En-route to the fission–fusion reaction mechanism: a status update on laser-driven heavy ion acceleration

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Abstract
The fission–fusion reaction mechanism was proposed in order to generate extremely neutron-rich nuclei close to the waiting point \( N = 126 \) of the rapid neutron capture nucleosynthesis process (\( r \)-process). The production of such isotopes and the measurement of their nuclear properties would fundamentally help to increase the understanding of the nucleosynthesis of the heaviest elements in the Universe. Major prerequisite for the realization of this new reaction scheme is the development of laser-based acceleration of ultra-dense heavy ion bunches in the mass range of \( A \approx 200 \) and above. In this paper, we review the status of laser-driven heavy ion acceleration in the light of the fission–fusion reaction mechanism. We present results from our latest experiment on heavy ion acceleration, including a new milestone with laser-accelerated heavy ion energies exceeding \( 5 \text{ MeV u}^{-1} \).

Keywords: laser-driven heavy ion acceleration, fission–fusion reaction mechanism, short-pulse laser

(Some figures may appear in colour only in the online journal)

1. Introduction

The nucleosynthesis of the heaviest elements in the Universe follows the rapid neutron capture process (\( r \)-process) at astrophysical sites like binary neutron star mergers [1]. The \( r \)-process passes through the neutron-rich side of the chart of nuclides. The generation of the involved isotopes, especially around the waiting point at the magic neutron number \( N = 126 \), is still out of reach for conventional accelerators. Hence, the nuclear properties of a large fraction of the \( r \)-process nuclei are presently unknown and cannot be studied in the laboratory.

Habs et al proposed to exploit laser-driven ion acceleration for the production of neutron-rich nuclei close to this waiting point and introduced the fission–fusion reaction mechanism [2]. This is a two-step process, based on the fission of heavy ions like thorium and the subsequent fusion of the neutron-rich fission fragments. Due to the limited density of conventionally accelerated ion bunches, this reaction
mechanism is hardly accessible using existing conventional accelerator facilities, where the fusion probability would be negligible. In contrast, short-pulse laser-based acceleration of heavy ions can approach solid-state-like density of the ion bunches, when realizing the acceleration in the Radiation Pressure Acceleration (RPA) regime [3–6]. Owing to the unprecedented high density of the laser-generated heavy ion bunches, the yield of the fission–fusion process is expected to reach usable reaction product numbers.

Thus, the development of laser-driven heavy ion acceleration in the RPA regime is a major prerequisite for the realization of the fission–fusion reaction mechanism. A second constraint is placed by the minimum energy required to overcome the fission barrier: the heavy ions need to achieve kinetic energies above ca. 7 MeV u$^{-1}$. Whilst laser-driven acceleration of protons and light ions has been extensively studied for about two decades [7–9], the acceleration of ions with mass numbers around $A \approx 200$ and above is still sparsely investigated.

To our knowledge, only two papers contain experimental data on laser-driven heavy ion acceleration in the mass and energy range relevant to the fission–fusion reaction mechanism. The first one was published in 2000 by Clark et al and reports on lead ions, laser-accelerated up to energies around 2 MeV u$^{-1}$ [10]. The ions originated from the front side of 2 mm thick lead targets, which were irradiated with a ps glass laser system providing a pulse energy of 50 J and an intensity of $5 \times 10^{19}$ W cm$^{-2}$. In the second relevant publication from 2015, Braenzel et al focused a Ti:sapphire laser pulse with an intensity of $8 \times 10^{19}$ W cm$^{-2}$ and an excellent laser contrast onto 14 nm thick gold foils and thereby accelerated gold ions to maximum energies of 1 MeV u$^{-1}$ [11].

Besides these experimental publications, two simulation papers were published by Petrov et al in 2016 and 2017, containing promising theoretical studies on gold ion acceleration. They investigated different acceleration mechanisms and their influence on the ion bunch parameters by varying the gold foil thickness [12] and the laser pulse duration [13]. In particular, they observed indications for RPA with short-pulse laser systems, delivering gold ion bunches with energies far beyond the fission barrier of 7 MeV u$^{-1}$. Hence, these 2D PIC simulation results make a strong case for soon fulfilling the demands on laser-driven heavy ion acceleration for the fission–fusion reaction mechanism [2, 14].

However, especially for the development of RPA, which would ideally deliver a high-density, narrow-bandwidth heavy ion bunch around 7 MeV u$^{-1}$, we will have to rely on the upcoming new generation of high-power laser systems, like the $2 \times 10$ PW laser which is currently under construction at the Extreme Light Infrastructure-Nuclear Physics (ELI-NP) facility in Mâgurele near Bucharest [15]. In the meantime, it is inevitable to gain knowledge on and control over heavy ion acceleration with the already available laser systems. In this paper, we report about our latest experimental progress on laser-based acceleration of heavy ions. We present the energy spectra of laser-accelerated gold ions originating from thin foils with varying thickness. Compared to the earlier studies of laser ion acceleration [10], we observe heavy ion energies that are a factor of 2.5 higher than reported before. Furthermore, we show the influence of radiative target heating on the ion energies and numbers.

2. Experimental setup

The experiment was performed at the Texas Petawatt laser (TPW) of the University of Texas at Austin [16], which delivered about 110 J laser pulse energy within 140 fs at a central wavelength of 1057 nm. The setup is sketched in figure 1. The TPW was focused by an off-axis parabola to a focal spot size of 10 $\mu$m. A single inline plasma mirror was used for contrast enhancement, which resulted in a laser intensity of $(8 \pm 2) \times 10^{20}$ W cm$^{-2}$ on target.

We employed freestanding gold foils with thicknesses of 50, 100 and 300 nm as targets. The foils were manufactured by the LMU target factory by physical vapor deposition. Hydrocarbons exist even in clean vacuum environments and will naturally accumulate on the target surface as contaminants. Due to their higher charge-to-mass ratio compared to heavier ions, they can strongly suppress or cancel heavy ion acceleration [17]. Therefore, we used a continuous wave laser with a wavelength of 532 nm and an adjustable output power up to 1 W for radiative target heating in order to remove the surface contaminants. The foils were heated above 500 $\degree$C, while the temperature was monitored by a commercial NIR spectrometer [18], which measured the spectrum of the thermal radiation of the laser-heated gold target foils.

As ion diagnostics, we employed a Thomson parabola spectrometer [19] in the target normal direction with a 200 $\mu$m entrance pinhole, accepting a solid angle of $2 \times 10^{-3}$ msr of the emitted beam. CR39 nuclear track detector sheets with a thickness of 1 mm in front of imaging plates (IPs) served as passive ion detectors. The CR39 was chosen as heavy ion detector, as a distinction between heavy particles (gold ions) and light particles (carbon ions) is easily possible by the different pit sizes.
as well as for C6+ lines indicate the analytically calculated parabolas for protons.

Follow-up studies for a more efficient target cleaning are already in progress.

The still appearing protons in figure 2 indicate that the target heating was insufficient to remove all proton contaminants. Follow-up studies for a more efficient target cleaning are already in progress. Meanwhile, the proton and carbon ion numbers are significantly reduced in heated shots. The beneficial effect on gold ions is evident, which indicates that target heating in general is an effective method.

Figure 3 shows the gold ion spectra for target foil thicknesses of 50, 100 and 300 nm. The spectra are integrated over all charge states, as the Thomson parabola spectrometer did not resolve single gold ion parabolas. For each thickness, spectra from shots on heated (red, yellow) and on unheated (blue) targets are presented. Clearly, the energy spectra are monotonically decaying, indicating the predominant acceleration in the Target Normal Sheath Acceleration (TNSA) regime [20]. While the shape of the spectra does not depend on the target thickness, the number of gold ions, which have been measured in target normal direction, increases with decreasing gold foil thickness. A clear difference between the energy spectra from heated and unheated shots is observable: the spectra from unheated shots decrease much steeper towards higher energies. The highest energies are achieved for shots on heated targets and exceed 5 MeV u⁻¹, independent of the target thickness. This measured maximum energy exceeds the highest kinetic energies, which have been reported so far for laser-accelerated heavy ions in this mass range [10], by a factor of about 2.5. The drop at energies below 1 MeV u⁻¹ is caused by the geometry of the spectrometer.

A direct comparison of our measurement with laser-accelerated heavy ion spectra in literature (see introductory section) is shown in figure 4. The green and blue curves show previous measurements by Braenzel et al [11] and Clark et al [10], respectively. The red curve shows our measurement for a heated, 50 nm thick gold foil, which represents an important step towards the indicated fission–fusion goal of about 7 MeV u⁻¹ for ²³²Th (grey shaded area). The yellow, dashed line shows a gold ion spectrum simulated by Petrov et al [13]. For this simulation, they used a gold target with a thickness of 20 nm covered with a 5 nm thick H₂O contamination layer on the rear side and laser parameters similar to the TPW laser (50 J, 180 fs, 5 μm FWHM focal spot size, 1 × 10²¹ W cm⁻² laser intensity).

Comparing the gold spectra from the TPW laser (measured) and simulation results for similar conditions reveals
that the simulation overestimates both ion energy and particle numbers. Our measurements show an increasing number of ions in the target normal direction towards thinner targets, which is likely to show an increased directionality of the ion bunch with decreasing foil thickness. However, 20 nm thick gold foil in comparison to a spectrum simulated for the TPW parameters and a gold foil thickness of 20 nm by Petrov et al. [13]. The grey shaded area indicates the rough energy range of the fission barrier for $^{232}$Th around 7 MeV u$^{-1}$, which to overcome is a basic prerequisite for the fission–fusion reaction mechanism.

Further studies on laser-driven heavy ion acceleration are already planned using high-power lasers with different pulse characteristics, like the PHELIX laser at the GSI in Darmstadt (200 J, 500 fs) and the ATLAS 3000 at the Centre for Advanced Laser Applications (CALA) in Garching near Munich (60 J, 20 fs) [14] with a peak intensity around $10^{22}$ W cm$^{-2}$. These experiments are preparations for studies at the new high-power laser at ELI-NP ($\sim 10^{21}$ W cm$^{-2}$) [15]. In particular, the transition from TNSA to RPA could come into reach for these laser intensities, paving the way to a more efficient acceleration of large ion numbers to higher energies, as they are required for the fission–fusion reaction mechanism.

4. Conclusion

We presented a status update on laser-driven heavy ion acceleration in the light of the fission–fusion reaction mechanism, which aims at generating neutron-rich heavy ions close to the $r$-process waiting point around $N = 126$. We showed promising results from a recent gold ion acceleration campaign at the TPW. In particular, we measured experimentally gold ions with energies of more than 5 MeV u$^{-1}$. The results and experiences support our optimism that the energetic requirements of the ion bunches for the fission–fusion reaction mechanism can be met with the soon operational next-generation laser systems.

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