Study of electron screening puzzle through interaction laser-matter

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Abstract

A direct measure of rates and/or cross-sections (S-factors) in laboratory is important to have a better understanding of many astrophysical processes. It is of paramount relevance 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 in dense and warm plasmas). We propose to study nuclear reactions at low energies inside dense and energetic plasmas generated in laboratory at unprecedented conditions thanks to the unique characteristics foreseen at the future ELI-NP laser facility.

Keywords: laser, S-factor, electron-screening,SiPM.

Introduction: The Physic Case

Performing accurate measurements of nuclear reaction rates of proton and alpha burning processes is essential for the correct understanding of many astrophysical processes, such as stellar evolutions, supernova explosions and Big Bang nucleosynthesis, etc. Direct and indirect measurements of the relevant cross sections have been performed over the years. Direct measurements using accelerated beams show that, at very low energies, the electrons in the targets atoms partially screen the Coulomb barrier between the projectile and the target [1], resulting in an enhancement of the measured cross section compared with the bare nucleus cross section [2]. The electron screening effect is significantly affected by the target conditions and composition [3], 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. Moreover astrophysical relevant reactions are performed in laboratories with both target and projectile in their ground state. However, at temperatures higher than about 108K, an important role can be also played by the excited states, as already deeply discussed in the pioneering theoretical work of Bahcall and Fowler [4]. Thus determining the appropriate experimental conditions that allow to evaluate 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. 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 the extreme conditions of density and temperature that can be reached in laser generated plasmas [5] Among the various nuclear reactions which have attracted relevant attention for astrophysical or cosmological reasons, we selected as first physical cases to study the $^{13}C(^{4}He,n)^{16}O$ and $^{7}Li(d,n)^{4}He$-^{4}He reactions: the former for its relevance in the frame of stellar nucleosynthesis, the latter for the role played in Big Bang primordial nucleosynthesis. Through the laser-targets interaction, we aim at producing plasmas containing mixtures of ^{13}C + ^{4}He and ^{7}Li + deuterons in order 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 phase [6]. In particular, it can be activated at the base of AGB stars, thus constituting one of the most interesting neutron sources in stellar conditions. These are in turn important for the so-called slow-process, i.e. the neutron induced reactions responsible of the heavy elements production. The ^{7}Li(d,n)^{4}He-^{4}He reaction was recently addressed by Coc et al. [7] as one of the most important reactions affecting the CNO abundances produced during the primordial nucleosynthesis (BBN). From such analysis, it was found that the ^{7}Li nucleosynthesis is strongly influenced by the ^{7}Li(d,n) ^{4}He-^{4}He reaction rate. Data collected by these authors give a variation of two order of magnitude on the ^{7} Li abundance during BBN epoch, around 1 GK of temperature, with respect to the reaction rate measured by Boyd et al. [8]; the latter is usually adopted for the BBN evaluation. These discrepancies can be explained if one considers that very few experimental data exist, and authors consequently assume a constant S-factor ranging between two extreme hypotheses from 5 to 150 MeVxb. Providing new experimental data focused on the determination of the outgoing neutron flux is essential in order to up-grade our knowledge of this process and consequently of the BBN at a temperature of about 1 GK. This critical temperature domain will be affordable by the peta-watts laser facility of ELI- NP [9].

Neutron Detectors

The proposed activity requires the construction of an experimental set-up based on a highly segmented detection system for neutrons. The segmentation is required in order to reconstruct the reactions kinematic, thus getting information on centre of mass energy distribution of the nuclear cross-sections. The ideal detection module must have: high efficiency, good discrimination of gammas derived by neutrons, good timing performance for ToF neutron energies reconstruction. In addition it must be able to work in hard environmental conditions, like the ones established in the laser-matter interaction area. Very recently, the possibility of manufacturing plastic scintillators with efficient neutron/gamma pulse shape discrimination (PSD) was demonstrated at LLNL laboratory [10] by using a system of a polyvinyl toluene (PVT) polymer matrix loaded with a scintillating dye, 2.5-diphenyloxazole (PPO). First characterization results show that PSD in plastic scintillators can be of similar magnitude or even higher than in standard commercial liquid scintillators. The result is a consequence of the large amount of scintillation dying material used in the polymer, a possibility never tested in the past. Another recent result obtained by our collaboration is the implementation of new photo-detectors based on silicon technology (Silicon PhotoMultipliers SiPM) [11]. These are now commercial devices characterized by a high photo-detection efficiency, high gain, single photon sensibility, excellent timing performance, low operative voltage and insensitivity to large electric and magnetic fields. These make such devices particularly suitable for applications in severe environmental conditions, such as those ones foreseen around the laser-matter interaction area at the future ELI-NP facility. A third important aspect is the signal processing, for which a relevant expertise has been developed within our collaboration [12]. We propose to implement a totally digital acquisition of the multi-hit signals foreseen in the proposed physics case. These basic technologies will be the pillars of our proposed detection system for the ELI-NP studies. The neutrons ToF-Wall should be consist of about 1000 modules each including one 25 cm^{2} area scintillator, 5 cm thick, one SiPM and a digital read-out channel. This allows a modular structure with easily adapted configurations around the inter action area. As an example at 2 m distance the total efficiency is estimated as large as about 18 % for 2 MeV neutrons and 6% for 13 MeV neutrons [13]. In such conditions the array can detect up to about 10^{5} neutrons per shot, which represents a challenging demand for measurement at ELI-NP. Efficient digital shape analyses can handle a multi-component folded signal still preserving the timing of each neutron detection and the n-γ discrimination.

SiPM test

During the 2014 we started with the R&D activities with the goal to realize a first prototype of detection module. In this framework we are waiting for a prototype of scintillator from the Scionix corporation, while we already got a large SiPM from ST-Microelectronics [14].

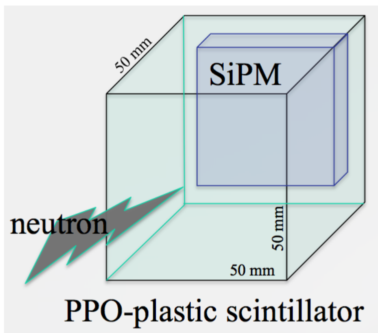

Figure 1: *Layout of neutron ToF-wall*

The Silicon PhotoMultiplier (SiPM) is a novel solid state photon counting detector. Its structure is based on a bidimensional microcell array of Geiger Mode Avalanche Photodiodes (GMAPs) with resistive quenching and connected in parallel in a single readout element. The voltage is 10-20% higher than the value of breakdown and can not be increased at will since the background noise is proportional to the voltage reverse of junctions. The operating values are around around 40-70 V.

The output signal from a SiPM is the sum analog signals of APD; in this sense, the matrix can be considered one analog instrument: while an APD is a binary device. Such devices are extremely compact, robust and easy to operate due to the low operating voltage. The array were arranged in a n x n regular square grid.

We start with several test on the ST-Microelectronic SiPM showed in Figure 2.

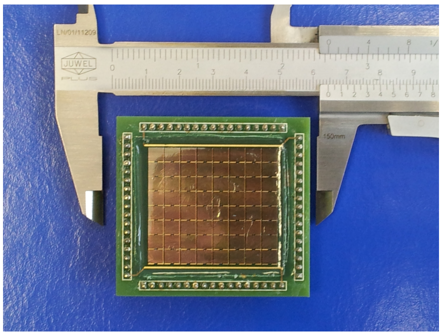

Figure 2: *The SiPM arrays prototype*

It consists of an 8 x 8 configuration, the total dimension is 3.5 x 3.5 mm^2, 4900 microcell and a geometrical fill factor of 36%. Each microcell in the array has a square geometry with an active area 32 x 32 μm^2 .The device has been tested by using a lower pulses spread on the whole surface to guarantee a uniform irradiation. The single laser pulse had a wavelength 641 nm and 50 ps pulse duration. The intensity was adjusted in order to have pulses with different of photons.

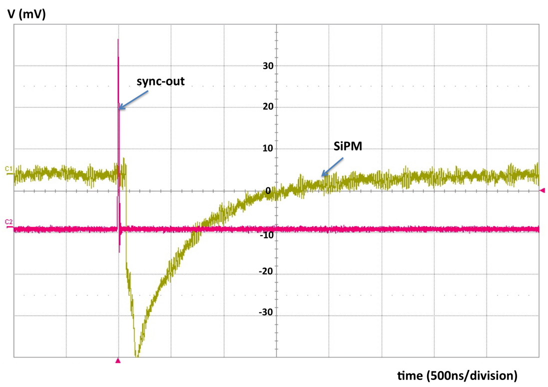

Figure 3: *Typical characteristic voltage of breakdown*

The dynamic characteristics were measured under single photon condition at room temperature.As can be notice from the signals reported in Figure 3 coming from the oscilloscope triggered by laser sync-out, the intrinsic time gitter of SiPM device is excellent and of the order of hundred of pico-seconds, compatible with the values required for the use at ELI-NP experiments. Typically SiPM signal obtained triggering the oscilloscope by laser sync-out (red signal). Actually we are performing some test, coupling the device with a plastic scintillator BC408 in order to get the information on the energy resolution of the whole detector.

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The InKiIsSy experiment. Pulse Shape Discrimination technique for the identification of light particles

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Abstract

In this contribution we present the InKiIsSy (Inverse Kinematic Isobaric System) experiment [1]. It was carried out at Laboratori Nazionali del Sud in April 2013. During this experiment the ^{124}Xe+^{64}Zn reaction was studied at 35 AMeV beam energy by using the 4π CHIMERA (Charged Heavy Ion Mass and Energy Resolving Array). Previously the systems ^{124}Sn+^{64}Ni and ^{112}Sn+^{58}Ni were analyzed in inverse (REVERSE) and direct (TIMESCALE) kinematics at 35 AMeV, in order to investigate the time-scale and mechanism of fragments formation. By comparing the two systems, effects that can be correlated to Isospin transport in reaction dynamics and symmetry energy term of nuclear equation of state at sub-saturation density were observed. For this reason, in order to disentangle the Isospin effects from size effects, the ^{124}Xe+^{64}Zn reaction is being analyzed at the same beam energy of 35 AMeV.

Keywords: Isospin, Chimera, Farcos, PSD technique.

Introduction

In recent years some experiments have been undertaken with the multi-detector CHIMERA [2, 3]. In particular, the systems ^{124}Sn+^{64}Ni and ^{112}Sn+^{58}Ni have been studied in inverse and direct kinematics. The main objective of these experiments has been to explore the mechanism of the primary processes which are responsible for fragments formation and investigate effects related to the Isospin of the systems, by comparing neutron rich (^{124}Sn+^{64}Ni) and neutron poor (^{112}Sn+^{58}Ni) systems [2, 8]. The time-scale of fragments formation from dynamical and pre-equilibrium emission to the sequential statistical one has been investigated. It has been shown that light fragments (Z≤9) are specially emitted in fast fragmentation of the neck connecting projectile-like fragments (PLFs) and target-like fragments (TLFs), while the emission of IMF (Intermediate Mass Fragments) with Z≥9 has been shown to happen at the last stage of the neck expansion process and has been associated with the Dynamical Fission mechanism, that takes place in a late stage of the re-separation of TLF-PLF binary system.
The analysis of these two systems (^{124}Sn+^{64}Ni and ^{112}Sn+^{58}Ni) has shown several interesting effects. For example, one of these effects has been observed in the IMF production cross-section. In fact, considering the production cross-section for statistical and dynamical break-up of PLF as a function of the charge of the IMF (Fig.1), it has been observed that, while the statistical emission has the same probability in both systems, the dynamical fission probability is enhanced up to a factor 1.5-2 in the neutron rich system, especially for the heaviest IMFs (Z≥9).

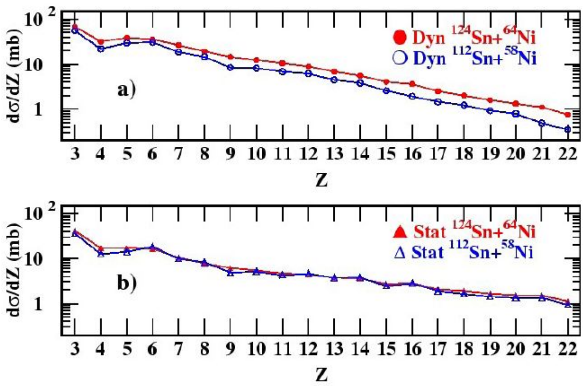

Figure 1: *Cross section associated to dynamical (upper panel) and statistical (lower panel) emission mechanism for neutron rich system (full symbols) and neutron poor one (empty symbols).*

This effect could be due to the very different N/Z ratio of the two systems. But, it also could be related to the different size of the two systems [2, 7, 8].

The InKiIsSy experiment

The InKiIsSy (Inverse Kinematic Isobaric System) experiment has been undertaken in order to disentangle the effects related to isospin from the ones related to the different size of entrance channel. During this experiment the $^{124}Xe+^{64}Zn$ reaction was analyzed at 35 AMeV beam energy. In fact, this system has the same mass of the neutron rich system ($^{124}Sn+^{64}Ni$) and an isospin near to the neutron poor one ($^{112}Sn+^{58}Ni$). These measuments were performed in April 2013 at INFN-LNS in Catania using CHIMERA multi-detector (Fig.2).

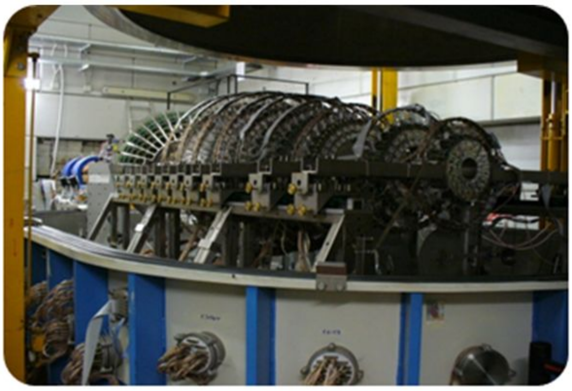

Figure 2: *Photo of CHIMERA multi-detector.*

It's a 4π detector for charged particles with high resolution and low energy thresholds. CHIMERA consists of 1192 telescopes grouped into 35 rings in a cylindrical geometry along the axis of the beam[4]. During this experiment, for the first time, CHIMERA was coupled to a prototype of FARCOS [9] array. FARCOS is a modular array of telescopes each of which consists in two double-sided silicon strip detectors (DSSSD) followed by 4 CsI(Tl) crystals (Fig.3).

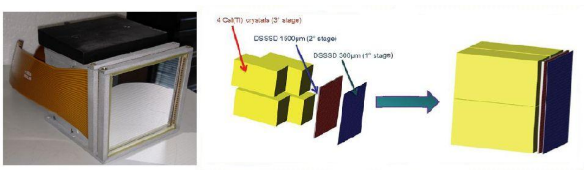

Figure 3: *Photo (left panel) and schematic representation (right panel) of one of FARCOS telescopes.*

Some of the main characteristics of FARCOS are its good energy and angular resolution and its high modularity. Moreover, FARCOS has wide dynamic range that goes from MeV to GeV. In fact FARCOS uses ΔE_1-ΔE_2-E telescopes with integrated electronics that allows to perform time of flight measurement and PSD (Pulse Shape Discrimination) analysis. In this way, the apparatus is able to determine the charge and mass of charged fragments in a very wide dynamic range. In particular, during this experiment, four prototypes of FARCOS telescopes were used in a 2x2 configuration. They were placed at 25 cm from the target and covered an angular region in order to detect LCP (Light Charged Particles) and IMF with high angular resolution. Specifically, in a reaction of this type ($^{124}Xe+^{64}Zn$) a large number of particles are produced. So, it's important to identify the various fragments produced, from light fragments to heavier ones.

Pulse Shape Discrimination technique

One of the techniques used for the identification of fragments is the Pulse Shape Discrimination (PSD) methods [10, 11]. In particular, it's used for the identification of light particles. It is based on discrimination through the analysis of the shape of the signal induced by the passage of particles in a detector. In fact, in certain types of scintillators, the passage of a particle can excite different levels, each characterized by a specific decay constant. Thanks to these scintillators we are able to discriminate by means of the pulse shape, that is, we can distinguish between different types of incident particles depending on the shape of the light pulse (Intensity vs time) emitted. For example, in the case of CsI(Tl) the fluorescence presents a fast component and a slow one:

$$N(t) = L_1 e^{\frac{-t}{\tau_{fast}}} + L_2 e^{\frac{-t}{\tau_{slow}}} \qquad (1)$$

where N(t) represents the number of photons emitted after a time t from the passage of the particle while $\tau_{fast} \approx 0.7\mu s$ and $\tau_{slow} \approx 3\mu s$ are the lifetimes of the two components. In particular, for the same energy released in the detector, the light distribution between the fast and slow components depends on the type of particle (charge and mass) that passes through it. In this way, by correlating with each other the intensities of the two components, it's possible to identify the particles. Before continuing with the identification of the particles, it is necessary to process the signal so as to obtain a pulse shape that depends on A and Z of the incident particle. To do this a *linear amplifier* is used. It has as input and output a linear signal, that is a pulse that provides information through its amplitude and shape. In particular, the linear amplifier has two main purposes: to amplify the signal from the preamplifier, and transform it in an appropriate manner, such as to allow further processing. In the case where information on the shape of the pulse is required, it's necessary a faithful amplification of the signal variation as a function of time; that is, it is important that the amplifier used does not introduce any distortion on the shape of the signal. In these conditions, what is obtained is a signal that depends on the values of A and Z of the particles considered.

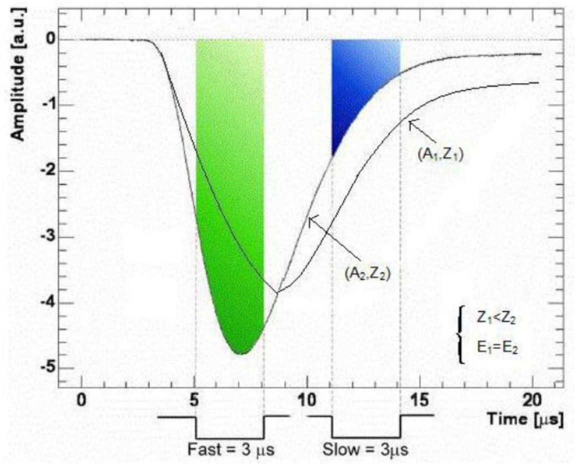

Figure 4: *Signals generated by two different particles of equal energy.*

In Fig.4 is possible to distinguish two signals generated by particles with different A and Z that, for the same integral and then for the same energy, have different shape. Therefore, using two *charge to digital converter* (QDC, electronic modules that produce a digital signal proportional to the charge collected), driven by two gate, it's possible to integrate the signal along the ascent phase and along the descent phase. This system produces two linear signals, respectively called *fast* and *slow*, which are treated separately, and then the results will be combined. In this way it is therefore possible to obtain a signal proportional to the two components. So, building a graph *fast* vs *slow*, we obtain the discrimination of the different atomic species and of various isotopes.

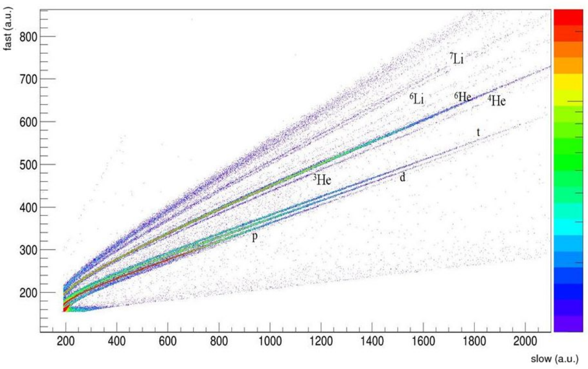

Figure 5: *Fast vs slow matrix for ^{124}Xe+^{64}Zn reaction.*

The Fig.5 shows an example of the results obtained by the construction of a *fast* vs *slow* matrix for ^{124}Xe+^{64}Zn reaction during the InKiIsSy experiment. As you can see in this graph, this technique allows us to separate in a very satisfactory manner the various fragments and also the various isotopes produced.

Conclusions

In conclusion, in this report the InKiIsSy experiment was presented. In particular, in previous experiments, the systems ^{124}Sn+^{64}Ni and ^{112}Sn+^{58}Ni have been analyzed in inverse (REVERSE) and direct (TIMESCALE) kinematics at 35 AMeV. The study of these two systems has shown several interesting effects that can be related to the different N/Z ratio of the two systems but also to the different size of the two systems. In order to disentangle the effects related to isospin from the ones related to the different size of entrance channel the ^{124}Xe+^{64}Zn reaction is being analyzed at 35 AMeV beam energy. In this reaction, a large number of particles are produced. So, to identify the various fragments produced, various identification techniques are used. One of these is the Pulse Shape Discrimination (PSD) methods. This technique, analyzing the shape of the signal induced by the particle in the detector, has allowed us to separate in a very satisfactory manner the various fragments and also the various isotopes produced. For the future, data analysis of the InKiIsSy experiment will be continued.

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