Nuclear astrophysics in a nutshell

Nuclear fusion reactions are known to be responsible for nucleosynthesis and energy production in stars. The reaction rate is given by the product of the Maxwell-Boltzmann distribution of the relative velocity of interacting species and the reaction cross section. This product is significantly different from zero in the energy interval named Gamow window. In this energy range, the cross section drops very quickly, making direct measurements challenging, if not impossible, depending on the counting rate and background.

The extrapolation of the measured cross section down to the Gamow window may provide an estimate of the rate, but experimental uncertainties make the extrapolation uncertain too. Moreover, given the possible existence of low energy resonances, the extrapolation of the cross section at lower energies is not always reliable and direct measurements inside (or close to) the Gamow window are required.

Gran Sasso National Laboratory (LNGS)

The Gran Sasso National Laboratory (LNGS), located in Assergi (Italy), is the largest underground research laboratory in the world. Its construction has been proposed 30 years ago by Prof. Antonino Zichichi. The excavation began in 1982 and the first experiments started taking data in 1987.

Inside LNGS, cosmic rays are effectively shielded by the 1400 m thick rock overburden. The muon flux is reduced by a factor of $10^6$ w.r.t. the surface and the muon-induced neutron flux is reduced by a factor of $10^8$ [1]. This background reduction allows many experiments to study rare processes such as neutrino interactions, neutrinoless double-$\beta$ decay, dark matter interactions and nuclear reactions at astrophysical energy.

From LUNA-400 kV to LUNA-MV

LUNA has been the first deep underground accelerator for nuclear astrophysics, operating since 1993. LUNA uses a 400 kV single-ended electrostatic accelerator [2], provided with two beamlines for solid targets and differential-pumping, windowless gas targets [3]. The accelerator has been especially designed to achieve high-current (up to 1 mA) proton and alpha beams with high stability (<5 eV/h drift).

A new phase of the LUNA project is beginning right now, with the installation of a 3.5 MV accelerator [4,5] in Hall B at LNGS. This machine will allow the investigation of some key reactions of He and C-burning in the energy range they are taking place in their respective astrophysical scenarios.

Some of the reactions that will be investigated are listed below [4,5]. $^{14}$N(p,$\gamma$)$^{15}$O: immediately after commissioning (to test the whole setup). Important for CNO cycle and neutrino flux estimation (reduction of the uncertainty at low-energy).

$^{12}$C + $^{12}$C; $^{12}$C(12C,$\alpha$)$^{20}$Ne, $^{12}$C(12C,p)$^{23}$Na and $^{12}$C(12C,n)$^{23}$Mg regulate the C-burning phase of massive stars (ignition, temperature, duration, evolution of a massive star up to the transformation into a white dwarf or a core-collapse supernova).

$^{13}$C($\alpha$,n)$^{16}$O there is a need to cover a wide energy range for better extrapolations, and a need to solve normalization problems related to indirect measurements at about 1 MeV.

$^{22}$Ne($\alpha$,n)$^{25}$Mg: main source of neutrinos in massive stars (lack of data below 800 keV).

$^{12}$C( $\alpha$, $\gamma$)$^{14}$O: the Holy Grail of Nuclear Astrophysics, to be investigated after 2023, in a second phase of LUNA-MV.

References