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Nuclear Reactions Studies in Laser-Plasmas at the forthcoming ELI-NP facilities

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Abstract. This work aim to prepare a program of studies on nuclear physics and astrophysics, which will be conducted at the new ELI-NP Laser facility, which actually is under construction in Bucharest, Romania. For the arguments treated, such activity has required also a multidisciplinary approach and knowledge in the fields of nuclear physics, astrophysics, laser and plasma physics join with also some competences on solid state physics related to the radiation detection. A part of this work has concerned to the experimental test, which have been performed in several laboratories and in order to study and increase the level of knowledge on the different parts of the project. In particular have been performed studies on the laser matter interaction at the ILIL laboratory of Pisa Italy and at the LENS laboratory in Catania, where (by using different experimental set-ups) has been investigated some key points concerning the production of the plasma stream. Test has been performed on several target configurations in terms of: composition, structure and size. All the work has been devoted to optimize the conditions of target in order to have the best performance on the production yields and on energies distribution of the inner plasma ions. A parallel activity has been performed in order to study the two main detectors, which will constitute the full detections system, which will be installed at the ELI-NP facility.

1. Introduction

Given its nature, the plasma state is characterized by a complexity that far exceeds the one exposed by the solid, liquid, and gaseous states. Correspondingly, the physical properties of nuclear matter (structure, reaction mechanisms, lifetimes, etc.) could change inside the plasma. Thus, the study of

these properties represents one of the most far ranging, difficult and challenging research areas today. Implications can cover also others fields, from quantum physics to cosmology, astrophysics, etc.
One of the crucial topics related to nuclear reactions in the ultra-low energy regime is the electron screening, which prevents a direct measurement of the bare nucleus cross section at the energies of astrophysical interest. Since in the laboratory interacting particles are in the form of neutral atoms, molecules or ions, in direct experiments at very low beam energy, electron clouds partially screen the nuclear charges thus reducing the Coulomb suppression. This results in an enhancement of the measured cross section compared with the bare nucleus one. The electron screening effect is significantly influenced by the target conditions and composition. In this context, it is of particular importance the measurement of cross-sections at extremely low energetic domains including plasmas effect, i.e. in an environment that under some circumstances and assumptions can be considered as “stellar-like”. A further key point is connected with the fact that in such environment nuclear reactions can be triggered also by the excited states of the interacting nuclei. Thus, determining the appropriate experimental conditions that set the role of the excited states in the stellar environment can strongly contribute to the development of nuclear astrophysics [1]. The study of direct measurements of reaction rates in plasma offers this chance.
The future availability of high-intensity laser facilities [2,3] capable of delivering tens of peta-watts of power into small volumes of matter at high repetition rates will give the unique opportunity to investigate nuclear reactions and fundamental interactions under extreme plasma conditions, including also the influence of huge magnetic and electric fields, shock waves, intense fluxes of γ and X rays originating during plasma formation and expansion stages.
A laser is a unique tool to produce plasma and very high fluxes of photons and particles beams in very short duration pulses. Both aspects are of great interest for fundamental nuclear physics studies. In a plasma, the electron–ion interactions may modify atomic and nuclear level properties. This is of prime importance for the population of isomeric states and for the issue of energy storage in nuclei. Nuclear properties in the presence of very high electromagnetic fields, nuclear reaction rates or properties in hot and dense plasmas are new domains of investigation. Furthermore, with a laser it is possible to produce electric and magnetic fields strong enough to change the binding energies of electronic states. If nuclear states happen to decay via internal conversion (IC) through these perturbed states, a modification of their lifetimes will be seen. The excitation of nuclear levels by means of energy transfer from the atomic part to the nuclear part of an atom is the subject of a large number of investigations. Their goal is to find an efficient mechanism to populate nuclear isomers in view of further applications to energy storage and development of lasers based on nuclear transitions. In addition, other new topics can be conveniently explored such as three-body fusion reactions as those predicted by Hoyle [4,5].
Several Laser facilities are under construction around the world to push the physics beyond the actual level of knowledge. Among of these, the Extreme Light Infrastructure for Nuclear Physics at Magurele (Bucharest) in Romania, will be the only one devoted to Nuclear Physics studies.
ELI-NP [2] will be made up of a very high intensity laser system, consisting of two 10 PW laser arms able to reach intensities of 10^{23} W/cm2 and electrical fields of 10^{15} V/m, and very short wavelength γ beams with very high brilliance (10^{13} γ/s) and energy up to 19.5 MeV. This combination allows for three types of experiments: stand-alone high power laser experiments, stand-alone γ beam experiments and combined experiments of both facilities. Here the low repetition rate (1/min) of the high power laser requires the same low repetition rate for the γ beam in combined experiments. While the standalone γ beam will be used with typically 120 kHz, the low repetition mode requires few very intense γ pulses. With the high power laser we do not plan to interact with nuclear dynamics directly, but we use the laser for ion acceleration or to produce relativistic electron mirrors followed by a coherent reflection of a second laser beam in order to generate very brilliant X-ray or γ beams. We plan to use these beams later to produce exotic nuclei or to perform new γ spectroscopy experiments in the energy or time domain. The production of heavy elements in the Universe, a central question of astrophysics, will be studied within ELI-NP in several experiments.
In this article some of the activities, related to the project of study of nuclear astrophysics at ELI-NP will be discussed. A brief introduction is given to present the main open problems on nuclear

astrophysics and the opportunity offered by the laser matter interaction scheme. Afterwards, it is shown a short presentation of ELI-NP project and the studies performed to prepare the future activities and test on plasma and nuclear detectors. Finally, same results of the tests performed on the new targets are presented and discussed.

2. Open problems on nuclear astrophysics

Accurate measurements of nuclear reaction rates of proton and alpha burning processes are essential for the correct understanding of many astrophysical processes, such as stellar evolutions, supernova explosions and Big Bang nucleo-synthesis, etc. To this aim direct and indirect measurements of the relevant cross sections have been performed over the years. Since in the laboratory interacting particles are in the form of neutral atoms, molecules or ions, in direct experiments at very low beam energy, electron clouds partially screen the nuclear charges thus reducing the Coulomb suppression [6]. This results in an enhancement of the measured cross section compared with the bare nucleus one [7]. The electron screening effect is significantly affected by the target conditions and composition [8]; it is of particular importance the measurement of cross-sections at extremely low energetic domains including plasmas effect, i.e. in an environment that under some circumstances and assumptions can be considered as “stellar-like” (for example, for the study of the role played by free/bounded electrons on the Coulombian Screening can be done in dense and warm plasmas). Electron screening prevents a direct measurement of the bare nucleus cross section at the energies of astrophysical interest. In the last decade, the bare cross section has been successfully measured in certain cases by using several indirect methods [9]. Habitually, astrophysical appropriate reactions are performed in laboratories with both target and projectile in their ground state. However, at temperatures higher than about 10^8K, an important role can be also played by the excited states, as already deeply discussed in the innovative theoretical work of Bahcall and Fowler [10]. In that case, the authors studied the influence of low lying excited ^{19}F states on the final ^{19}F(p,alpha) reaction, predicting an increase of a factor of about 3 in reaction rate at temperatures of about 1-5 GK.

Thus determining the appropriate experimental conditions that allow the role of the excited states in the stellar environment could strongly contribute to the development of nuclear astrophysics. The study of direct measurements of reaction rates in plasma offers this chance. In addition others new topics can be conveniently explored such as three body fusion reactions as those predicted by Hoyle [4], lifetime changes of unstable elements [11] or nuclear and atomic levels [12] in different plasma environments; other fundamental physics aspects like non-extensive statistical thermodynamics [13] can be investigated in order to validate/confute the general assumption of local thermal equilibrium that is traditionally done for plasmas. The future availability of high-intensity laser facilities capable of delivering tens of peta-watts of power (e.g. ELI-NP) into small volumes of matter at high repetition rates will give the unique opportunity to investigate nuclear reactions and fundamental interactions under extreme conditions of density and temperature that can be reached in laser generated plasmas [14], including the influence of huge magnetic and electric field, shock waves, intense fluxes of X and γ-ray originated during plasma formation and expansion stages.

To investigate these research topics, we are proposing the construction of a general-purpose experimental set-up, where it will be possible to study the electronic screening problem in a wide variety of cases and configurations with different purposes [4,5,15]. Through the laser-target interaction, we aim at producing plasmas containing mixtures of ^{13}C + ^{4}He and ^{7}Li + d appropriate to investigate inner-plasma thermo-nuclear reactions. The ^{13}C+^{4}He reaction is of key interest for the investigation of the helium burning process in advanced stellar phases [16]. The ^{7}Li(d,n)^{4}He-^{4}He reaction was recently addressed by Coc et al. [17] as one of the most important reactions affecting the CNO abundances produced during the primordial nucleosynthesis (BBN). Very few experimental data exist, and authors consequently assume a constant S-factor ranging between two extreme hypotheses values.

Also, we propose to investigate the ^{11}B(^{3}He, d)^{12}C* reaction in a plasma. Nucleonic matter displays a quantum-liquid structure, but in some cases finite nuclei behave like molecules composed of clusters of protons and neutrons. To perform the proposed experiments, providing relevant data concerning the aforementioned reactions and others, we aim to take advantage from the excellent and unique

performance of the ELI-NP [2] facility and realize an experimental setup where two laser beams generate two colliding plasmas. The reaction products (neutrons and charged particles) will be detected through a new generation of plastic scintillators wall and through a new silicon carbides wall.
The use of colliding plasma plumes appropriate for nuclear physics studies was suggested few years ago at LNS [14] and recently adopted also by other research teams [18]. One of the possible schemes may be the following: a first laser pulse imping on a ^{13}C, ^{7}Li or ^{11}B solid thin target (few micro-meters) producing, through the well-known TNSA [19] (Target Normal Sheath Acceleration) acceleration scheme, boron, carbon or lithium plasma. The rapidly streaming plasma impacts on a secondary plasma, prepared through the interaction of a second laser pulse on a gas jet target (made by ^{4}He, D_2 or ^{3}He). TNSA [19] was intensively studied in the last years; experiments [20] and models [21] show that this acceleration scheme works very well in the intensity domain between 10^{18}-10^{20} W/cm^2. The produced ions expand along a cone, whose axis is normal to the target surface, with a relatively low emittance [22].

3. Experimental Set-Up

The project will take advantage from the excellent and unique performance of the ELI-NP facility to create two colliding plasmas using two separate laser beams. The use of colliding plasma plumes suitable for nuclear physics studies [23] was proposed few years ago [14] and recently adopted to achieve such goal [18]. The idea is the following: a first laser pulse impinging on a 13C, 7Li or 11B solid thin target (few micro-meters) produces, through the TNSA (Target Normal Sheath Acceleration) [20] acceleration scheme, boron, carbon or lithium plasma. In view of this, an extensive experimental investigation programme is in progress, aiming at the optimization of targets and interaction configuration [24,25]. The rapidly streaming plasma impacts on a secondary plasma, prepared through the interaction of a second laser pulse on a gas jet target (made by 4He, D2 or 3He). The proposed activity requires also the construction of a highly segmented detection system for neutrons and charged particles. The segmentation is required for the reconstruction of the reactions kinematic. The ideal neutron detection module for these studies must exhibit: high efficiency, good discrimination of gammas from neutrons, good timing performance for ToF (Time of Flight) neutron velocity reconstruction. In addition, it must be able to work in hard environmental conditions, like the ones established in the laser-matter interaction area. All these aspects may be met by configuration based on 50x50x50 mm^3 PPO-Plastic scintillator plus a SiPM [26] read-out and a totally digital acquisition of the multi-hit signals. Concerning the charged particle detector, an R&D activity was funded by INFN on Silicon Carbide [27]. In this framework we aim to realize a wall of detectors. The SiC detectors have been proven recently to have excellent properties [28,29]: high energy and time resolution, resistance to radiation, low sensitivity to visible light, etc. The use of segmented SiC detectors would be very helpful for the study of nuclear reactions where only the position and energy measurement of light charged particles can give access to the desired information. In conclusion, we present in this contribution the research project that our collaboration will conduct in the next years @ELI-NP. More details about these activities are reported in reference [2].

4. Experimental Investigation on acceleration mechanisms and target.

A experimental campaign aiming at investigating the ion acceleration mechanisms through laser-matter interaction in femtosecond domain has been carried out at the Intense Laser Irradiation Laboratory (ILIL-Pisa, Italy) [30] facility with a laser intensity of up to 2 10^{19}W/cm^2. In recent years, laser ion acceleration has gained much interest focusing on fast ions emitted from a solid target by intense laser irradiation [31,32]. Protons and heavier ions can be accelerated up to tens MeV per nucleon via various mechanisms such as target normal sheath acceleration (TNSA) [19,20,33,34], radiation pressure acceleration (RPA) [35-39], and break-out afterburner acceleration (BOA) [40-42]. Our work concerns the TNSA regime, in which an intense laser pulse is focused (> 10^{18} W/cm^2) on different micrometers thick foil target.
In this context, we carried out a systematic experimental investigation to identify the role of target properties in TNSA, with special attention to target thickness and dielectric properties. We used a full range of ion, optical, and X-ray diagnostics to investigate laser-plasma interaction and ion

acceleration. We focus on the results obtained using a Thomson Parabola Spectrometer (TPS). In the TPS, often used in such experiments, ions with different charge-to-mass ratios are separated into distinct parabolas. This allows to extract information for each ion species when several ions are generated simultaneously in a given solid angle. In the paper [43] we discuss the energy spectra of light-ions depending on structural characteristics of the target. Surface and volume contributions to the ion acceleration have been clearly identified by using a unique target configuration consisting of a thin CD_2 foil. Preliminary results show that protons and deuterons temperatures show opposite trend, suggesting a complex interplay between surface and volume acceleration [43] .

More experimental campaign [44] aiming at investigating the ion acceleration in laser-driven plasma with the production of a quasi-monoenergetic beam has occurred. At the LENS (Laser Energy for Nuclear Science) laboratory of INFN-LNS in Catania, experimental measures were carried out; the features of LENS are: Q-switched Nd:YAG laser with 2 J laser energy, 1064 nm fundamental wavelengths, and 6 ns pulse duration. Measures demonstrate that at the reached values of fluence even when using ns lasers, quasi-mono-energetic protons and aluminum ion beams can be generated. The presented results [45] represent a very stable and reproducible phenomenon. The production of mono-energetic protons from aluminum target was predicted by our previous work that correlated the spectrum to the initial proton distribution on the target. Preliminary results show the production of multi-charged ions having very narrow energy spreads [45-46]. The presented results are no singular manifestations, but represent a very stable and reproducible phenomenon. The production of quasi mono-energetic Al^n from aluminum target was predicted by our previous work [47] that correlated the spectrum to the initial ions distribution on the target. A linear dependence between the energy of the laser and the energy of the mono-peaks of ions produced is evident.

Also, we investigate the effects of innovative nanostructured targets [48] based on Ag nanowires on laser energy absorption in the ns time domain. The tested targets were realized at INFN-Bologna by anodizing aluminium sheets in order to obtain layers of porous Al^2O^3 of different thicknesses, on which nanowires of various metals are grown by electro-deposition with different heights. Targets were then irradiated by using a Nd:YAG laser at different pumping energies. Advanced diagnostic tools were used for characterizing the plasma plume and ion production. As compared with targets of pure Al, a huge enhancement (of almost two order of magnitude) of the X-ray flux emitted by the plasma has been observed when using the nanostructured targets, with a corresponding decrease of the "optical range" signal, pointing out that the energetic content of the laser produced plasma was remarkably increased. Signs of plasma stagnation, of great interest for carrying out inner-plasma studies, have been found [48]. Special targets, based on Co, Ni and Fe NWs, with high absorbance in the VIS and NIR range, have been irradiated with the same laser LENS. From preliminary results [49], a higher X-ray intensity was observed for all samples compared to bulk-Al, with about a ten-fold increase for Co NWs and around a five-fold increase for Ni and Fe NWs. Further tests are needed to explain such a difference among metals, which cannot be accounted in terms of different atomic numbers. Moreover, there are strong indications that plasma conditions for NWs targets are quite different from those obtained for bulk targets. This indication could be very promising, since it could open the possibility to study specific nuclear reactions in plasma, at high rates. Concerning the results on the plasma temperature analysis, NWs and the bulk-Al target seams have close temperatures. This scenario is consistent with the indication that plasma conditions for NWs targets are quite different from those obtained for bulk targets, at least in terms of plasma density and/or plasma stagnation [14]. If confirmed, these results could be very useful for nuclear physics studies, because can contribute to the increasing of the total reaction events.

All these experimental observations, although in a preliminary stage of analysis, provide a quite complete characterisation of the laser–target interaction regime in our experimental conditions and a reference set of data for the upcoming ELI-NP facility installation.

5. References

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