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Communication

Femtoscopy for the NAno-Plasmonic Laser Inertial Fusion Experiments (NAPLIFE) Project

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Abstract: Hanbury-Brown and Twiss analysis is used to determine the size and timespan of emitted particles. Here, we propose to adapt this method for laser-induced nanoplasmonic inertial confinement fusion to determine the parameters of emitted Deuterium and Helium^4 nuclei. This communication is a short article that presents part of a larger study over multiple years. It presents a cutting edge method that is new in the field of Inertial Confinement Fusion.

Keywords: nuclear fusion; laser induced fusion; nanoplasmonics

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1. Introduction

This article summarizes the contribution of Laszlo P. Csernai et al. at the 52nd International Symposium on Multiparticle Dynamics, held on 24 August 2023 in Gyöngyös, Hungary.

Two particle correlations are used to analyze the size and timespan of hadronization in relativistic heavy ion collisions [1]. Originally, the interference of two particles emitted from chaotic sources was first applied by Hanbury-Brown and Twiss [2], where photons were exploited to determine source sizes for both laboratory and stellar sources from the 1950s. Correlations of identical pions were shown to be sensitive to source dimensions in proton–antiproton collisions by Goldhaber, Goldhaber, Lee, and Pais in 1960 [3]. In the 1970s, these methods were refined by Koonin [4] and by Gyulassy et al. [5]. The initial stages of this development are described in [6]. The application of this method was summarized later in [7,8], and essential details and developments were contributed in [9–11] to applications involving high-energy heavy ion reactions. Here, we address developments related to fluid dynamical model applications of this method, including collective flow parameters [12,13], based on the emitted Boson wave function.

Initial experimental verification measurements have observed nuclear reactions, specifically, the formation of deuterium due to energetic laser irradiation [14–17]. This is attributed to proton acceleration, achieving neutron transmutation from target nuclei [18]. In [19], we proposed two-sided laser irradiation in a single linear geometry to achieve energetic and stable ignition. This configuration exploits the Laser Wake Field Acceleration (LWFA) mechanism to form a Laser Wake Field Collider (LWFC) [20]. Thus, the emitted protons and the formed deuterium nuclei are accelerated primarily in the direction of the electric field (**E**-field) of the irradiation laser beam. As the laser beam is transversely polarized, the particle emission is orthogonal to the direction of laser irradiation in the colliding beam configuration (see Figure 1, where laser light comes from left and right, while the nanoantenna is orthogonal to that line).

In the NAPLIFE project, gold nanorod antennas are embedded in a polymer target. These are of resonant wavelength, and consequently serve as dipole accelerators of the neighbouring protons and other charged particles. These nanoantennas are orthogonal to the direction of laser irradiation and parallel to the **E**-field of the laser beam. The direction of acceleration is the same. According to our numerical simulations, the direction of the accelerated protons is sharply centered around the direction of the **E**-field. The orientation becomes more angularly peaked as the irradiation time increases. The number of accelerated and emitted protons (and ions) increase with the irradiation time as well.

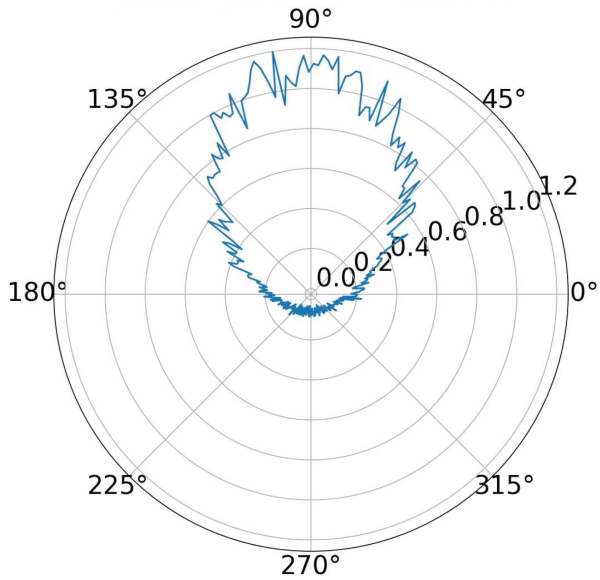

Figure 1. Angular distribution of emitted protons along a nanorod antenna irradiated from **two** sides in the LWFC configuration (in the front/back directions) with a 30 mJ constant intensity laser pulse with $I = 4 \cdot 10^{17}$ W/cm^2 and with a step function profile in the rest frame of the antenna. The distribution is shown one time period T_P after the initial transients t_o, i.e., at $t_o + T_P = 11.94$ fs after the start of the irradiation. The antenna and the $\vec{E}$-field of the laser beam point in the 90° direction. The outermost contour (1.0 MeV/c) belongs to the momentum of all protons emitted into a solid angle domain of $4\pi/300$. The momentum of the most energetic protons is 13 keV/c. The number of proton marker particles in the EPOCH generated sample is 337,058.

Furthermore, the protons may reach the multi-MeV energies sufficient for nuclear reactions, particularly for transmutation reactions.

The time period of the irradiating laser beam in our simulations was $T_P = 2.65$ fs, which corresponds to $\lambda = 800$ nm in vacuum. The total irradiation time for the beam to cross a target of 21 µm was about 106 fs. These correspond to our present experimental test parameters. We assume that the intensity of irradiation is constant at this time.

With increasing laser irradiation time, the energy of the electromagnetic field is converted to the energies of the accelerated and emitted ions and atoms. This leads to a decrease in the energy of the electromagnetic field in the calculation box of the simulation [21].

2. Method of Analysis

We used a high-resolution Particle In Cell EPOCH kinetic model, similar to the approach in PICR fluid dynamics [12,13]. This model has been used to evaluate rotation in off-central high-energy heavy ion reactions [22], tpoint out the possibility of Kelvin–Helmholtz Instability (KHI) [23], and to assess the flow vorticity [24] and polarization/vorticity arising from local rotation [25]. The numerical viscosity and resulting entropy production have been evaluated using this model in [26].

In the field of ultra-relativistic heavy ion physics two particle correlation studies have been used for a long time. These provide a high level of sophistication for determining the size and timespan of an emitting source as well as its shape, dynamics, expansion, and rotation. In the present, given the limited budget of the NAPLIFE laser fusion project, highly structured detector systems are not available; however, one or two detectors are accessible. These enable us to draw some conclusions from these two particle correlation studies.

Notably, smaller detector acceptances may provide sufficient data for important and essential consequences [27,28].

3. Correlation Function

The Boson two-particle correlation function is defined as the inclusive distribution divided by the product of the inclusive one-particle distributions such that [1]

$$C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)}, \tag{1}$$

where p_1 and p_2 are the 4-momenta of particles. Here, we use the "momentum correlation" technique, as in high energy heavy-ion physics, in contrast to the original "HBT space–time correlation technique".

Using the emission function $S(x, k)$ discussed in [29], the correlation function from a fluid dynamical model result can be calculated with good precision [30–33]. For this calculation, we need the flow velocity distribution and the local momentum distribution of the given type of particles at each location.

This is usually the Jüttner distribution, assuming the same local thermal equilibrium as in fluid dynamics.

4. Nonthermal Particle Distribution

In the case of the NAPLIFE project, we avoid the development of thermal equilibrium. The incoming laser beam is one-dimensional, and the proton and ion distribution is dominantly one dimensional in the orthogonal direction.

In such a situation, the momentum distribution is not isotropic, instead being typically distributed in one direction. The particles emitted from the surface of the target are not represented well by the Jüttner (relativistic Boltzmann) distribution, as this includes particles emitted backwards into the target. This is the situation at point of hadronization and "freeze out" in ultra-relativistic heavy ion reactions. Bugaev remedied this problem in [34] by introducing the "Cut-Jüttner" distribution, with a step function $\Theta(x)$ or $\Theta(p_\mu d\sigma^\mu)$ used to eliminate the particles moving back into the source. The discontinuity of this distribution is removed by adding the negative mirror image of the Jüttner distribution on the opposite side of the surface. The distribution created in this way, called the "Cancelling-Jüttner" distribution [35], goes smoothly to zero at the surface, while the negative part is cancelled out by the step function. For such out-of-equilibrium situations, the so called Cancelling Jüttner (CJ) distribution [35,36], is introduced in case of high-energy particle momentum distribution as follows:

$$f_{CJ}(p^\mu) = \frac{\Theta(p^\mu d\sigma_\mu)\ n(x)}{C_\pi\ (2\pi\hbar)^3} \left(\exp\frac{-p^\mu u^R_\mu}{T} - \exp\frac{-p^\mu u^L_\mu}{T} \right) \tag{2}$$

where $d\sigma_\mu$ for a single nanorod is the unit normal vector pointing in the direction of the nanorod antenna, the four-flow vectors $u^R_\mu = (\gamma, \gamma v, 0, 0)$, $u^L_\mu = (\gamma, -\gamma v, 0, 0)$ are in the reference frame of the front, and $n(x)$ is the local particle density.

The CJ distribution strongly resembles the distribution obtained in the EPOCH kinetic theory. The increasingly narrower distributions can be simulated using an increasing velocity parameter $\pm v$ in u^R_μ and u^L_μ.

In our case, the particle emission is in the direction of the nanorod, which points in the direction of polarization of the laser light. The deuterium and He^4 particles have their main direction of emission in this direction, which is the symmetry axis ($d\sigma^\mu$) of the distribution. The spread of the distribution around this direction can be fitted by the velocity v and "temperature" T parameters of the CJ distribution.

The correlation function was evaluated in a simplified situation in [37], demonstrating the kind of information that can be gained using two-particle correlation analysis.

In the case of more involved time dependence of the source, the correlation function becomes more complex as well, which requires adequate analysis.

5. Outlook

At relatively small laser beam energy pulses from ≈30 mJ energies, it is possible to can obtain nuclear reactions, i.e., deuterium production [38]. This is due to the increased proton energy caused by the catalyzing effect of nanorod antennas. The volume and time extent of the "irradiation volume" was theoretically estimated in [17]. Recent theoretical analyses indicate that nanorod antennas may catalyze proton acceleration [39], enabling nuclear transmutation and consequent fusion reactions.

Two particle correlations with even just one or two particle detectors can provide experimental measurements for the dynamic configuration of fusion ignition. Thus far, the application of femtoscopic methods to measure the sizes of deuteron sources is on the level of a conceptual proposal, and should be followed up with a more detailed technical design report that includes a concrete technical setup proposal. We envisage further studies for the proton, deuteron, and alpha (α) nuclei and for Deuterium and Helium4 atoms depending on our future experimental possibilities. Incidentally, we observed the creation of deuterium atoms via their Balmer–alpha line radiation in the plume emerging from the crater caused by the laser shot [38].

Further problems may arise from the Coulomb repulsion among charged atoms and ions at later stages. In the application of the femtoscopic momentum correlation method, measurement of the sizes of deuteron and alpha sources in the laser-induced production process may be hindered by the Coulomb repulsion.

For targets with oriented nanorods, the angular distribution of proton emission can be verified experimentally, which confirms the directed proton acceleration mechanism by the applied nanorod catalyzed fusion method [37].

Author Contributions: L.P.C., T.C., I.P. and K.T. Proposed the method of femtoscopy and performed kinetic model calculations; M.C., A.S. and D.V. Performed calculations for the Electrodynamic field dynamics; T.S.B. and N.K. Assessed the general outcome of the applicatiom of this eveluation method. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available on request from the authors.

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Conflicts of Interest: L.P. Csernai is Chief Executive and proprietor of Csernai Consult Bergen. Authors declare no conflict of interest.

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