famous B^2FH paper by Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle, Synthesis of the elements in stars [2], in which the abundance of the elements in the Universe was calculated for the first time, and the writeup of a series of lectures delivered by Al Cameron at Purdue University in March–April 1957 on Stellar evolution, nuclear astrophysics, and nucleogenesis [3], where the term appears for the first time.

Starting in the 1960s, it became increasingly clear that violent phenomena take place in the Universe, at energies much larger than the MeV scale typical of nuclear physics. And, in parallel with the development of the Standard Model of subnuclear physics, "particle astrophysics" took shape. In theory, cross-fertilisation developed in several places, in particular at Caltech with William Fowler and his school, including Gary Steigman, David Schramm, John Bahcall, Richard Bond, George Fuller, Edward "Rocky" Kolb and others. And the term "astro-particle physics community" appears for the first time in 1984, as used by Steigman in a review of the book "The very early universe" edited by G. W. Gibbons, S. W. Hawking and S. T. C. Siklos [4]. However, the term did not gain acceptance in the community for many years, in which the discipline was still referred to with negative terms such as "non-accelerator particle physics" and "passive physics".

3. Cosmic Rays

Cosmic rays are high-energy particles reaching the Earth from space. In the strictest sense of the term, as considered in this section, they are electrically charged. More generally, the term includes also neutral particles, γ-rays (Section 6) and neutrinos (Section 4). Charged cosmic rays consist mainly of protons, helium, a small fraction of heavier nuclei, and electrons. They are produced by galactic and extragalactic sources able to accelerate them to the highest energies up to 10^{20} eV and beyond, with a spectrum decreasing with energy over more than 30 orders of magnitude. This "primary" radiation, entering the atmosphere and hitting its nuclei produces "secondary" radiation—mesons and baryons. These are unstable and decay into other hadrons, charged leptons and neutrinos.

A substantial literature exists on the history of cosmic rays. Here we shall simply recall how and when they were discovered (for details see [5]), their fundamental role in particle physics before the advent of proton accelerators operating at GeV-scale energy, and their unique role as messengers of very high energy cosmic phenomena today. Astroparticle physics indeed.

In the early years of the twentieth century the observation that a charged electroscope rapidly discharges when a radioactive source is brought close to the instrument led to the conclusion that the spontaneous discharge is due to penetrating radiation. The discharge rate was then used to measure the level of radioactivity. This was initially believed to be due to nuclear decays in the rocks. This remained the view till 1911.

From 1907 to 1911, Domenico Pacini (1878–1934), a meteorologist, performed campaigns of ionisation rate measurements (Figure 1 Left) at different altitudes on the mountains, over a lake and over the sea. Noticing substantial differences between the sites, in 1910 he concluded that the soil could not be the only source of the penetrating radiation. In 1911 he had the decisive idea of measuring under the surface, immersing an electroscope at a depth of 3 m in the sea, near Livorno at 300 m from the shore. The radioactivity was reduced, by about 20%, but did not disappear. He concluded that the radiation was coming from outside and was absorbed by the water (this being the start of underwater and underground experiments) and that a sizable cause of ionisation exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the soil [6].

Figure 1. Left: Domenico Pacini looking into an electroscope. Wikimedia Commons. **Right**: Victor Hess in preparation of a balloon ascension. Wikimedia Commons.

In the same year, 1911, Victor Hess (1883–1964) measured the dependence of radioactivity on the distance from the ground with two high altitude ascents in a balloon (Figure 1 Right), up to 1300 m, again measuring the discharge rate using specially developed electroscopes. He did not observe any effect. The discovery came the next year, when he performed seven ascents, the last reaching 5200 m. This time he found that the ionisation rate decreases slightly during the first kilometre ascent, reaches a shallow minimum and then increases rapidly. He concluded that, at sufficiently high altitudes, when the radiation from the ground has been absorbed, the observed radiation originates from above. It has to be of extra-terrestrial origin [7]. It will be called "cosmic rays" by Robert Millikan in 1925 [8].

With the discovery by James Chadwick of the neutron in 1932, the constituents of our matter—proton, neutron, electron and photon—were known. The discoveries of "new" leptons and hadrons will be in cosmic rays.

In 1932, Carl Anderson discovered the positron, the first antiparticle [9].

In 1937, Jabez Street and Edward Stevenson [10] and independently Carl Anderson and Seth Neddermeyer [11,12] discovered the muon, at sea level. Its lifetime, about 2 μs, is long enough to traverse the entire atmosphere.

In 1947, George Rochester and Clifford Butler [13], discovered the first "strange" particles.

In 1947, Giuseppe Occhialini, Cecil Powell et al. [14] discovered the (charged) π meson, the mediator of the nuclear force, in the Mt. Chacaltaya Cosmic Ray Laboratory at an altitude of 5200 m in Bolivia.

In 1953, cosmic ray experiments flying balloons at high altitudes gave rise to the θ-τ puzzle, which will be solved with the discovery of parity violation.

When proton accelerators reached the multi-GeV energy level, with the Bevatron at Berkeley in 1954, the field shifted to artificial beams. The antiproton was discovered in 1955.

The research in elementary particles using cosmic rays, practically extinct in the West, survived in the East, with constant developments in Japan; to the extent that a new long-lived hadron was discovered in 1971 during an exposure flown at high altitude on a Jet Cargo aircraft of the Japan Air Lines by Kiyoshi Niu (1930–2023) and collaborators [15]. The group had developed a technique, called Emulsion Cloud Chamber, based on "vertical" emulsion plates, i.e., perpendicular to the mean direction of the tracks, for sub-micrometre resolution. Such plates were assembled in complex sandwiches together with lead plates and plates of other materials. They observed the event of associated production of two particles shown in Figure 2. The primary interaction has all the features of a strong interaction. Two particles decay, after 1.38 cm and 5.14 cm respectively, corresponding to proper times of order of several 10^{-14} s. Therefore, the two particles are produced in association and decay weakly. The primary particle had an energy of several TeV, as evaluated by the measured energies of the secondary particles. Niu dubbed the particle decaying in point (B) in the figure as "*X*" and evaluated its mass to be 1.8 GeV if it was a meson, 2.9 GeV if it was a baryon. A few months later, Shuzo Okawa and collaborators [16] reached the conclusion that *X* possessed a new quantum number, beyond isospin and strangeness, now called charm. For a historical recollection see Discoveries of naked charm particles, and of lifetime difference among charm species carried out using Compact ECC (Emulsion Cloud Chamber) by K. Niu [17].

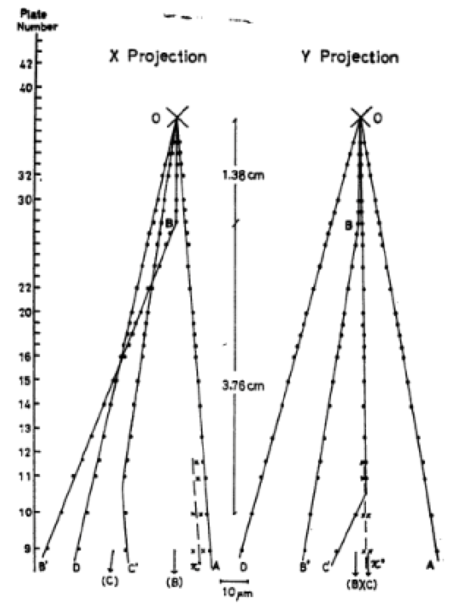

Figure 2. The first associated production of charm particles. The vertical axis is the number of the plate in the detector sandwich. Niu et al. A possible decay in flight of a new type of particle [15], with permission of the Physical Society of Japan.

Strangely enough, in retrospect, the discovery remained largely ignored in the West. In 1974, the first bound charm-anticharm meson, called J/ψ, was discovered independently by Burton Richter et al. at the SLAC e^+e^- collider and by Samuel Ting et al. at the Brookhaven proton accelerator.

In the last decades the study of cosmic rays has become a powerful tool for studying violent phenomena in the Universe. Techniques developed in particle experiments at accelerators, like tracking chambers, calorimeters for energy measurement, time-of-flight systems with sub-nanosecond resolution, have been adapted to these observations. These instruments have been flown at very high altitudes with balloons and later in space missions. The energy spectra and the composition—protons and heavier nuclei—of cosmic rays from about 100 MeV to several TeV are measured. Unlike laboratory experiments, the mechanical structure of space detectors must cope with the harsh launch environment and, once in orbit, a far from friendly environment for the apparatuses, must operate without maintenance for many years. Stringent qualification procedures and risk analyses defined by the Space Agencies must be followed.

The first particle spectrometer was PAMELA, launched on board the Russian Resurs-DK1 satellite on 15 June 2006. The experiment, which successfully collected data for a decade, was an effort of the WiZARD Collaboration, which, starting in the 1980s under the leadership of Robert Golden (1940–1995), had successfully built and flown a series of balloon-borne, and later satellite-borne, experiments. The Alpha Magnetic Spectrometer (AMS) followed, under the leadership of Samuel Ting. With an acceptance two orders of magnitudes larger than PAMELA's, it was deployed on the International Space Station in May 2011, designed to take data for the entire lifetime of the ISS. AMS is collecting up to about 10^9 nuclei and isotopes (D, He, Li, Be, B, C, …, Fe) accurately measuring their spectra, detecting anti-nuclei if they exist, searching for dark matter and for signatures of unknown phenomena.

Above several TeV energies the cosmic ray flux becomes too low to be studied in space. The extreme energies are today studied on ground with very large detector arrays, like the Pierre Auger Observatory covering a 3000 km^2 area in the Argentine pampas at 1400 m altitude.

4. Neutrino Telescopes

At the end of the 1950s Moisey Markov (1908–1994), Head of Nuclear Physics Division of the Academy of Sciences of the USSR, was the first to propose the possibility to perform experiments using both artificial and natural neutrino beams. He assigned two PhD theses, to Docho Fakirov On interactions of the high-energy cosmic ray neutrinos with a substance [18] and to Igor Zheleznykh On possible studies of high-energy neutrino interactions at accelerators [19–22]. In hindsight, the quantitative estimates of the fluxes appear quite well approximated (Thanks to S. Petcov for a translation from Bulgarian of parts of the Fakirov thesis), but twenty-six years later, at the 17th International Conference of History of Science, Markov recalled to have submitted in 1959 a report on the topic "On the high-energy neutrino physics" to the International Conference on High-Energy Physics in Kiev. But, after negative reactions of a few colleagues and of the convenor of the weak interactions section, who asked "Are you serious?" (Zheleznykh and Markov had assumed in their calculation that the neutrino total cross section would continue to increase linearly with energy as observed at lower energy, in retrospective rightly, but the majority of theorists thought that instead it had to saturate at several GeV), Markov withdrew the report [23].

It was understood in the 1970s that a neutrino "telescope" had to be deep, 1000 m or more. The signal consists, as proposed by Markov, in the observation in an underground detector of the Cherenkov light produced by charged secondaries from neutrino interactions, using the Earth as a shield. The background is made up of atmospheric neutrinos coming from above, which occasionally fool the detectors and appear to come from below, and must be sufficiently attenuated. In 1980, Alexander Chudakov (1938–2005) proposed installing an observatory in Lake Baikal, which is 1.3 km deep, has very clear water, and allows chains of optical units to be lowered from the ice surface, which is thick enough in winter to reach the site by lorry. The construction of the Baikal Underwater Neutrino Telescope (BUNT) was, from the very beginning in the 1990s, directed by Grigory Domogatsky (1941–1924).

In parallel, in the same years, the 1970s, John Learned was pushing for neutrino astronomy, launching the DUMAND project, a km^3 detector, to deploy strings of optical units in the Pacific ocean near Hawaii. Deploying one-kilometre-long strings of photodetectors to a few kilometres depth, with the necessary cables to provide electrical power to the photomultipliers and service electronics, and to read out the signal, in the middle of the ocean is a very complex and risky operation. DUMAND was initially supported by the US Department of Energy, but, unfortunately, the project was terminated in 1995, prior to starting the full deployment [24]. However, its ideas were fundamental for the next steps.

The next step was the proposal put forward in 1988 by Francis Halzen and collaborators [25] of a neutrino telescope at the South Pole, deploying the optical units strings in deep "pits" drilled into the ice with hot water. The project, named Antarctic Muon and Neutrino Detector Array (AMANDA), with a volume of about 6 million cubic metres, was successful, and in 2005, after nine years of operation, became part of its successor, the IceCube Neutrino Observatory, which reached a cubic-km instrumented volume in 2010. Extragalactic neutrino sources of extremely high energies (several PeV) started to be observed.

The first proposal of a neutrino observatory in the Mediterranean Sea, NESTOR, was advanced by Leonidas Resvanis, building on the experience of DUMAND and BUNT, in a 3800 m deep site close to the coast of Pylos, in the Peloponnese. Surveys of the sea floor were conducted between 1989 and 1991. In 2003 a prototype was deployed and data were collected. The project, however, lacked sufficient resources.

The NESTOR collaboration initially included scientists from France and from Italy. The French component abandoned the collaboration and in 1997 Jean-Jacques Aubert and Luciano Moscoso proposed the ANTARES project, to deploy a neutrino observatory in France, off the coast of Toulon of about ten million cubic metres. Its construction was completed in 2008 and data taking finished in 2022.

In 1998, the NEMO proposal for a cubic-km detector was put forward in Italy under the leadership of Emilo Migneco. Sea campaigns, started in July 1998, identified as the best candidate a site offshore of Capo Passero, the South-East "tip" of Sicily about 3500 m deep in a wide plateau. In the years 2004–2007 the so-called "Phase-1 apparatus" was built and operated, testing the deep sea main technological solutions developed by the collaboration for the construction of a km^3-scale neutrino telescope.

In the 2000s, the three Mediterranean neutrino telescope projects ANTARES, NEMO and NESTOR joined forces to develop, construct and operate a km^3-scale neutrino telescope in the Mediterranean Sea. Starting in 2006, a three-year EU-funded Design Study was developed, followed by the "preparatory phase" studies KM3NET-PP, still funded by EU, from 2008 to 2012 [26], in which technical aspects, legal status, governance, etc. were developed. A Technical Design Report was published in 2010 [27]. In July 2016, the KM3NET Collaboration finally presented a "Letter of Intent for ARCA and ORCA" [28], where the former, Astroparticle Research with Cosmics in the Abyss, is designed for the study of very high energy cosmic neutrinos, complementing IceCube in the Northern Hemisphere, to be deployed off shore of Capo Passero with a cubic kilometre volume, and the latter, Oscillation Research with Cosmics in the Abyss, will be dedicated to the study of oscillations in the atmospheric neutrinos, to be deployed in a smaller size, off shore of Toulon. The implementation of the project then started, a multi-year enterprise. Recently, it came as a pleasant surprise the observation by ARCA of the highest energy neutrino ever detected, 120^{+110}_{-60} PeV [29], already with only 0.15 km^3 instrumented at the time of the observation. The complementarity of ARCA w. r. t. to IceCUBE is also the exploring in time different regions of the sky, due to the Earth diurnal rotation, something that does not happen at the poles.

5. Underground Laboratories

The Standard Model of particle physics was gradually built with theoretical breakthroughs motivated and tested by experiments at accelerators, increasing their energies to levels sufficient to produce its components, fermions and bosons. But we soon came to understand that accelerators could not be sufficient. The reason is the following: the different forces of nature seem to become equal, to become "unified" as we say, at high energies. Unfortunately the energy scale of the unification, the Planck scale, is extremely high, so high that we will never be able to reach it with an accelerator. This might also be the scale at which quantum aspects of gravity show up. Fortunately there is another way. Phenomena characterised by a high energy scale do, in fact, happen naturally even at the lower, every day, energies. But the higher is their intrinsic energy scale, the more rarely they happen. Underground laboratories are dedicated to the search for these natural, but extremely rare, nuclear and subnuclear phenomena. This search requires very low radioactive background environment. Taking an analogy, we all have observed with astonishment and admiration the innumerable population of stars in the dark heavens of the night. But we don't see stars during the day, even if they are still shining. Starlight is much fainter than sunlight. To be able to see the weak luminous signal from a star we need darkness, the absence of the strong "background" of the sunlight. Similarly we cannot hear the chirp of a cricket in the noise of a freeway, but we need silence. We cannot detect the signals of very rare nuclear decays in the presence of the much higher natural radioactivity background. This background noise is due to cosmic rays, falling on the surface of the Earth and to decays of radioactive nuclei present, in traces, in all materials.

Experiments deep underground, in mines and in road tunnels, started early, but full-fledged laboratories with permanent support facilities for the experiments, were created starting in the late 1960s and 70s.

As for the prehistory, I begin here by recalling two important discoveries of experiments in mines of the early 1960s.

The first one was the discovery of cosmic-ray neutrinos. Two independent experiments, one in the Kolar Gold Mine in South India at a depth of 2700 m [30] and one in the East Rand Property Gold Mine in South Africa at a depth of 3200 m [31] observed muon tracks at large zenith angles. The observed count rate was substantially larger than the calculated rate of muons produced in the atmosphere reaching the detector due to the large slant depth of rock they would have had to cross. The authors concluded that those muons had been produced by neutrinos in rocks not too far from the detector.

The second discovery was with solar neutrinos. The theoretical model of the Sun necessary to calculate the expected solar neutrino flux on Earth and the study of the ways to experimentally detect them began in the 1950s. In 1964 two fundamental back-to-back papers by Raymond Davis Jr. (1914–2006) [32] and John Bahcall (1934–2005) [33] laid down the experimental and theoretical principles to measure the electron neutrino flux using the reaction $^{37}\text{CL} + \nu_e \rightarrow {}^{37}\text{Ar} + e^-$. The experiment had to be shielded from the cosmic-ray background deep underground and was installed in the Homestake Gold Mine, in Lead, South Dakota, in a chamber excavated on purpose at a depth of 1478 m. It became operational in 1967. Since the first results in 1968 [34] the experiment showed that the measured electron neutrino flux was only about one third of the calculated one. This became the famous "solar neutrino puzzle", that was finally solved with the discovery that electron neutrinos have a substantial probability to change to another flavour in their journey from the centre of the Sun to the Earth, the first evidence of physics beyond the Standard Model.

The Homestake experiment attracted the interest of many scientists worldwide, in particular in the USSR, where the competition, scientific in this case, with the USA was given great importance both at the community and at the government level. In 1963 the President of the Academy of Sciences of the USSR, Matislav Keldysh sent a letter to the Central Committee of the Communist Party of the Soviet Union with a request of a special decree on the development of investigations in the field of neutrino physics and astrophysics, as well as about construction of underground facility for this purpose. The Decree of the Soviet Government about construction of Baksan Neutrino Observatory (BNO) was issued. The scientific programme of the new lab was then developed by George Zatsepin (1917–2010) and Alexander Chudakov (1921–2001), including cosmic rays, supernovae, atmospheric and solar neutrinos. The chosen site was under Mount Andyrchi in Baksan Valley in the Northern Caucasus. A further Decree of the Soviet government in 1966 funded the construction of the surface facilities, that will be named "Neutrino village", the tunnel to reach the deepest location, and several laboratories along the tunnel sides and at its end.

A curiosity is that the tunnel does not go straight to the chosen final site, but initially points to a different direction that is later changed. The solution of the puzzle, due to the Soviet Union's obsessive security policy, is as follows [35]: a young Olga Ryazhskaya had been charged by Zatsepin to calculate the rate of muons producing nuclear effects as a function of depth [36]. Having done that, when a certain length of the tunnel was excavated, she installed a set of counters to measure the muon flux. She found it to disagree with her calculations. Checking them, and their correspondence with the accurate map of the mountain surface she had been given, she could not find any mistake. When the excavation had further advanced she measured the flux again at a deeper location. The disagreement was now strong. Taking courage, she talked to Zatsepin, who put the problem to the engineer responsible for the civil works. The engineer was confident to be right; being quite high in the party hierarchy he knew that the maps of the Caucasus regions, while very accurate, were turned by 12° on purpose, for security reasons, and he had duly corrected for that. When, however, a third check at an even deeper point by Ryazhskaya showed an even stronger contradiction, he discovered, asking his source, that the map he had received was the faithful version and that he had corrected for a non-existing fake. Indeed, the Communist Party held the science—even basic science—in very high regard.

Historically, the second underground laboratory, the INFN Laboratorio Nazionale del Gran Sasso (LNGS), was built in Italy. In 1979 the President of the Italian Senate, Amintore Fanfani, called a special meeting of the Senate Commission for Public Works. The only point in the agenda was the discussion of the proposal to build a large, high-technology, underground laboratory. The proposal had been submitted by the President of INFN, Antonino Zichichi. This was the official birth of the Gran Sasso Project.

The proposal of such a large and complex facility, while strongly pushed forward by the INFN Council, that in 1984 would restructure its scientific commissions and the budget structure to have a specific line of approval and funding of astroparticle physics and neutrinos, was not initially universally accepted. It was widely believed in the community that a project of the size and complexity proposed by Zichichi—some even called it "Napoleonic"—was far too ambitious for the kind of research that could realistically be expected. A much smaller laboratory, dedicated to a single experiment might be sufficient.

For example, on 17 October 1980, the groups that were building in the Mont Blanc tunnel the NUSEX experiment searching for proton decay, submitted a letter of intent [37] for the next generation experiment, in which the location in the Gran Sasso tunnel was ranked 5th after Simplon, Mont Blanc, Fréjus and Gotthard, on the basis of the residual muon flux, which the deeper it is, the lower the flux. They did not consider that it is impossible in practice to stop the traffic in an operational tunnel to build a laboratory. In retrospect, in addition, no experiment in the Gran Sasso laboratory will be limited by the residual muon background.

Problems were also initially raised at CERN, and we read in a recollection by Zichichi [38]:

… the CERN Director-General (DG), Léon Van Hove, during CERN Council meeting declared that Zichichi's Gran Sasso project was invented to stop the new collaboration between Italy and France to realize a joint venture in underground physics using the Fréjus tunnel. After this unprecedented attack against a very important initiative in Italy, the other CERN DG, John Adams, called the author into his office to tell him "not to worry". This ended all attacks from CERN against the project.

Figure 3 shows a sketch of the Gran Sasso Project (in Italian "Progetto Gran Sasso") presented by Zichichi at the above mentioned meeting of the Public Works Commission of the Italian Senate ("Commissione Lavori Pubblici" in Italian). The scientific programme would include not only the search for proton decay, which was the focus at the time, but also neutrino astrophysics, the search for unexpected cosmic phenomena and neutrino oscillations, using neutrinos from natural sources, like those produced by cosmic rays in the atmosphere, those from the Sun and those from Supernovae, as well as artificially produced ones at the CERN proton accelerators. In addition, other scientific sectors could profit from the unique location, such as "biologically active matter" and "ground stability". To this end, the three halls of the laboratory (sizes of the order of 100 m × 50 m × 20 m) were oriented towards CERN. Another component, not shown, was an array of detectors at Campo Imperatore, the plateau of the mountain directly above the underground halls, for the study of the cosmic air showers, including the detection of muons in coincidence with the underground detectors (LVD and MACRO). In addition, other branches of science were to be hosted, from biology to geology. All of this, and more, would happen in the following years.

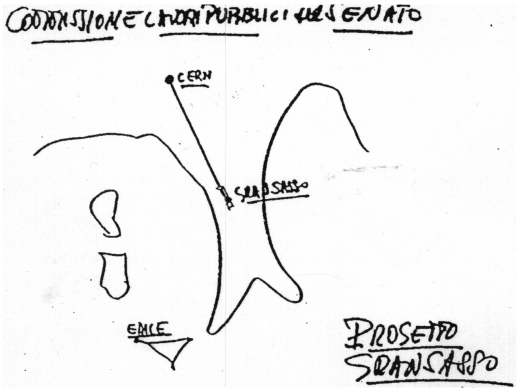

Figure 3. Sketch by Zichichi for the Italian Senate Public Works Commission, with the option to shoot a neutrino beam from CERN to Gran Sasso to study the behaviour of neutrinos with long flight time, and Erice in Sicily where Zichichi had created a School of Subnuclear Physics.

In advancing his proposal in 1979, Zichichi took into account the fact that ANAS, the Italian road authority, was excavating a tunnel under the Gran Sasso massif. This was a unique opportunity for the excavation of the large halls necessary for the experiments at a reasonable cost. A measurement campaign showed particularly low radioactivity levels in the Gran Sasso rocks. The Italian Parliament approved the Gran Sasso Project and a first appropriation to ANAS in 1982. By 1987, ANAS had completed the civil engineering works (Figure 4) and the first experiments had begun construction; two years later, the first module of the large MACRO experiment was taking data.

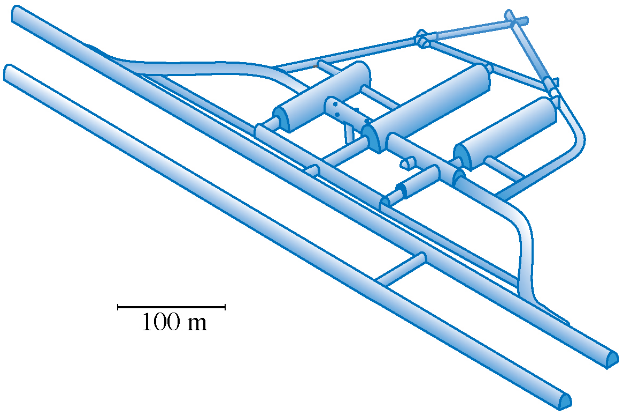

Figure 4. The Gran Sasso laboratory, with its three experimental halls and connecting tunnels. The smaller tunnels perpendicular to the halls host services and small experiments. The "triangle" of tunnels beyond the halls hosts a set of interferometers for ground stability studies. The West-East and East-West directions motorway tunnels are also shown. Credits LNGS-INFN.

The infrastructure, the INFN Laboratori Nazionali del Gran Sasso (LNGS), includes an external campus and specialised personnel to provide the support necessary for the experiments. It was developed under the leadership of Nicola Cabibbo, INFN President from 1983 to 1992, and Enrico Bellotti, LNGS director from 1987 to 1992. The facilities include mechanical, chemical and electronic workshops, assembly halls, computers and networking services, and a very low background assay facility. The latter is of fundamental importance for the experiments searching for extremely rare phenomena. The one at LNGS is unique in its size and completeness of the available radioassay techniques: Ge spectroscopy, Rn emanation assay, neutron activation, liquid scintillation counting, mass spectrometry, and more. The surface campus also includes offices, administration, secretariat, safety and environmental protection services, public relations services, the library, meeting halls, the canteen and a few sleeping rooms.

LNGS is used by a large international scientific community, currently 1300 scientists from 30 different countries.

I shall not attempt a review of the many underground laboratories of the world, but direct the interested reader to my "The world deep underground laboratories", written in 2012 [39], as an introduction to a focus point on EPJ plus on the existing laboratories, both operational and under project. I requested a description, including historical aspects, to the Directors or Responsible of: ANDES [40], Baksan Neutrino Observatory [41], CJPL [42] (then quite small, but which has developed today into the largest underground facility, although without the services available at LNGS), Canfranc Underground Laboratory (LSC) [43], India-based Neutrino Observatory (INO) [44], Kamioka Underground Observatories [45], LNGS [46], Modane Underground Laboratory (LSM) [47], SNOLAB [48], Sanford Underground Research Facility at Homestake (SURF) [49].

6. X and γ Rays

Today X-ray and γ-ray astrophysics are among the primary branches of the discipline, and with dedicated space missions for the former, space missions and very large surface observatories for the latter. The detectors and data analysis procedures are, to a large extent, the result of transfer and adaptation from particle physics. Here I only provide two relevant examples from the early years, when particle physics was still based on cosmic rays, along with a few hints about the present.

The first is the case of Bruno Rossi (1905–1993), an outstanding scientist who made exceptional contributions to cosmic ray physics, in Italy and in the USA. In the late 1950s particle physics shifted from cosmic rays to accelerators as already recalled. In the same years, after the launch of Sputnik in 1957, space missions and vehicles were developed at increasing pace. Rossi, at MIT, Boston, turned in those years his attention to the opportunities for science of space, armed with his scientific knowledge of cosmic rays. He thought to X-ray astronomy, considering that, due to the strong absorption by the atmosphere, differently from other astronomical observations, X-ray sources must be searched outside the atmosphere. Since the beginning of his career in Florence, he had built with his hands and used Geiger counters. He also had invented the coincidence circuit [50] that we now call with his name. These devices were light and robust enough to fly on rockets; could them be used in space?

In 1959, Martin Annis founded the private company American Science and Engineering Inc. (AS&E), as a research and development contractor for NASA. To guide his efforts, he called in Rossi as the Chairman of the Board of Directors. Rossi asked Annis to hire a former student of Occhialini in Milan, the young Riccardo Giacconi (1931–2018) and a few former MIT students. With this group, Rossi guided the development of the detectors for rocket experiments. The important discovery came in 1962, with the Aerobee rocket launched from the White Sands Missile Range, New Mexico, on June 18. The detectors in the payload were three Geiger counters with 20 cm^2 mica windows of different thicknesses in order to accept X-rays with different energy thresholds. The rocket reached a maximum altitude of 225 km and remained above 80 km for a total of 350 s. A powerful point source was discovered, a new astrophysical object, Scorpius X-1, outside the solar system [51]. X-ray astronomy was born.

For photons, as for the charged cosmic rays, the transfer with adaptation to experiments in space of techniques developed at accelerators, such as silicon strip detectors, to track e^+e^- pairs from photon conversion, calorimeters to measure the total energy, etc. led to major missions: the Chandra X-ray observatory in 1999, the XMM-Newton mission in 1999, INTEGRAL in 2002, Swift in 2004 and Fermi Gamma-ray Space Telescope in 2008. Differently from charged particles, that are deflected by cosmic magnetic fields, the measurement of the incoming direction of the photons allows to identify the astrophysical source. Energy, arrival time and polarisation are also measured.

The second example is the birth of the atmospheric Cherenkov telescopes technique for the observation of high energy γ-rays from the Earth surface, today one of the main ones, including CTAO (Cherenkov Telescope Array Organisation), a very large project presently under construction. These telescopes employ Cherenkov emission from extended air showers (EAS) in the upper atmosphere, produced by cosmic particles.

In 1948, Patrick Blackett suggested that about one part in ten thousand of the mean light of the night-sky might be expected from Cherenkov radiation produced in the atmosphere by cosmic rays [52].

To check this prediction, in 1953 [53], William Galbraith and John Jelly, members of the cosmic ray group of the Harwell Laboratory in the UK, set up the simple instrument shown in Figure 5. A photomultiplier (PM) was installed in the focus of a parabolic mirror, surrounded by an array of 16 Geiger counters (not shown), each with an area of 200 cm^2, to detect extended cosmic ray showers, if any. The number of coincidences between the PM and Geiger array signals was found one thousand times larger than the computed accidental coincidence rate. Short-duration light pulses (<200 ns) from the night sky associated with cosmic rays were observed for the first time.

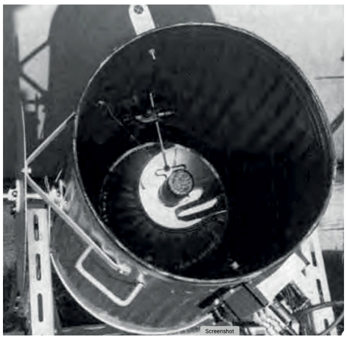

Figure 5. The simple detector of Galbraith and Jelly described in [53]: a dustbin with a small parabolic mirror (25.4 cm in diameter, 11.7 cm focal length) and a phototube. The field of view of the "telescope" was approximately ±12° from the zenith.

The next step should be credited to Alexander Chudakov [54], who started to explore the phenomenon on the Pamir Mountains at an altitude of 3800 m, with the purpose to study the lateral distribution of the light flux relative to the core of the showers, and also to investigate the relation between the intensity of the light flash and the size of the shower. As in the case of Galbraith and Jelly, the arrangement included an optical component to detect the light flash, and an array of Geiger counters to detect the EAS in coincidence, if any, but in a much more complex structure. The Geiger array consisted in 5 units each containing 96 counters. The optical component consisted in 8 units, each made of a PM at the focus of a parabolic mirrors. Two of them, called master units, were located at the centre of the counter array and used to give it the trigger. The other six were located at different distances that could be varied to measure the light intensity as a function of the distance from the core. Even if very small by the today's standards, the Chudakov "telescope" contained already the basic elements, once more imported from cosmic-ray technologies.

The next breakthrough is the introduction of the imaging atmospheric Cherenkov (IAC) technique, proposed by Trevor Weekes (1940–2014) and Keith Edward "Ted" Turver in the late 1970s [55]. An image of the shower is obtained by placing a mosaic of PMs, called camera, in the focal plane of a parabolic mirror. This gives a powerful means to separate the gamma-induced showers from the much more abundant ones produced by cosmic protons and nuclei, exploiting the different shapes of the two types of shower. The IAC technique was first implemented in the Whipple telescope, on Mount Hopkins in Arizona, at an altitude of 2300 m. The Whipple 10 m reflector had been built in 1968, as the first atmospheric Cherenkov telescope for gamma-ray astronomy, initially with a single non-imaging PM in the focal plane. In 1969, Trevor Weekes was appointed Resident Director of the Mount Hopkins Observatory, renamed in 1981 Fred Lawrence Whipple Observatory, in honour of the great astrophysicist and former Director of the Smithsonian Astrophysical Observatory. Under the guidance of Weekes, in 1982, the first imaging camera was installed, a close-packed array of 37 photomultipliers. In 1989, by rejecting 98% of the background with a gamma-ray image analysis on the basis of the predicted properties, a strong signal from the Crab Nebula was detected with 9 sigma significance [56]. The Whipple 10 m telescope was decommissioned in 2013. Over its glorious 45-year lifetime, the focal plane camera had evolved with an increasing number of smaller and smaller PMs, up to 379 pixels in 2003, producing images of ever increasing resolution.

7. Underground Nuclear Astrophysics

The following is an interesting example of cross-fertilisation between astrophysics and nuclear physics.

The nuclear fusion reactions in the stars take place at energies below the Coulomb barrier, meaning that the energies at which nuclei collide are less that the repulsive electrostatic barrier. They do proceed thanks to the tunnel effect, in an energy range, called the Gamow peak, where the product of the penetration factor, which decreases exponentially with energy, and the fusion reaction cross section, that increases as the distance decreases, is a maximum.

In 1972 Willy Fowler proposed [57] a nuclear solution of the "solar neutrino puzzle" (Section 4). This could be the case if the cross section of the reaction $^3\mathrm{He} + {}^3\mathrm{He} \rightarrow 2\mathrm{p} + {}^4\mathrm{He}$ were much larger than assumed in the solar model. Indeed, the cross sections of the nuclear reactions were not measured at energies down to the Gamow peak because they are too small, and the solar model used extrapolations from higher energies where measurements existed. If a resonance existed in the unmeasured energy range, the deficit of neutrino flux observed at Homestake could be explained.

The main reason preventing the measurement of these cross sections was the background induced by natural radioactivity, cosmic rays and gammas. In 1991, Gianni Fiorentini and Claus Rolfs proposed to install underground in the greatly reduced background of the Gran Sasso laboratory a small 30 kV ion accelerator to measure the $^3He + {}^3He \rightarrow 2p + {}^4He$ cross section down to the relevant energies [58]. The project was called Laboratory Underground for Nuclear Astrophysics, LUNA, joking with the name that in Italian means moon.

Thanks to the reduction of the environmental background by six orders of magnitude, LUNA measured the cross section down to a counting rate of only two events per month. No resonance was found, nuclear physics was not the solution to the solar neutrino puzzle, a result described by John Bahcall, the author of the solar model, as the most important advance in 30 years of nuclear astrophysics.

LUNA continued in the following years [59], with important new results both for solar and for stellar astrophysics. For example the reduction by a factor of two, compared with the previously assumed values, in the cross section of the reaction $^{14}N + p \rightarrow {}^{15}O + \gamma$ [60] led to an increase of about 10^9 years of the estimated age of the globular clusters, the oldest structures in galaxies.

8. Policy

As we have discussed, already in the 1980s astroparticle physics was growing to large scales, with experiments and observatories requiring investments at the 10^8–10^9 $/€ level, large international collaborations, with well-developed managerial structures, accurate planning of the resources over the many years required for the construction and then the exploitation of the infrastructure, reaching the status of “megascience”, similarly to accelerator particle physics and astrophysics/cosmology. The process required international coordination at the agencies and governments level. I shall discuss the principal steps of this process in this section.

A specific intergovernmental body existed at the time, the Mega Science Forum (MSF) established in 1992 by the Organisation for Economic Co-operation and Development (OECD) to discuss issues related to the funding and management of large research facilities. In 1997, the MSF approved the proposal submitted by the author, in the name of the Greek and Italian governments, of a “Workshop on Deep-Sea Neutrino Telescopes”. This was held in Taormina (Italy) on 22–23 May of the year, organised by the INFN, under the guidance of the author. The final report was published, after approval of the MSF Assembly (the members of which are representatives of the Governments). A conclusion was that the issue was not yet mature enough to be treated at government level, with the suggestion to create a forum at the scientific community level, specifically with a request to the International Union for Pure and Applied Physics (IUPAP), stating that: “to develop and sustain the field of experimental high-energy neutrino astrophysics over the long term, a new committee should be established, possibly within the International Union of Pure and Applied Physics (IUPAP), on the model of that body’s existing disciplinary committees”.

My vision, however, also in my responsibility of Director of the LNGS of the INFN, was wider, namely that the proposed international committee should not be limited to neutrino telescopes but should include the entire astroparticle discipline. Consequently, in September 1997, after a discussion with Peter Tindemans, Chair of the MSF, I wrote to the President of the IUPAP, Jan Nilsson, with the request to consider such a committee. The answer came the following month, on 9 October 1997, from Burton Richter, then IUPAP President, stating that:

“The IUPAP Council, at its September meeting with the Chairs of all of IUPAP’s Commissions, has come to the conclusion that a new mechanism to foster international collaboration in the field of particle astrophysics would be of considerable benefit”.

“The Council of IUPAP, together with the Commission Chairs, has been considering for some time the future activities of the organization, and has concluded that there are areas of great scientific importance where no effective mechanism exists to facilitate the development of scientific consensus and promote international cooperation on large-scale projects and activities. Particle astrophysics is one such area where collaborations are growing larger and experiments are becoming more costly”.

The decision was not to create a new “Commission” but a Committee, under C-4 (the Commission then for “Cosmic Rays”), as a more flexible body, with simpler procedures for member appointment and suitable, differently from a Commission, to be closed at a certain time if needed. An ad hoc working group was appointed, with Alessandro Bettini (Chair), Thomas Gaisser, Bernard Sadoulet, Yoji Totsuka, Arthur McDonald and Wick Haxton, charged with developing the charter and recommending the initial members of the new committee, which is “to serve as a facilitator and forum for the development of large-scale collaborations in this area at the initiative of the scientific community. It should not try to establish priorities among projects”, stressing the need to move rapidly with the request to submit the recommendations by January 1998.

The discussions in the ad-hoc group, with the Chairs of the relevant IUPAP Commissions, and with leading figures of the field brought to the conclusion, among others, that nuclear physics research, such as that for neutrino-less double-beta decay, and gravity, mainly gravitational waves, also had to be included. For the latter a discussion forum already existed, called GWIC (Gravitational Wave International Committee), chaired by Barry Barish, to whom we proposed transforming GWIC into a panel of the new committee. The following discussion in GWIC approved the proposal.

The committee was called Particle and Nuclear Astrophysics and Gravitation International Committee (PaNAGIC) becoming IUPAP Working Group 4 (WG4) [61]; its creation was approved by IUPAP in 1999, to support international exchange of ideas and help in the convergence of the international scientific community in the large-scale activity in the emerging field of particle and nuclear astrophysics, gravitation and cosmology.

Its purposes were:

- To promote and provide a forum for the international coordination of large-scale projects in these areas of research.
- To develop a common culture in these emerging and rapidly evolving fields.
- To promote and help to organize regular world-wide meetings, workshops and schools in these areas.

These interdisciplinary sectors included:

- Study of basic constituents of matter and their interactions by non-accelerator means.
- Study of the sources, acceleration mechanisms and propagation of high energy particles in the Universe.
- Study of nuclear and particle properties and processes of astrophysical interest in the Universe.
- Study of gravity, including the detection and the astrophysical sources of gravitational waves.

Beyond GWIC [62], a second subpanel, named HENAP, was created for High Energy Neutrino Astrophysics [63].

PaNAGIC met regularly over the years, reporting to the IUPAP General Assembly meetings, chaired by the author from 1998 to 2004, by E. Fernandez from 2005 to 2008 and D. Sinclair from 2009 to 2010, when it was terminated.

PaNAGIC, with its scientific discussions and coordination activities, had played a critical role in setting both a conceptual and institutional foundation for the emerging field of astroparticle physics, providing the scientific justification for large-scale international projects. The ball had now to pass to intergovernmental organisations.

In Europe six scientific agencies took actions in 2011 to found ApPEC (Astroparticle Physics European Consortium) with the aim to promote and coordinate astroparticle physics effort in Europe. This led to the European Commission funded ASPERA (AStroParticle European Research Area) in July 2006, a network of 16 European Agencies and CERN. An important achievement of ASPERA was the elaboration of a common European Roadmap for the future of astroparticle physics, published in 2008. The report underlined the priority of seven large-scale facilities:

- CTA, a large Cherenkov Telescope Array (now CTAO, see Section 6)
- KM3NeT, a cubic kilometre-scale neutrino telescope in the Mediterranean Sea (Section 4)
- Tonne-scale detectors for dark matter search
- A tonne-scale detector for double-beta decay
- A megaton-scale detector for proton decay search and neutrino physics and astrophysics
- A large array for the detection of charged cosmic rays
- A third-generation underground gravitational antenna

At the global level, in the same year, the OECD Global Science Forum, the successor of the MSF, established a Working Group on Astroparticle Physics. It had brought together government-nominated representatives of eighteen countries, two intergovernmental organizations, an independent scientific organisation, and invited experts. Its work came to an end in March 2011 when the final report was issued [64]. In it: the Working Group recommends the establishment of a venue for consultations among officials of funding agencies that make significant investments in the field. The overall goal should be to ensure that, during the next 10–15 years, progress in astroparticle physics will be a globally coherent response to the scientific challenges, using an optimal set of national, regional, and international projects. The new consultative group would be called the Astroparticle Physics International Forum (APIF), and would be a subsidiary body of the OECD Global Science Forum. Funding agency officials would be nominated by the delegations to the GSF, and by the governments of interested non-OECD member countries.

In the same year APIF was established by the Organisation.

At the scientific community level, to liaise with APIF, IUPAP established its WG10, ApPIC (Astroparticle Physics International Committee) in 2011, with Michel Spiro as the first Chair.

ApPIC was terminated in 2019 absorbing its activity in Commission 4. C4, one of the oldest in IUPAP, which had been created in 1947 "to promote the exchange of information and views among the members of the international scientific community in the general field of Cosmic Ray Physics", in 2019 changed its name from "Cosmic Rays" to "Astroparticle Physics", including:

- The nature and characteristics of the electromagnetic, particle and other radiation present in the cosmos;
- The theory and models concerning the origin of this radiation;
- Non-accelerator high energy physics
- The specialized technologies necessary in the field and their application

The rise of "astroparticle physics" to a well-defined and well-established branch of physics was now complete.

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