Preface

This book contains the lectures given at the III European Summer School on Experimental Nuclear Astrophysics held from the 2^{nd} to the 10^{th} of October 2005 at the Santa Tecla Palace Hotel, about 15 km north-east of Catania, in the spectacular environment of the "Timpa" area, a green protected resort specific for its volcanic soil and vegetation directly on the Mediterranean sea.

One hundred between students and young researchers from more than 20 different countries attended high level lectures and were also encouraged to present their work and results.

The scientific program of the school spanned a wide range of issues dealing with various aspects of nuclear astrophysics, such as nucleosynthesis, microwave background radiation, γ-ray line astronomy, indirect methods and radioactive ion beams. Nuclear astrophysics plays a key role for understanding the energy production in stars, the stellar evolution and the concurrent synthesis of the elements and their isotopes. It is also a key to explain the ashes of the early universe, to determine the age of the universe itself, to predict the neutrino luminosity of the Sun and supernovae, etc. In this field nuclear reactions represent the "bone structure" for the above aspects, whose rates need to be determined in the laboratory. Although impressive progress has been made over the past decades, which was rewarded by various Nobel prizes, there remain major problems, which challenge the basis of the present understanding.

A list of the lecture topics is given below:

- Microwave background and big bang nucleosynthesis;
- Underground laboratory studies of pp and CNO and astrophysical consequences;
- Stellar evolution in general and in special effects (*e.g.* dredge-up, explosive mechanisms, etc.);
- Modern detection techniques in direct reactions;
- Electron screening in the laboratory and in stars;
- Indirect methods: Coulomb dissociation, ANC, THM, R Matrix;
- s-process and extended mixing in AGB and massive stars;
- Chemical evolution of the Galaxy;
- Supernova R-process and Cosmochronometry;
- Radioactive ion beams;

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- Radioactivity in the Universe and Solar system;
- Gamma-ray bursts;

It is hard to imagine the very beginning of the Universe. Physical laws were quite different from what we know today, due to the presence of incredibly large amounts of energy, in the form of photons. Some of the photons became quarks, and then the quarks formed neutrons and protons. Eventually huge numbers of Hydrogen, Helium and Lithium isotopes formed. The process of forming all these nuclei is called big bang nucleosynthesis. Theoretical predictions about the amounts and types of elements formed during the Big Bang have been made and seem to agree with observation. Furthermore, the cosmic microwave background (CMB), theoretically predicted as a fossil relic left over from the big bang, was discovered in the 1960's and mapped out at Berkeley in the early 1990's.

The 1983 Nobel Prize in Physics was shared by two astrophysicists, Subrahmanyan Chandrasekhar and William A. Fowler, for their work on stellar nucleosynthesis. Hydrogen, Helium, and Lithium were formed, at least in part, during the "Big Bang", but (in large part as a result of Fowler's work and the work he has inspired) it is now clear that all other nuclei were synthesized in stars and dispersed in the explosions at the end of their lives, except for the rest of the Lithium and for the Beryllium and Boron, which were produced from those heavier elements by cosmic ray bombardment in the interstellar medium. All this has been established by calculations modelling the interior structures (temperature, pressure, and composition as a function of radius) of many types of stars, and the changes in those quantities over time as the star burns up its nuclear fuel, as well as by the observed abundances.

The atoms heavier than Helium up to the iron group were made in the stellar cores. The lowest mass stars can only synthesize helium. Stars around the mass of our Sun can synthesize helium, and carbon. Massive stars (M greater than 10 solar masses) can synthesize helium, carbon, oxygen, neon, magnesium, silicon, sulfur, argon, calcium, titanium, chromium, and iron. Elements heavier than iron are supposed to be made either in massive supernovae, from the so-called rapid (r) neutron captures on heavy nuclei, or in slow (s) n-capture processes occurring in less massive stars in the final asymptotic giant branch (AGB) phases. In particular, the ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg reactions are considered as the neutron sources for the *s*-process isotopes, and pre-existing Fe (seed nucleus) reacts with these neutrons, producing the heavier elements.

The synthesized elements are dispersed into the interstellar medium by supernova explosions and stellar winds. These elements will be later incorporated into giant molecular clouds and eventually become part of future stars and planets.

Many of the nuclei generated in the explosions are unstable with quite short halflives. Among the various astrophysical sites of thermal nucleosynthesis of the radioactive nuclei we find AGB and Wolf-Rayet stars, novae, and type Ia and type II supernovae. Many groups of physicists have taken the opportunities offered by the recent developments of radioactive ion beam technology to investigate reactions involving unstable nuclei.

By constructing proper models for *s*- and *r*-processes in stars, one can deduce the age of the Galaxy accurately. Hence, the age of the universe can be obtained by adding the galactic ages to the time interval between the Big Bang and the start of galactic star formation. In old stars, the age can be sometimes estimated from the decay of long-lived nuclei. For the oldest stars of the Galaxy this would give a lower limit to the duration of the galactic life itself. It has been considered that the Th-Eu pair might be a good cosmochronometer, although it is going to be replaced by the U/Th ratio.

Concerning our Galaxy, a great deal of new data have become available during the last decade, revealing in principle the chemical history of the Milky Way and building up a set of observational constraints that have to be fulfilled by any successful theoretical model. These observational results deal in particular with issues like the age-metallicity relation, the star metallicity distribution, the abundance ratios of an increasing number of chemical elements, both in halo and local disk stars, and the radial abundance gradients. These observational efforts have been accompanied by the publication of several theoretical models which try to interpret the data.

Accretion from a hydrogen rich envelope of one star onto the electron degenerate surface of a compact evolved companion can generate the conditions required for a thermonuclear runaway. In a binary system such a case might occur when material from the outer layers of a red giant is transferred on to the surface of a white dwarf. Such an event is what we observe as a classical nova, and understanding the sequence of nuclear reactions that take place there is the key to understand the observed light curves and elemental abundances in the ejecta. Similarly, X-ray bursters can be interpreted as due to accretion on to a neutron star. In this case the deeper gravitational potential wells lead to hotter temperatures and higher pressures, and consequently the nuclear reaction pathways follow faster, more extreme routes. The rate at which the various reactions occur is determined not only by the environment, but also by the properties of the nuclei involved, typically their masses, halflives, modes of decay and properties of any excited states.

The most energetic part of the electromagnetic spectrum bears the purest clues to the synthesis of atomic nuclei in the universe. The decay of radioactive species, synthesized in stellar environments and ejected into the interstellar medium, gives rise to specific gamma ray lines. The observations gathered up to now show evidence for radioactivities throughout the galactic disk, in young supernova remnants (Cas A, Vela), and in nearby extragalactic supernovae (SN 1987A, SN 1991T and SN 1998bu), in the form of specific gamma ray lines resulting, respectively, from the radioactive decay of ^{26}Al, ^{44}Ti, ^{56}Co and ^{60}Fe. Nuclear excitations by fast particles also produce gamma ray lines which have been observed in great detail from solar flares, and more hypothetically from active star forming regions where massive supernovae and WR stars abound. The 511 keV line arising from $e^+ + e^-$ annihilation also provides important information on explosive nucleosynthesis, as well as on the nature of the interstellar medium where the positrons annihilate. INTEGRAL, the main mission devoted to high resolution nuclear spectroscopy, is leading to important progress in this field.

As mentioned, nuclear reactions are at the heart of nuclear astrophysics. They influence sensitively the nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter, and control the associated energy generation, neutrino luminosity, and evolution of stars. A good knowledge of the rates of these fusion reactions is essential to understand this broad picture. However low-energy studies of these reactions are hampered predominantly by background effects of cosmic rays in the detectors, leading typically to more than 10 background-events per hour in common detectors. Conventionally, passive or active shielding around the detectors can only partially reduce the problem of cosmic ray background. The best solution is to install accelerator facilities in underground laboratories. As a pilot project, a 50 kV accelerator facility has been installed in the Laboratory Nazionali del Gran Sasso, where the flux of cosmic-ray muons is reduced by a factor of 10^6 compared with the flux at the surface. This unique project, called LUNA has allowed physicists for the first time to directly measure important reactions of the pp-chain and CNO cycle.

In addition, the improvement in detection techniques, in particular the developement of the recoil separator ERNA, has allowed researchers to reach, in challenging reactions such as the ^{12}C(α,γ)^{16}O one, which determines the C/O ratio left at the end of the core-He burning phase, quality and precision never reached, but still far from the energy region of astrophysical interest.

Indeed, in several astrophysical contexts the energy values involved are so low that, for charged particle induced reactions, the Coulomb barrier makes it very difficult to extract the excitation function. For this reason, only in a few cases low-energy cross section measurements are experimentally available. However, at ultra-low energies measurements suffer from the complications due to the presence of atomic electrons. Their shielding effect on the nuclear charge is usually referred to as electron screening and determines a steep rise of the cross section at those energies, observed in a number of low-energy fusion reactions. In order to extract the cross section around the Gamow peak, an extrapolation procedure of the bare nucleus cross section $\sigma_{\rm b}(E)$ supported by theoretical arguments can be performed from higher energies, where negligible electron screening effects are expected (*e.g.* $E/U_{\rm e} \geq 100$, $U_{\rm e}$ being the electron screening potential energy).

Usually the extrapolation is performed by using the definition of the smoother bare nucleus astrophysical factor $S_{\rm b}(E)$:

$$S_{\rm b}(E) = E\sigma_{\rm b}(E)\exp(2\pi\eta) \tag{0.1}$$

where $\exp(2\pi\eta)$ is the inverse of the Gamow factor (η is the Sommerfeld parameter), which removes the dominant energy dependence of $\sigma_{\rm b}(E)$, due to the barrier penetrability.

In order to parameterize the cross section rise due to the screening effect, an enhancement factor is introduced as follows:

$$f_{\rm lab}(E) = \sigma_{\rm s}(E)/\sigma_{\rm b}(E) \approx \exp(\pi\eta U_{\rm e}/E) \tag{0.2}$$

where $\sigma_{\rm s}(E)$ is the cross section of shielded nuclei.

In the astrophysical environment, the cross section under plasma conditions $\sigma_{\rm pl}(E)$ is related to the bare nucleus cross section by a similar enhancement factor:

$$f_{\rm pl}(E) = \sigma_{\rm pl}(E)/\sigma_{\rm b}(E) \approx \exp(\pi\eta U_{\rm pl}/E) \qquad (0.3)$$

that can be calculated from the knowledge of the plasma screening potential $U_{\rm pl}$, depending on important properties of the plasma such as the Debye-Hückel radius. A measurement of $U_{\rm e}$, which is needed to calculate $\sigma_{\rm s}(E)$ from equation (0.2), would also help to better understand $U_{\rm pl}$.

However the $U_{\rm e}$ values deduced in fusion reactions are quite larger in all cases than the upper limit, given by the adiabatic model as the difference between the electron binding energies of the separate atoms in the entrance channel and that of the composite atom. This disagreement in laboratory experiments is not justified yet, and it does not help in understanding the effects under astrophysical conditions.

A weak point in the laboratory approach – and thus in the deduced $U_{\rm e}$ value – is the need for an assumption about the energy dependence of $\sigma_{\rm b}(E)$ at ultra-low energies. In order to avoid the extrapolation, alternative experimental methods for determining $\sigma_{\rm b}(E)$ appear highly desirable. In recent years a number of indirect methods have been introduced, such as the Coulomb Dissociation, the ANC (Asymptotic Normalization Coefficient) and the Trojan Horse Method (THM). These methods have been successfully applied, the first two to radiative capture reactions and the THM to charged particle induced ones, in order to obtain the bare nucleus $S(E)$-factor and therefore the electron screening potential without extrapolation.

Moreover, a great deal of information was supplied with the application of the R-matrix method to nuclear astrophysics, which is an ideal tool to treat collision processes.

Crucial problems related to various aspects of nuclear as well as astro-physics are still open, triggering new research in this field and the enthusiasm to organize events, such as our ENA school.

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The School has been honored by the welcome address of Prof. Ferdinando Latteri, Rector of the Università di Catania, On. Fabio Fatuzzo, member of the national Parliament, On. Raffaele Stancanelli, councillor of the Sicilian government, Prof. Marcello Rodonò, director of the Department for Astronomical and Astrophysical Observatories, Prof. Francesco Porto, director of the Department of

Physics and Astronomy, Prof. Salvatore Lo Nigro, director of the “Centro Siciliano di Fisica Nucleare e Struttura della Materia”.

This book is dedicated to the Memory of Prof. Marcello Rodonó, who passed away on October, the 23rd 2005.

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