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Explosion characteristics of small plasma spheres produced with high intensity femtosecond laser-pulses

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Laser-produced intense ion beams constitute themselves as a source for new applications [1-3]and several work is devoted to understand the underlying physical processes for the ion beam generation. While the ion emission outside a laser irradiated target can be measured directly, the ion dynamics inside a dense target is difficult to access. Under these circumstances fusion neutron spectroscopy has been shown to be a powerful tool because neutrons produced in fusion reactions penetrate dense matter almost undisturbed while their energies reflect the ion collision kinematics [4,5]. In close context several investigations have been performed to study laser driven deuterium fusion with compact sub-ps short pulse laser systems in order to establish short pulse neutron sources [5-10]. Here we describe experimental studies of the deuteron acceleration created by the interaction of high intensity laser pulses with heavy water D_2O droplets. The analysis of the ion kinematics inside the dense droplet is based on the fusion reaction d + D $\rightarrow$ ^{3}He + n + 3.269 MeV. The deuteron emission to the outside of the target has been directly measured. A detailed calibration of our spectrometer was important for the data analysis. In particular we tried to infer the yield of neutrons which is produced inside the target droplet. Taking these findings into account, a new spray target [11,12] was developed in order to exploit and optimize the neutron production from laser-irradiated plasma spheres.

The experiments have been carried out with 35 fs laser pulses at 815 nm center wavelength from the MBI-High-Field-Ti:Sapphire-laser [13]. For the present experiments, up to (600 – 800) mJ pulses in a beam of 70 mm in diameter are focused with a f/2.5 off axis parabolic mirror. Interaction intensities of ~ 10^{19} W/cm^2 have been estimated from the energy content and pulse duration in a focal area with a diameter of ~ 6 µm. Heavy-water targets have been produced with a commercial and well-characterized [14] 1 MHz pulsed nozzle from Micro Jet Components (Sweden). A 10 Hz laser shot repetition was used in the experimental runs. The laser is focused 15 mm below the jet-nozzle outlet where the liquid jet is decomposed into a train of droplets. For simulation calculations we assume a droplet-diameter of ~ 20μm and a droplet-separation of 70 μm (center to center). Secondary deuterated polystrol $(CD)_n$ - targets of different size and position have been exposed to the ions emitted from the laser irradiated Primary Droplet Target (PDT). These secondary targets have been employed to investigate the accuracy of the neutron detection efficiencies in the presence of a large gamma flash and to monitor the deuteron yield.

A Thomson parabola spectrometer with a MCP-CCD readout registered the ion emission at an observation angle of 135 degree (laser propagation direction corresponds to 0°). Four neutron detectors (N1-N4) were positioned at observation angles of 0^0, 135^0, 90^0 and 45^0 relative to the laser beam at distances between 322 cm and 349 cm viewing the target through 2 mm Al windows. Directly in front of each scintillator a 6 cm thick lead disc was positioned in order to reduce the amplitude of the prompt γ-pulse. The laser pulses were counted with an optical diode (TD) which serves also as a trigger for the acquisition system incorporating the time of flight (TOF) neutron spectrometers. Another optical diode (PD) registered the plasma light emission attenuated through a colored-glass filter in a wavelength-band between 350 nm and 600 nm. The signal of this diode was used as a marker of the laser droplet interaction.

Measured deuteron spectra have a mean temperature parameter of about $T_d = 100$ keV. From the measured neutron intensity with a secondary target of definite size an integral deuteron emission between 5×10^{11} and 8×10^{11} deuterons into 4π sr is deduced. These data correspond to the directly measured deuteron numbers with the Thomson-spectrometer. From these numbers it follows that about 0.2-0.3% of all deuterons contained in the 20 μm droplet are accelerated to energies larger than about 10 keV. The energetic deuterons consume several percent of the incident laser energy. For simulation calculations these spectral data are used.

In respect of the spherical symmetry of the target and the observed angular emission characteristic in our experiment [15] we refer here to inward and outward accelerated deuterons from the droplet. In order to infer data for the inward accelerated deuterons a careful analysis of the whole target system is indispensable. A closer look to the target system itself reveals that obviously the neighbor droplets in the train of droplets can not be neglected. Thus we have two SDTs (Secondary Droplet Targets) one above and one below the Primary Droplet Target (PDT). In order to investigate the uncertainties of the neutron detection efficiencies of all four detectors a secondary target was chosen in such way that the produced neutron time-of-flight and intensity distributions are the same for all four neutron detectors. This was achieved by positioning concentric to the line of droplets and 2.1cm below the laser focus a circular secondary target. The spectra can be well reproduced with an absolute outward emitted number of 5×10^{11} deuterons into 4π sr. Thus we know that the timing of our n-spectrometer is consistent which is important for the further spectral investigations and we are able to estimate the n-signal from neighbor – droplets. We obtained only ~ 10^3 neutrons per laser-pulse and (40%-80%) of that signal comes from the neighbor droplets.

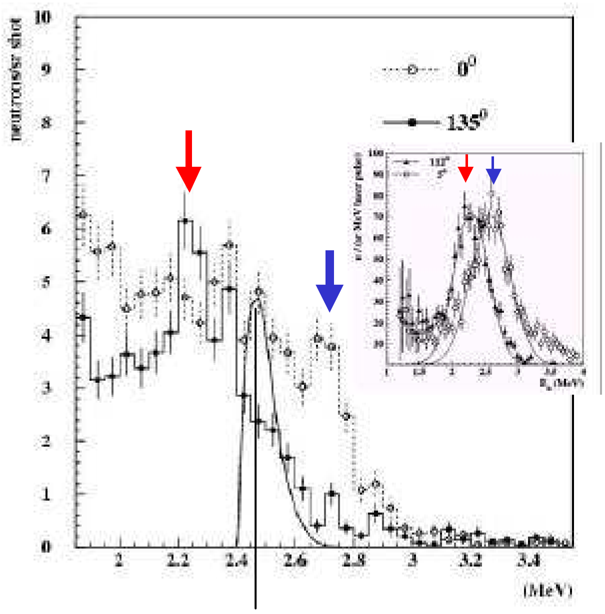

Fig. 1 Measured neutron spectra of the 0° (laser propagation) and 135° n-detector from the D_2O-droplet target system: the blue- and red-shifted components indicate energetic deuterons moving in the forward (laser) direction, line – calculated n-signal from the droplet neighbors; insert: measured spectral shifts from a flat D-target [5]

After calibration we can investigate the inward deuteron acceleration from shifts in our spectra and therefore we have to transforme the TOF into energy spectra. In Fig. 1 we show the summed energy spectra for a forward (0^0) and a backward detector (135^0). Neutrons in the forward direction (0°) are more energetic than those in the backward direction (135°) which indicates that these neutrons must have been produced inside the target droplet by energetic deuterons preferentially moving in the forward direction. This finding is corroborated by the observation that the energy deviations are almost symmetric to 2.45MeV: about +300 keV at 0^0 and –200 keV at 0^0. This finding is very similar to the reported [5] neutron energy distributions in a solid target.

In addition a newly developed pulsed water-spray is used as a further target source[11]. The laser beam was focused up to ~10^{19} W/cm^2 with the same optic as in the droplet experiment.

The position of the focus was close below the nozzle within the 2 mm extended cloud of $10^{11}cm^{-3}$ micro-spheres (diameter 150 nm). The neutron emission is shown in Fig. 2 and has been calculated with the measured deuteron emission spectrum and assuming for a simple model calculation (line in Fig. 2) a sphere (radius 1 mm) of cold D_2O matter around the interaction point.

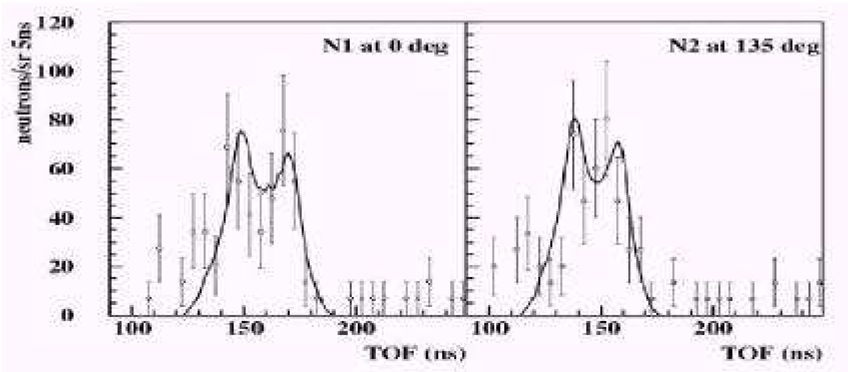

Fig. 2 Neutron emission from a laser irradiated ($8x10^{18}$ W/cm^2) D_2O-spray (0° - laser propagation; line: calculated signal with $8x10^{10}$ deuterons (determined from spectral measurement) interacting with the cold target surrounding the laser heated core

In summary, under our experimental conditions the irradiated droplet does contribute only marginally to the measured neutron signal while a considerable fraction is due to neutron production in the deuteron exposed neighbor droplets. Neutrons from the laser-irradiated droplet emitted in the forward direction are more energetic than backward emitted neutrons which is similar to the observations with a solid target. Because laser-driven micro-spheres are very efficient deuteron emitters a heavy water spray-target was developed which has shown to deliver 6000 neutrons per pulse.

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