Preface

In this book a collection of the lecture notes given during the Tenth European Summer School on Experimental Nuclear Astrophysics is given. The school belongs to the European Network of Nuclear Astrophysics Schools (ENNAS), a network made by the European schools on nuclear astrophysics and related areas (the Santa Tecla, the Sinaia, the Russbach schools), having the common effort of preparing and educating young physicists in nuclear physics, astrophysics and their mutual relationship in the nuclear astrophysics field. The school, whose first edition was held in 2001, took place from 16 to 23 of June 2019 in Catania. The School venue and host was the INFN Laboratori Nazionali del Sud, one of the 4 INFN national laboratories whose main activity is focused in Nuclear and particle astrophysics. A total of 70 between young students and researchers from more than 20 countries of all the world attended the lectures and were also encouraged to present their work work and results. Lectures were given by twenty of the best top scientists in the field.

The school has tried once more to present to the young students the global picture of nuclear astrophysics research in the last years. Thus the scientific program of the school covered a wide range of topics dealing with various aspects of nuclear astrophysics, such as stellar evolution and nucleosynthesis, Big Bang, direct and indirect methods, radioactive ion beams. Nuclear astrophysics plays a key role for understanding energy production in stars, stellar evolution and the concurrent synthesis of the chemical elements and their isotopes. It is also a fundamental tool to explain the ashes of the early universe, to determine the age of the universe through the study of pristine stellar objects and to predict the evolution for the Sun or Stars. The bone structure for the above aspects is based on nuclear reactions, whose rates need to be determined in laboratories. Although impressive progress has been made over the past decades, which was rewarded by Nobel prizes, several open questions are still unsolved, which challenge the basis of the present understanding.

A list of the lecture topics is given below:

- Big Bang Nucleosynthesis;
- Stellar nucleosynthesis;
- Plasmas in stars and laboratories;
- Radioactive ion beams;
- Neutron star mergers and r-process;
- Detector and facilities for nuclear astrophysics;
- Direct and Indirect methods in nuclear astrophysics;

An often quoted statement of Carl Sagan, ”We are all star stuff”, is exhaustively describing one of the great discoveries of the XX century as well as the main aim of nuclear astrophysics. The present theory of stellar nucleosynthesis (based on the famous paper B2FH) predicts chemical evolution of the Universe, which is testable by looking at stellar spectral lines, meteorites, pre- solar grains or other means of investigation. Big bang nucleosynthesis tells us that the early universe consisted of only the

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light elements, and so one expects the first stars to be composed of hydrogen, helium, and lithium, the three lightest elements. The achievements of WMAP and Planck missions, with the precise measurement of many cosmological parameters,have re-ignited the interest on the primordial nucleosynthesis, especially for the still unclear Lithium primordial abundance. Stellar structure and the H-R diagram indicate that the lifetime of a star depends greatly on its initial mass and chemical composition, so that massive stars are very short-lived, and less massive stars are longer-lived. As a star dies, nuclear astrophysics argues that it will enrich the interstellar medium with heavy elements (in this case all elements heavier than lithium, the third element), from which new stars are formed. This account is consistent with the observed correlation between stellar metallicity and red shift.

The theory of stellar nucleosynthesis would not be very convincing if reliable nuclear physics inputs are adopted. By carefully scrutinizing the table of nuclides, nuclear astrophysicists were able to predict the existence of different stellar environments which could produce the observed isotopic abundances, and the nuclear processes which must occur in these stars. This is also valid for elements heavier than iron production, when fusion reactions are of negligible importance and the main nucleosynthetic path goes through p-process, r-process, and s-process. Many of the nuclides generated in the huge explosion triggered by the last burnings in the life of a massive star are unstable. Then in order to understand what is going on in Supernovae explosions, Gamma-ray bursts, Novae it was pointed out that the physics of radioactive beams should be explored. Many group of physicists have then taken the opportunities offered by the world-wide developments of radioactive ion beams facilities to start to investigate such environments. In this field also the weak interaction processes are important and in some cases, like type II Supernovae, dominant. This is extremely important in the multi-messenger astronomy era.

In order to better understand our Universe, a precise knowledge of nuclear inputs for nuclear astrophysics is therefore needed. They influence sensitively the nucleosynthesis of the elements in the early stages of the universe and in all the objects formed thereafter and control the associate energy generation, neutrino luminosity and stellar evolution. Thus a good knowledge of reaction rates is essential to understand this broad picture. Studies at the energies typical of nuclear astrophysics for charged particle induced reactions (few keV - 1 MeV) are severely hampered by the low signal-to-noise ratio, essentially due to the tiny cross sections that have to be measured (as low as picobarn in some cases). The best experimental solutions to this main problem will be discussed in this book and presented in their details. Selected experimental techniques such as underground facilities, recoil separators, spectrometers will be reviewed together with the wide field of nuclear astrophysics research opened by the development of radioactive ion beams in several laboratories of the world.

Detectors and facilities useful for the next decade of nuclear astrophysics studies were reviewed in the lectures and a big attention was devoted to future research possibilities for studies. This knowledge and facilities will be of groundbreaking importance for solving the future quests for this field. Although all these efforts in some cases (such as the $^{12}C+^{12}C$ interaction, the $^{12}C+^{16}O$, the $^{12}C(\alpha,\gamma)^{16}O$ and many others) the goal is far from being achieved by means of direct measurements. Moreover the presence of the electron screening effect makes very hard and sometimes impossible the measurement of the bare nucleus astrophysical factor, that is the quantity needed for astrophysics. Thus extrapolations are often adopted. An alternative way to by-pass these problems and measure the bare nucleus astrophysical factor or cross section is given by the indirect methods. Among them the Coulomb Dissociations, the ANC, and the Trojan Horse Method will be reviewed.

In recent years, new possibilities of exploring the universe have opened. In this view, stars and galaxies are nowadays investigated not only by means of electromagnetic spectra but also through new “eyes”, in the framework of the multi-messenger astronomy. In particular, gamma rays and gravitational waves play an important role for a better understanding of what is going on in the universe.

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C. Spitaleri
M. La Cognata
L. Lamia
R.G. Pizzone
S. Romano