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Study of nuclear reactions in laser plasmas at future ELI-NP facility

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Abstract

In this contribution we will present the future activities that our collaboration will carry out at ELI-NP(Extreme Light Infrastructure Nuclear Physics), the new multi peta-watt Laser facility, currently under construction at Bucharest (Romania). The activities concerns the study of nuclear reactions in laser plasmas. In this framework we proposed the construction of a new, general-purpose experimental set-up able to detect and identify neutrons and charged particles.

1 Introduction

Plasma is the most common form of ordinary matter known in the universe. One of the crucial aspects is the possible appearance of new phenomena in nuclear physics (nuclear reactions, nuclear structure or nuclear properties) in plasmas. The discovery, for example, that, in the nuclear reactions, at very low energies the electrons of the target atoms partially screen the Coulomb barrier between the projectile and the target nuclei, with a resulting enhancement of the fusion cross section, opens new and important perspective on astrophysics and cosmology. Such an effect, called "electron screening", affects our knowledge of nuclear processes in stellar plasmas. Getting information about this process wold be extremely important. A further important issue concerns the influence of nuclear excited states on fusion cross-section. Nuclear reactions, relevant for astrophysical studies have been performed in the past at other laboratories, with both target and projectile in their ground state. However, in high temperatures plasmas ($> 10^8 K$), an important role can also be played by the excited states, as already deeply discussed in the pioneering theoretical work of Bahcall and Fowler [1]. 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 reaction rate of a factor of about 3 at temperatures of about 10^9 K. Thus, determining the appropriate experimental conditions that allow the role of the excited states in the stellar environment to be evaluated could strongly contribute to the development of nuclear astrophysics. The direct measurement of reaction rates in plasma offers this chance. In addition, other new topics can be conveniently explored by studying nuclear reactions in plasmas, such as, for instance, three body fusion reactions (as those predicted by Hoyle [2]), lifetime changes of unstable elements [3] or nuclear and atomic levels [4] in different plasma environments and fundamental physics issues like non-extensive statistical thermodynamics [5]. This last topic can be investigated in order to validate/confute the general assumption of local thermal equilibrium that is traditionally adopted for plasmas [6].

2 Physics case

In 2013 our collaboration submitted a scientific project, which aims to perform nuclear reactions studies in Laser plasmas at the future ELI-NP facility. Among the various nuclear reactions which have attracted relevant attention also for astrophysical or cosmological reasons, the collaboration selected as the first case study the ^{13}C(^{4}He,n)^{16}O and ^{7}Li(d,n)^{4}He-^{4}He reactions; the first for its relevance in the frame of stellar nucleosynthesis, while the second for the role played in Big Bang primordial nucleosynthesis. We aim to produce plasmas containing mixtures of ^{13}C + ^{4}He and ^{7}Li + d in order to investigate inner-plasma thermo-nuclear reactions. In relation to the studies of weakly bound nuclear states, the collaboration selected also, as a first case of study, the ^{11}B(^{3}He, d)^{12}C* reaction. Nucleonic matter displays a quantum-liquid structure, but in some cases finite nuclei behave like molecules consisting of clusters of protons and neutrons. Clustering is a recurrent feature in light nuclei, from beryllium to nickel. Cluster structures are typically observed as excited states close to the corresponding decay threshold; the origin of this phenomenon lies in the effective nuclear interaction, but the detailed mechanism of clustering in nuclei has not yet been fully understood. It is extremely interesting to study such aspects in a laser produced plasma.

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 was proposed few years ago [7] and recently adopted to achieve such goal [8]. The idea is the following: a first laser pulse impinging on a ^{13}C, ^{7}Li or ^{11}B solid thin target (few micro-meters) produces, through the TNSA (Target Normal Sheath Acceleration) [9] 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 [10,11] 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).
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 [12] 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. In this frame work we aim to realize a wall of detectors. The SiC detectors have been proven recently to have excellent properties [13-14]:

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 [15].

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