**Please specify an acronym, a project title and the name(s) of the project leader(s)**

NUCATOLE NUClear Astrophysics Towards the clarification of Lingering Experimental problems

M. La Cognata (PI), D. Lattuada, A. Tumino, J.P. Fernandez Garcia, F. De Oliveira Santos, S. Pisano, S. Typel

**In the sections below, please provide details on** *(2 pages max.):*

**1. Research objectives**

The origin of the chemical elements is a key question in physics. In particular, nuclei heavier than iron are mostly produced by neutron captures, either slower (s-process) or faster (r-process) than the beta decay rates. Observations of gravitational waves (e.g. the event GW170817) and the concurrent measurements of electromagnetic radiations opened a new era in physics, leading to multimessenger astronomy. Such observations proved that the r-process is taking place during Neutron Star Mergers, by observing and interpreting the electromagnetic transient (the so-called kilonova) following the gravitational event.

To understand such events, from progenitor neutron stars and merger dynamics to nucleosynthesis that powers emissions and pollutes the interstellar medium, a large number of physical inputs is necessary. In this framework, nuclear cross sections play a key role, especially those of reactions involving neutrons and short-lived nuclei, as well as the nuclear equation of state, involving hadronic degrees of freedom.

Currently, neutron-capture cross section data for short-lived nuclei are unavailable, as targets cannot be produced, so one has to rely on nuclear models, often inaccurate, to calculate the relevant cross sections. Indirect methods such as the Trojan Horse Method (THM) and novel approaches such as the use of high-power lasers could be fruitfully used to measure the relevant cross sections and benchmark the theoretical models. This would make many physical problems connected with the leading field of multimessenger astronomy accessible to nuclear physics laboratories such as CERN-ISOLDE, GSI, GANIL, and LNF, while GSI and ECT\* may provide the theoretical support.

European research institutions are strongly committed both in the investigation of gravitational events and multimessenger astronomy, and in the field of the physics of radioactive nuclei. Here we aim at linking the efforts, by extending the reach of existing radioactive ion beam facilities and of the next generation ones, to provide crucial input for modeling r-process nucleosynthesis and the sources to be targeted in multimessenger studies.

Nuclear astrophysics is, in essence, a highly interdisciplinary domain connecting the low-energy physics community, with diverse areas including astronomy, atomic physics, nuclear physics (from low energy reactions to heavy ion collision) and hadronic physics, as in the case of studying the nuclear equation of state, an essential ingredient in the modeling of the merger of neutron stars. While projects such as Horizon CHETEC-INFRA have significantly strengthened these synergies, further development towards novel techniques is necessary to extend the reach and the available physics portfolio of existing facilities, thus improving the services they offer, and to connect with other communities providing for the know-how in hadronic physics. The following sections will detail specific research objectives.

***1.a Indirect methods in nuclear astrophysics***

The THM offers a distinct advantage by requiring fixed beam energies to span the whole excitation function including energies of astrophysical interest. Moreover, the breaking of the TH nucleus and the intercluster motion would make it possible to fine tune the effective interaction energy of the indirectly measured reaction. Both features perfectly align with the capabilities of most RIB facilities (like GANIL, CERN-ISOLDE, and GSI-FAIR) for which it is not easy to carry out energy changes in small steps, as it would be required to measure cross sections for astrophysical energies. Furthermore, THM enables the study of reactions at astrophysical energies even when facilities deliver beams at significantly higher energies.

***1.b Reactions in laser-induced hot and dense plasmas***

One of the main issues in nuclear astrophysics is the smallness of cross sections. While astrophysical environments compensate for this with a large number of interacting nuclei, laboratory experiments suffer from a drastically reduced signal-to-noise ratio. While indirect methods make it possible to measure larger cross sections, the increase in the number of interacting species can be achieved by measuring reaction cross sections in hot and dense plasmas. These plasmas are produced in the interaction of high-power lasers with specifically designed targets, such as cryogenic systems. A distinctive advantage of this approach is the possibility to investigate nuclear reactions under conditions similar to the astrophysical ones, where electron screening by plasma electrons plays a role. Such conditions are very different from the laboratory ones and laser-induced plasmas are a unique environment where these processes can be studied. Nuclear reactions in plasmas can be studied using two complementary approaches: the generated plasma can act as a target while a standard beam (stable or radioactive) can be used to induce the reaction of astrophysical importance (as is done at GSI); or, nuclear reactions can occur in the plasma itself, given the high temperatures and densities (a capability anticipated at LNF).

***1.c Theoretical developments***

A common thread in such advances in nuclear astrophysics is the need of more advanced theoretical frameworks, for which we will establish connections with GSI, ECT\* and the University of Seville. In the application of indirect methods, the off-shell propagation of the transferred particle needs to be considered explicitly before it interacts with the second nucleus in the initial state of the THM reaction to participate in the reaction of astrophysical interest. The interactions in the initial and final state of the THM reaction require modeling via optical potentials, moving beyond plane-wave approximations. A strong connection with the theory of direct reaction is therefore crucial, especially as we aim to study multi-resonant reactions entering the Hauser-Feshbach statistical regime, crucial for the investigation of reaction entering the r-process. On the other hand, for studying reactions in plasmas, hydrodynamic system modeling is a necessary tool for the optimization of laser and target systems.

***1.e Training of younger generations and outreach***

The research activity will be complemented by a strong focus on training young scientists in the field of nuclear astrophysics. Given the highly interdisciplinary nature of nuclear astrophysics, specialized schools are necessary to provide future researchers with the tools to identify key open issues, carry out experiments and assess the astrophysical impact of their findings. In this respect, the long-standing European Summer School on Experimental Nuclear Astrophysics (ESSENA) is a crucial asset for the community. Training through devoted schools will be complemented by outreach activities, with the aim of disseminate the research results as well as to attract younger people, especially women and minorities, to science.

1. **Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)**

Foreseen TA infrastructures are: CERN; GSI/FAIR, ECT\*, LNF Frascati (Italy)

**3. Estimated budget request**

Excluding transnational access to labs for experiments, our budget is approximately € 200.000. This includes € 100.000 for tools and consumables (interaction chamber for plasma studies, detector systems and plasma diagnostics), € 85.000 for a two-year postdoctoral position, and € 15.000 to support two editions of the ESSENA school.

**4. Participating and partner institutions**

INFN with LNS Catania and LNF Frascati, TU Darmstadt and GSI, University of Seville, GANIL