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Nuclear astrophysics in the era of multi-messenger observations at INFN-LNS

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Gravitational waves detection in neutron mergers and the parallel observations in the visual and IR spectrum have triggered a new era in astronomy, the so-called multi-messenger era, where information of astrophysical significance is carried by different messengers. The possibility to identify a source and follow its time evolution has opened a new window on exotic phenomena, allowing us to pinpoint a realistic site for the r-process.
Such more in-depth analysis of the astrophysical scenarios calls for a parallel comprehensive study of the nuclear processes powering them. In this contribution I will review the research activity that is presently carried out and it is under development at the INFN-Laboratori Nazionali del Sud (Italy). It can be broadly divided into three categories: (i) constraining the r-process through a better understanding of the s-process; (ii) the study of nuclear reactions involved in the r-process; (iii) studying the opacity of a plasma made up of lanthanides.
Understanding the s-process nucleosynthesis plays a pivotal role since abundances of r-nuclei are deduced by subtracting the calculated s-process yields from the galactic chemical abundances. Therefore, uncertainties on s-elements production directly reflects on the r-process yields. Now, while the 13C(a,n)16O neutron source is well constrained, the 22Ne(a,n)25Mg one, supplying a larger neutron flux than 13C(a,n)16O, is still affected by large uncertainties, calling for further studies to better constrain the s-process and so the r-process. Also, the investigation of neutron-capture cross sections, especially in the case of branch point nuclei, can help constraining the r-process nucleosynthesis. With this respect, the Trojan horse method (THM) is an indirect approach developed at LNS making it possible to study reactions of astrophysical importance (also neutron-induced) at the corresponding Gamow energies.
Such studies are important for point (ii) as well. In this case, other processes such as the study of the 12C+12C fusion reactions are very important. In fact, the cross section influences the rate of core collapse supernovae and, consequently, the neutron star birth rate. This is also independently determined from 26Al galactic abundance, so the reactions responsible from the production and destruction of 26Al plays an important role to cast light on the neutron star formation rate. With this respect, 26Al (n,p) and (n,a) reactions on the ground and isomeric state have a strong influence on the 26Al yield from core-collapse supernova explosion, and their study will be performed through the THM in the near future.
Also beta decay of r-nuclei has a great relevance in determining the abundance pattern deduced from the galactic material. In particular, beta-delayed neutron emission (βn) is a form of radioactive decay in which an electron, an anti-neutrino and one or more neutrons are emitted. The initial abundance distribution is shaped by the decay half-life T1/2, but the neutron emission affects the final abundances in two ways: on the one hand it shifts the decay path to lower masses and on the other hand it provides a source of neutrons for late captures that shift masses in the opposite way. Thus, a good knowledge of Pn and T1/2 values of the nuclei between the valley of stability and the r-process path is needed for a correct understanding of the observed abundances. The availability of FRIBS radioactive ion beams (and of the forthcoming separator FRAISE) and of the polycube neutron counter at LNS will make it possible to perform high accuracy studies of βn processes.
The third point is also extremely important, since along with a gravitational-wave signal and a short burst of γ-rays, neutron star mergers give rise to a transient optical–near-infrared (kilonovae). Unlike supernova absorption lines, the identification of kilonova atomic species is not secure. Therefore, the identification of

r-nuclei in the ejecta is achieved by investigating the transient light curves, the maximum being directly connected with the optical thickness of the ejecta. The measured light curves suggest that the opacity is dominated by transitions from the lanthanides. However, predictions of the transient light curves and spectra suffer from the uncertain optical properties of heavy ions. At LNS we will have the unique opportunity to produce a controlled lanthanides plasma, with more accurate determination of temperature and density with respect to laser induced plasmas. The possibility to produce such stable and controlled plasmas is under study at LNS (Pandora project).

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