Status and perspectives of the INFN Laboratori Nazionali del Sud

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Abstract. The nuclear research carried out at the Laboratori Nazionali del Sud is mainly based on two ion accelerators, a 15 MV Tandem and a K800 superconductive cyclotron. The large variety of stable and radioactive beams produced and their wide energy range, together with the availability of high performance detection systems, allow for experimental research in the fields of the nuclear structure, reaction mechanisms and nuclear astrophysics. A continuous upgrading of the beam production and detection facilities is performed to maintain the role of the LNS in the panorama of the European nuclear laboratories. In addition the research activity in astroparticle physics led to the construction of two underwater laboratories in front of the sicilian coast. They allow to check and validate submarine technologies in view of the realization of the European project KM3NeT, consisting in the installation of an observatory for high energy cosmic neutrinos in deep sea. All these experimental resources also represent formidable tools for applied researches that cover multidisciplinary fields concerning proton therapy, cultural heritage, seismology, environmental sciences and many others.

1. Introduction

The Laboratori Nazionali del Sud (LNS), one of the four national laboratories of the Istituto Nazionale di Fisica Nucleare (INFN), started its operation at the beginning of eighties, thanks to the installation of a Tandem accelerator with nominal maximum voltage of 13 MV. It was later upgraded to 15 MV and since that time is running without any relevant interruption till today. The second important step in the development of LNS was represented by the acquisition of the K800 superconductive cyclotron (CS) designed and realized by the LASA group in Milan and transferred to LNS at the beginning of nineties. After the commissioning the CS started to operate as post-accelerator of the Tandem beams, but few years later it was possible to decouple the two accelerators and let them run independently thanks to the construction of ECR ion source producing high charge state ions to be injected into the cyclotron. From that time LNS can offer to the nuclear community a large variety of stable beams with energies ranging from few A·MeV to 80 A·MeV depending on the ions to be accelerated and on the accelerator used for that.

More recently an ISOL low energy radioactive beam facility (EXCYT) was installed, based on the combined use of the two accelerators and in addition just few years ago the CS beam started to be used also for in-flight production of intermediate energy unstable beams. These two facilities allowed to extend the LNS nuclear research to unstable beams induced reactions at both low and intermediate energies.
The field of the LNS activities has been expanded in the last decade with the NEMO project, an initiative aimed at the design and construction of a submarine observatory for high energy cosmic neutrinos to be deployed in the Mediterranean seafloor, just in front of the sicilian coast. Today the permanent LNS staff consists of about 110 INFN people, including researchers, technologists, administrators and technicians. In addition about 40 researchers from other public institutions, mainly from the University of Catania, are associated to the LNS activities, together with a huge number of undergraduate and PhD students, post doc fellows and young temporary researchers that lead the total number of people daily working at LNS above 200. An idea of the impact of LNS on the scientific community can be also given by the number of users that is around 300 per year, one third of them belonging to foreign research institutions.

2. Beam production facilities
The two LNS accelerators are shown in figures 1 and 2. Figure 2 also reports the operative diagram of the cyclotron, showing the ion beams accelerated up to now and their respective
energies. It can be seen that the maximum attainable energy is 80 A·MeV for the lightest beams and it has been obtained for protons and $^{12}$C. For the heaviest elements the maximum energy is 25 A·MeV and $^{197}$Au beams with this energy have been produced, indeed.

Today the cyclotron is endowed with two ECR sources. One is working at room temperature (Cesar) and the second one (Serse) is based on superconductive technologies and works at liquid helium temperature.

Figure 3 shows a layout of the LNS accelerator hall and experimental rooms. The main elements of the facility EXCYT are also schematically shown.

EXCYT is a first generation ISOL facility using the cyclotron to produce the primary beam and the Tandem as post accelerator. The cyclotron beam is produced at intermediate energy and delivered to a production target thick enough to stop the beam. The large number of different species produced in the beam-target interaction are then extracted by heating the target and transported to a charge exchange channel that provides them with a negative ionization. A multiple stage separator along the line allows to get a clean exotic beam of the requested species that can be injected into the Tandem, accelerated and sent to the experimental hall where the nuclear processes induced by this beam can be studied.

![Figure 3. (Color online) Layout of the accelerator area and experimental rooms.](image)

The $^{8}$Li was chosen as the first EXCYT beam and it was produced by using a 45 A·MeV $^{13}$C primary beam and a graphite target. Owing to the low efficiency of the charge exchange process (around 3%) the final beam intensities attainable by EXCYT are low, if compared to the usual stable beam intensities. In fact the maximum intensity obtained for the first $^{8}$Li beam was about $7\cdot10^4$ particles/s. It implies that special care has to be taken when planning an experiment with the EXCYT beams, in order to compensate the low intensity in some way, for instance using $4\pi$ detector arrays.

Following the requests of the LNS users, the development of a $^{15}$O beam is now under way, for which one expects a charge exchange efficiency more favourable than for $^{8}$Li by a factor close to 10.

Radioactive beams at intermediate energy are also produced at LNS using the well known technique of in-flight projectile fragmentation, where the primary beam is again provided by the cyclotron. A thin production target is placed just after the extraction line of the CS. The interaction of the primary beam with this target produces many different ions moving in the forward direction together with the residual beam and approximately with the same velocity. By a proper setting of the two 45 degree dipoles used for the beam transport, particles with a given magnetic rigidity are selected and separated from the other reaction products and from
the residual beam. Due to the limited selectivity of these magnets, actually a 'cocktail' beam is transported along the line to the experimental room where the set up of the experiment is mounted. In this last part of the line each beam particle has to cross a tag detector consisting in a thin double side strip silicon detector, that gives a measure of its energy loss and position. This information, together with the measurement of the time of flight on a given path, allows the complete identification of each single beam particle and measurement of its energy. In the off-line analysis of the experiment, mass, charge and energy of the projectile can be assigned to each event, so that in principle multiple experiments are feasible with these beams. Intensities of the order of $10^4$ particles/s have been achieved during the first runs of the facility. After a careful study of the transport beam line, new focusing elements have been installed and a new articulated diagnostics system has been implemented on the line leading to the CHIMERA room, so that a gain by a factor around 25 - 30 is now expected in the intensity of the radioactive beams when delivered to CHIMERA.

3. Detection facilities
The development of the beam production facilities has been accompanied by the parallel development of detection facilities. The first big $4\pi$ detector designed and realized at LNS was MEDEA (see figure 4), an array of 180 BaF$_2$ crystals that can detect and identify light particles and gamma rays. Later the detector has been coupled to a superconductive solenoid (SOLE), able to separate the very forward emitted reaction products from the residual beam. MACISTE, a zero degree array of telescopes, each one made of a ionization chamber and a plastic detector, completes the apparatus, allowing the detection and clear identification of the heaviest reaction products emitted in the forward direction. Looking at a possible development in the employment of the detector, an experimental study is taking place to verify the response of the MEDEA crystals to neutrons.

Figure 4. (Color online) The Medea-Sole-Maciste detector.

Big efforts of several researchers belonging to LNS, to the Catania INFN unit and to other italian and foreign groups led to the realization of CHIMERA, a $4\pi$ charged particle detector made of 1200 telescopes each one consisting of a CsI(Tl) E-stage and a Silicon $\Delta E$ stage (figure 5).

The detector has been, and still presently is, widely used by large international collaborations to study the physics of collisions at the Fermi energy. A very recent upgrade of the detector concerns the implementation of a hardware pulse height analysis of the signals coming from both the E and $\Delta E$ stages. This analysis, applied to the signals coming from the Silicon stage,
allows to identify the low energy ions that stop in the such stage. On the other hand, the most penetrating particles that leave in the $\Delta E$ detector a signal indistinguishable from the background can be efficiently identified by a pulse shape analysis of the signal produced in the $E$ stage. This important upgrading of the detector extended the field of operation of CHIMERA on both the low and the high energy sides.

Figure 5. (Color online) The CHIMERA 4$\pi$ detector.

MAGNEX (figure 6) is a high resolution, large acceptance (50 msr) magnetic spectrometer, that was specially designed for both inclusive and coincidence experiments at Tandem energy with stable and unstable beams. Its main elements are a quadrupole magnet, vertically focusing the particles, and a horizontally focusing dipole. The focal detectors is made of a gas chamber that measures the energy loss of the ejectiles and a wall of Silicon detectors for the measure of their residual energy. Adding the measurement of the flight time one gets a complete information on emission angle, energy, charge and mass of the ejectiles. Thanks to an agreement between LNS and the Nuclear Physics Institute of Orsay, the neutron detector EDEN has been temporarily transferred to LNS and coupled to MAGNEX, forming a unique experimental complex able to perform exclusive measurements specially useful for studies on the formation and decay of neutron-rich systems.

Figure 6. (Color online) The Magnex spectrometer.
Of course besides these big devices, LNS owns a number of smaller modular detectors (CLAD, Hodo-Big, Hodo-small, Trasma, etc.), whose geometry can be changed according to the requirements of each specific experiment.

4. Research with accelerators

In the past years most of the beam time of the two accelerators (around 75% on average) has been allocated to nuclear physics experiments, whilst about 25% of the beam time has been used for application studies and interdisciplinary activities. It is impossible here to recall all the excellent results deduced from the several experiments performed with the LNS beams in these last 30 years. It must be underlined that, even if only some examples are mentioned in the sequel, there is a huge amount of studies in nuclear structure and in reaction mechanisms that should deserve to be mentioned as well. Moreover it is to be acknowledged here the work of the small but active group of nuclear theorists operating at LNS. Most of the experimental studies in the field of intermediate energy collisions have been developed in harness with them, who have interpreted in the most suitable way the role of theorists in a nuclear laboratory.

Nuclear research with stable and unstable Tandem beams concerns the nuclear astrophysics, the spectroscopy of neutron-rich nuclei, the study of dissipative processes in the nuclear interaction, the structure of the light nuclei and its effects on the reaction mechanisms and so on.

![Figure 7](image-url)  
**Figure 7.** The $^{18}O(p,\alpha)$ excitation function as deduced by the Trojan Horse method (data from Ref. [1]).

Nuclear astrophysics represents one of the leading research topic at LNS. The development of the Trojan Horse method and its application to several nuclear systems allowed the indirect extraction of astrophysically relevant quantities concerning the interaction between charged particles, otherwise unaccessible by direct measurements because of the huge Coulomb barrier to incident energy ratio. Such measurements can be of crucial impact on our knowledge of the processess occurring in stars. For instance the recent discovery of a resonance at 20 keV [1][2] in the $^{18}O(p,\alpha)^{15}N$ reaction (figure 7) implies a 40 % increase of the value of the astrophysical factor with respect to the value included in the NACRE compilation for that process.

In the field of the nuclear structure interesting results have been recently achieved from the comparison of the scattering cross sections of Be isotopes on $^{64}Zn$, measured at LNS with a $^9$Be
beam and at ISOLDE with $^{10}\text{Be}$ and $^{11}\text{Be}$ beams. It has been observed that the halo structure of $^{11}\text{Be}$ heavily affects the scattering cross section [3] which is strongly suppressed with respect to the scattering cross section of the other two isotopes (figure 8). This effect has been related to the increased contribution of absorption processes that in halo nuclei can occur even at large distances.

![Figure 8](image)

Figure 8. (Color online) Comparison of the $^{9,10,11}\text{Be}+^{64}\text{Zn}$ scattering angular distributions (data from Ref. [3]).

As already mentioned, the EXCYT experiments have to take into account the low beam intensities that presently can be produced. So the first experiments using the $^{8}\text{Li}$ beam have been planned keeping in mind this limitation. As a clear example, one can mention the measure of the scattering excitation function of the $^{8}\text{Li}+\alpha$ system that was performed using the resonant scattering method on thick gas target.

![Figure 9](image)

Figure 9. (Color online) $^{8}\text{Li}+\alpha$ scattering excitation functions at three angles (unpublished data).

The method consists in delivering the beam into a reaction chamber filled with He gas at
a pressure high enough to stop the beam and detecting the recoil α-particles. The gas acts as target and as degrader at the same time and one can measure the excitation function in a wide energy range, with a single beam energy, saving a lot of beam time. The goal of the experiment was the search for resonances in the scattering cross section that could be related to population of cluster states in $^{12}$B with $\alpha$-$^{8}$Li configuration. The resonances showed in the preliminary excitation functions at different angles and reported in figure 9 need to be better understood by a comparison with cluster model calculations, before drawing definitive conclusions.

The first campaigns of experiments with the beams produced by the CS concerned the study of the collisions and the behavior of the nuclear matter at intermediate energy. The de-excitation modes of the GDR in medium mass nuclei, the study of dissipative processes, the nuclear caloric curve and the phase transition in nuclei were among the subjects of the experimental campaigns with the cyclotron. Afterwards, the availability of the powerful detector CHIMERA gave the opportunity to perform exclusive experiments with multiple coincidences, thanks to the high granularity of the detector. The unambiguous reconstruction of the final state for each event allows to investigate in greater details the physics at the Fermi energy, including the different aspects of the projectile multifragmentation process that is typical of these energies [4],[5] and the role of the entrance channel isospin on the dynamics of collisions [6].

As an example of recent results, it has been found that in semi-peripheral three-body reactions, besides the fragments produced by the sequential decay, the most neutron-rich intermediate mass fragments (IMF) are emitted in the very first stage of the collision (<40 fm/c), from a region of overlap of the two colliding nuclei. Furthermore, it was possible to establish a kind of emission chronology for the IMFs, in the sense that with increasing IMF charge the corresponding emission time scale also increases to values as large as 300 fm/c or more [5]. This is shown in figure 10, where the correlation between the relative velocities of the IMFs and the projectile-like or target-like fragments is reported for the system $^{124}$Sn+$^{58}$Ni at 35 A·MeV.

**Figure 10.** (Color online) IMF production yield of the $^{124}$N+$^{64}$Ni at 35 A·MeV reported as a function of the fragment relative velocities (data from Ref. [5]).

Moreover few years ago the study of the emission of two correlated protons from the excited $^{18}$Ne represented the first interesting result achieved thanks to the development of in-flight fragmentation beams. The relative energy spectrum of the two coincident protons (figure 11)
emitted after the interaction of a secondary \( ^{18}\text{Ne} \) beam with a lead target showed a peak at the expected p-p relative energy that could reflect the preformation of a di-proton in \( ^{18}\text{Ne} \), as effect of the pairing interaction [7].

\[ \text{Figure 11. (Color online) Relative energy spectrum of two coincident protons emitted by excited } ^{18}\text{Ne} \text{ (data from ref. [7]).} \]

The two accelerators represent also a useful tool for a number of non-nuclear activities that are performed at LNS. The beams are used, indeed, also for radiobiological studies, researches on the modifications induced by ion beams on the behaviour of superconductive materials, investigation on the radiation hardness of electronic components to be used in space missions. For these measurements LNS has recently received the ESA certification, an acknowledgment of the reliability of the work jointly performed by the LNS staff and a private partner company to set up the system. Furthermore the CS is also used for therapy purpose in the frame of an agreement involving LNS, the University of Catania and the University Hospital. Since 10 years patients affected by uveal melanoma are treated with a 62 MeV proton beam produced by the CS. Every year five weeks of beam time are devoted to these protontherapy sessions.

Finally, a procedure of elemental analysis of archaeological finds with the Tandem and CS beams has been set up, allowing to deduce, in a non destructive way, information on their internal composition. Ancient coins, paintings, documents and other cultural heritage samples have been processed. Exploiting the wide energy range of the LNS beams such kind of analysis can be performed at different depth, from the surface to the inner layers.

5. Technological research without accelerators

The panorama of the LNS activities also includes a large number of technological researches that do not require the use of accelerators. Among these initiatives one must recall the study of scintillating fibers as cheap, easy-to-use tools for a continuous, efficient monitoring of nuclear waste repositories, an issue that is part of the INFN-Energy strategic project. Moreover an explicit mention is deserved by the development of portable PIXE-\( \alpha \), XPIXE-\( \alpha \) and BSC-XRF systems that allow ‘in situ’ non destructive analysis of cultural heritage finds. The use of these instruments is, of course, complementary to the analysis technique based on the use of ion beams, already described. In connection with this activity a laboratory has been
installed at LNS for the home production of the $^{210}$Po sources that are needed for the operation of the portable instruments.

Finally intense efforts have been devoted to the design and realization of innovative ion sources. The competence acquired during the past years in this field by the LNS source group is worldwide acknowledged and is witnessed by the involvement in a large number of national and international projects. Valuable contributions have been given, and are still given, to the realization of ion sources in Italian (LNS, Legnaro National Laboratory, the Italian center for hadrotherapy CNAO) and European (GSI, ESS) laboratories.

6. Astroparticle physics

More than ten years ago another scientific initiative was undertaken by the LNS researchers in collaborations with colleagues of other INFN units, in the field of astroparticle physics. It is the NEMO project, that concerns the design and realization of an undersea telescope for high energy cosmic neutrinos to be installed in the Mediterranean Sea, with the goal of extending the present limits of the observable universe.

Today the project NEMO is completely integrated in the European project called KM3NeT, born from the collaboration of researchers from several European countries and included in the first road map of research infrastructures of ESFRI.

The structure of the telescope will consist of a number of towers, about 800 m tall, each one supporting the optical sensors to detect the Cherenkov light emitted by the muons produced by the decay of neutrinos after interaction with the sea water. The towers are expected to cover a water volume of the order of 1 km$^3$. Calculations and simulations are carried out to determine the parameters of the most efficient configuration of the detector, namely the number of towers, the number of detectors in each tower, the distance between adjacent towers and so on.

In the meanwhile a number of measurement campaigns have been performed to check and compare the characteristics of the proposed sites that could host the telescope. For the high transparency of the water, the low biological activity and a suitable morphology of the seafloor, the Italian collaboration has proposed a site at 3500 m depth, about 100 km offshore the Sicilian coast. A parallel R&D activity has been carried out to test and validate the mechanical and electrical solutions for the construction and deployment of the elements of the telescope on one side, and for the transfer of the electrical power and retrieve of the signals from the detectors on the other side. As a necessary support to this activity, two underwater laboratories have been realized and fully equipped. One is the so called ‘test site’ located at 2000 m depth, 20 km offshore the Catania port, and the second one is the Italian candidate site for the final installation of the observatory. Both of them are connected with the respective on-shore stations by electro-optical cables, 25 and 100 km long respectively.

These infrastructures have attracted the interest of several researchers operating in contexts other than astroparticle physics, since they represent a unique opportunity to perform observations and measurements in deep sea. Thus several multidisciplinary collaborations grew up in fields like seismology, geophysics, marine biology, environmental sciences. Moreover the two laboratories participate to the European Network of Excellence ESONET and to EMSO, a European large-scale infrastructure composed of seafloor observatories for long-term monitoring of environmental processes.

7. Perspectives and conclusions

LNS was born as a nuclear physics laboratory and is still playing a role in the panorama of the European laboratories, thanks to the reliable operation of its accelerators and to the large variety of stable and unstable beams produced. To maintain this role, improvements and upgrades have already been made in the last years, for instance on the transport line of the fragmentation beams, and others are in progress, for instance on the two ECR ion sources of the cyclotron.
Moreover it is to be checked the interest of users to exploit the beams produced by EXCYT at low energy, that could avoid the bottleneck of the charge exchange channel. In this case a new beam line should be installed downstream the mass separator. Anyway the traditional nuclear research at LNS has to be reinforced, primarily for its contribution to a deeper knowledge of the nature, but also for its wide implications in the development and application of nuclear technologies and methodologies to interdisciplinary researches.

The astroparticle project of the deep sea neutrino observatory is the foreseeable medium term future of the Laboratory and will require increasing attention and dedicated resources. Enormous R&D efforts have been made in the last ten years on the different aspects of the project concerning optical and acoustic sensors, electronics and mechanics, in the frame of the KM3-NeT collaboration. Submarine technologies have been developed and validated by taking advantage of the underwater laboratories installed in front of the sicilian coast, that in turn have stimulated the birth of innovative scientific collaborations in interdisciplinary research fields.

Applications and technological developments represent the third proficuous field of activity at LNS, a very articulated field spanning from radiobiology to medical diagnostics and therapy, from science of materials to seismology. These activities bring additional visibility to the Laboratory and contribute to a harmonic development of fundamental and applied research at LNS.

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