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Production and diagnostics of multiphase plasmas using laser ablation and ultrasonic wave

レーザーおよび超音波誘起気–液マルチフェーズプラズマの創製とプラズマ診断

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A topic in this talk is liquid-phase laser ablation, which is a method for producing a multiphase plasma consisting of a solid (the ablation target), a liquid (the ambient medium), and a gas (the cavitation bubble). In addition, the liquid-phase laser ablation plasma has a temperature and a pressure corresponding to a supercritical fluid. Another topic is “sonoplasma”, which is a plasma produced at the collapse of acoustic cavitation. The acoustic cavitation is induced by the irradiation of ultrasonic wave onto a liquid. The sonoplasma is rather new terminology, but we believe that it has been used in the field of sonochemistry for a long time. The study of sonoplasma may open a new interdisciplinary research field.

1. Introduction

In this talk, we mainly focus on plasmas produced in liquids without using electricity. An alternative to electricity is to use optical power. Irradiating an intense laser pulse onto a solid target immersed in liquid produces a dense plasma with a high pressure. This is called liquid-phase laser ablation, which attracts much attention recently as a new method for synthesizing functional nanoparticles. Liquid-phase laser ablation induces the formation of a cavitation bubble. The cavitation bubble is not a static bubble but has dynamics of expansion, shrinkage, and collapse. The inside of the cavitation bubble at the collapse has a high temperature and a high pressure, resulting in the production of secondary plasma. This plasma does not need electricity, and is produced by the mechanical power of the collapsing bubble. We have found the importance of the cavitation bubble in the synthesis of nanoparticles by liquid-phase laser ablation.

Another alternative to electricity is to use acoustic power or ultrasonic wave. It has been known from many years ago that a liquid irradiated by intense ultrasonic wave emits optical radiation (sonoluminescence). The mechanism of the sonoluminescence was a mystery for a long time, but rather recently, it has been shown that the sonoluminescence is originated from a plasma produced at the collapse of cavitation bubble induced by the ultrasonic wave [1]. This plasma is sometimes called “sonoplasma”. We have found a simple way for producing standing sonoplasmas efficiently.

2. Liquid-phase laser ablation

Laser ablation plasmas have high densities since they are produced from solid targets directly. This is also the case in the very early stage of laser ablation in vacuum; however, the lifetime of the high-density plasma is short in vacuum because of the rapid expansion of the laser ablation plume. The ambient medium confines the plume tightly in liquid-phase laser ablation, resulting in in a small, dense plasma. We observed no line emissions from liquid-phase laser ablation plasmas [2]. The blackbody radiation indicates a high density and rapid quenching in the liquid-phase laser ablation plasma.

After the disappearance of optical emission, we observe the formation of a gas phase; that is a cavitation bubble. Since the cavitation bubble is formed by abrupt vaporization, it has a high pressure at the beginning. The high pressure drives the expansion of the bubble. It is important here that the expansion cannot stop due to the inertia even after the inside of the bubble has a negative pressure. The cavitation bubble begins to shrink after the maximum size because of the negative pressure, and the shrinkage cannot also stop even after the bubble pressure reaches the ambient pressure. This results in the high bubble pressure at the collapse [3]. In addition, since the bubble dynamics is adiabatic, the bubble temperature in the expansion phase is ultralow, while the bubble temperature at the collapse is ultrahigh [3]. The cavitation bubble provides us an interesting reaction

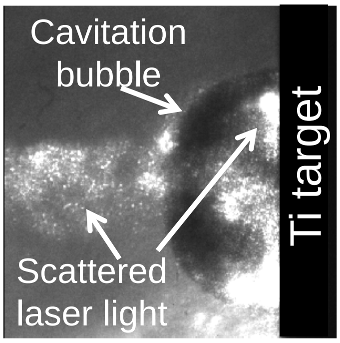

Fig. 1 Superimposed image of shadowgraph and laser light scattering observed in liquid-phase laser ablation of a titanium target.

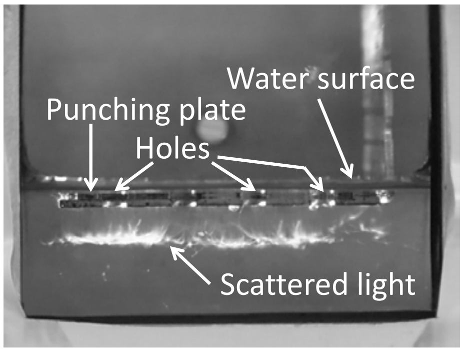

Fig. 2 Photograph of a sonoplasma production system with the help of a punching plate. Cavitation bubbles are seen by light scattering.

field with unique physical parameters.

We have found that the cavitation bubble plays an essential role in the synthesis of nanoparticles by liquid-phase laser ablation. Figure 1 shows a superimposed image of shadowgraph and laser light scattering. The location and the size of the cavitation bubble is observed by shadowgraph imaging, while the location of nanoparticles is detected by laser light scattering. As shown in the figure, nanoparticles are stored in the cavitation bubble until the collapse [4]. Since nanoparticles are immersed in the high-pressure, high-temperature reaction field at the collapse of the cavitation bubble, the size [5] and the structure [6,7] of nanoparticles are controlled by the physical control [8,9] of the dynamics of the cavitation bubble. The importance of the cavitation bubble in the synthesis of nanoparticles is also reported by another group [10].

3. Sonoplasma

We believe that sonoplasmas are used by chemists for a long time. The enhancement of liquid-phase chemical reactions with the help of ultrasonic wave is called sonochemistry. It utilizes radicals produced at the collapse of cavitation bubbles. Chemists are not so interested in the plasma at the collapse of cavitation bubbles, but the study of sonoplasma may open a new interdisciplinary research field. Of course sonochemistry is also in a close position to the study of liquid-phase plasmas.

We have noticed that the insertion of a punching plate is a simple, efficient way for producing standing sonoplasmas [11]. Figure 2 shows a picture of a vessel which is filled with water. The vessel has an ultrasonic transducer at the bottom, and ultrasonic wave at a frequency of 32 kHz is propagating from the bottom toward the water surface. This situation is rather similar to an ultrasonic clear used in a glasses shop. The water is illuminated by white lamp light, and cavitation bubbles are seen like white cloud by light scattering. We did not observe remarkable formation of cavitation bubbles in the absence of the punching plate. However, as shown in Fig. 2, we obtained the efficient formation of cavitation bubbles below the punching plate. The group of crowded cavitation bubbles did not move and were standing. We confirmed that the production rate of gold nanoparticles from $HAuCl_4$ solution was enhanced by a factor of 8 by inserting the punching plate. Now we are trying to have electrical discharges inside collapsing cavitation bubbles [12].

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