Friction

Research Article

Experimental study on deuterium–deuterium thermonuclear fusion with interface confinement

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ABSTRACT: Nuclear fusion is recognized as the energy of the future, and considerable effort and capital have been put into the research of controlled nuclear fusion in the past decades. The most challenging thing for controlled nuclear fusion is to generate and maintain a super high temperature. Here, a sonication system combined with micro-scale fluid control techniques was built to generate cavitation within a limited region. As bubbles were rapidly compressed, the high-temperature plasma generated inside led to particle emissions, where a $Cs_2LiYCl_6:Ce^{3+}$ (CLYC) scintillator is used to collect the emission events. The pulse shape discrimination methods applied to the captured signals revealed that only gamma ray events were observed under sonication with normal water, while obvious separation of neutron and gamma ray events was surprisingly identified under sonication with deuterated water. This result suggested that neutrons were emitted from the sonicated deuterated water, i.e., deuterium–deuterium thermonuclear fusion was initiated. This study provides an alternative and feasible approach to achieve controllable nuclear fusion and makes great sense for future studies on the application of fusion energy.

KEYWORDS: collapsing bubble; bubble wall dynamics; interface mass transfer; interface confinement; thermal nuclear fusion

1 Introduction

As is known to all, the sun and stars are powered by the fusion of hydrogen into helium. If nuclear fusion can be successfully recreated on Earth, it holds the potential of virtually unlimited supplies of low-carbon and low-radiation energy. In the past decades, plenty of efforts and huge amount of money have been put into fusion-related researches, including inertial [1] and magnetic [2] confinement projects worldwide, yet the way to practical application of fusion as an energy supply is still long and unpromising. In 1996, Moss et al. [3] numerically studied the temperature inside a sonoluminescent cavitation bubble and suggested that the high temperature and pressure formed inside a collapsing bubble may satisfy the occurrence criteria of deuterium-deuterium thermonuclear fusion reaction, if the oscillating bubble is applied with proper acoustic activation. Since then, generating high temperatures inside cavitation bubbles has been considered a promising alternative to achieve fusion in the laboratory [4]. Ever since the original work of single bubble sonoluminescence [5], considerable efforts have been made to understand oscillating cavitation bubbles and their accompanying phenomena [6–14], and researchers found that the collapsing cavitation bubbles could be extremely compressed, resulting in high temperatures and pressures [15–20]. In 2002, Taleyarkhan and his co-workers [21–23] claimed that they observed neutrons emitted from imploding cavitation bubbles in a series of experiments, but their results have been greeted with criticisms ever since. Shapira and Saltmarsh [24] and Barbaglia et al. [25] tried to reproduce this work, but both of them ended up unsuccessfully. This misfortune greatly struck the following research on related fields thereafter. However, the great potential applications of controlled fusion initiated by cavitation bubbles still attract many researchers [26, 27], as well as the pure hydrogen energy [28].

Astrophysical studies have reported that both the gravity induced by the star matter itself and the electron/neutron degenerate pressure are crucial for the evolution of the star [29]. As the gravity overcomes the effect of electron/neutron degeneracy pressure, the star would enter the gravitational collapse stage, which greatly increases the temperature inside the star [30]. These astrophysical discoveries have inspired researchers

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to explore extreme pressure and temperature conditions in laboratory environments. Previous studies have proven that cavitation bubbles could be intensively compressed in a short time, and the material inside the bubbles would become plasma at high temperatures [13, 31]. Just like the evolution of the stars, the matters inside the bubble, as well as the physical process the high-temperature plasma experiences, play an important role in the collapse of the bubbles. The sheath formed near the bubble interface helps to constrain the energy state of the high-temperature plasma. If the maters inside the bubble could be remarkably increased and the bubble could be compressed with high velocity, the temperature inside the bubble might reach the criteria for thermal nuclear reaction. Hence, it makes sense to develop techniques that could bring the bubble into fiercer collapse with more matters inside.

During the oscillation of cavitation bubbles, the movement of the bubble wall during the collapse stage is surely faster than that during the expansion stage, and the mass transfer from liquid to vapor during the expansion stage plays an important role in the growth of the cavitation bubble. Accordingly, the greater this bubble wall acceleration difference between the collapse stage and expansion stage is, the larger the mass inside the bubble would be. During the collapsing stage, the moving velocity and acceleration significantly increase, leading to the formation of a shock wave inside the bubble. Moreover, the material inside the bubble is highly compressed, causing an extreme physical state with high temperature and pressure and finally generating high-temperature plasma inside the bubble. The greater the mass inside the bubble and the fiercer the bubble wall dynamics, the higher the temperature. In this work, a unique sonication system was built to generate cavitation within a limited region, where a static electrical field was also imposed. Here, owing to the propagation and reflection of ultrasonic waves within the confined space, the cavitation bubbles experienced much more complex driving pressure than ever before. Thus, the mass transfer behavior through the bubble interface into the bubble inside was considerably enhanced because of the fiercer bubble wall dynamics. Since previous studies [24, 27] have acknowledged that the emission of neutrons from the collapsing bubbles in deuterated liquid could be utilized to examine whether the nuclear fusion reaction occurs during sonication, an independent neutron detection system, which is based on the CLYC scintillator, was established here to study the particle emissions from collapsing cavitation bubbles. Pulse shape analysis (PSA) [32, 33] and rise time analysis (RTA) [34, 35], which are applied on waveforms collected with the detector during the sonication experiments, both displayed obvious separation of neutron and gamma ray events, indicating the occurrence of deuterium-deuterium thermal fusion in sonication with deuterated water.

2 Experimental setup

The arrangement of the sonication platform and the neutron detection system is shown in Fig. 1(a). A vibration horn, with a frequency of 15,560±15 Hz and a vibrating amplitude of 35 μm, was used to initiate cavitation in the sonication chamber, which was mounted on an electrical elevator. Figure 1(b) shows a schematic of the sonication chamber. A coolant jacket with an inlet temperature of 290 K was installed to cool the temperature of the solution during sonication. Generally, cavitation bubbles possess a weak negative electric potential property due to the generation of hydroxyl radicals during sonication. It has been suggested that the electrostatic force can promote the stability of bubbles during collapsing [36], which is beneficial for further increasing the temperature and pressure inside the bubbles. Tantalum pentoxide has a wide electrochemical window due to its high dielectric constant, so the electrolytic water reaction is difficult to be initiated even when a high voltage is applied. In this work, the voltage applied between the tip of the vibration horn and the bottom sample, which was covered with tantalum

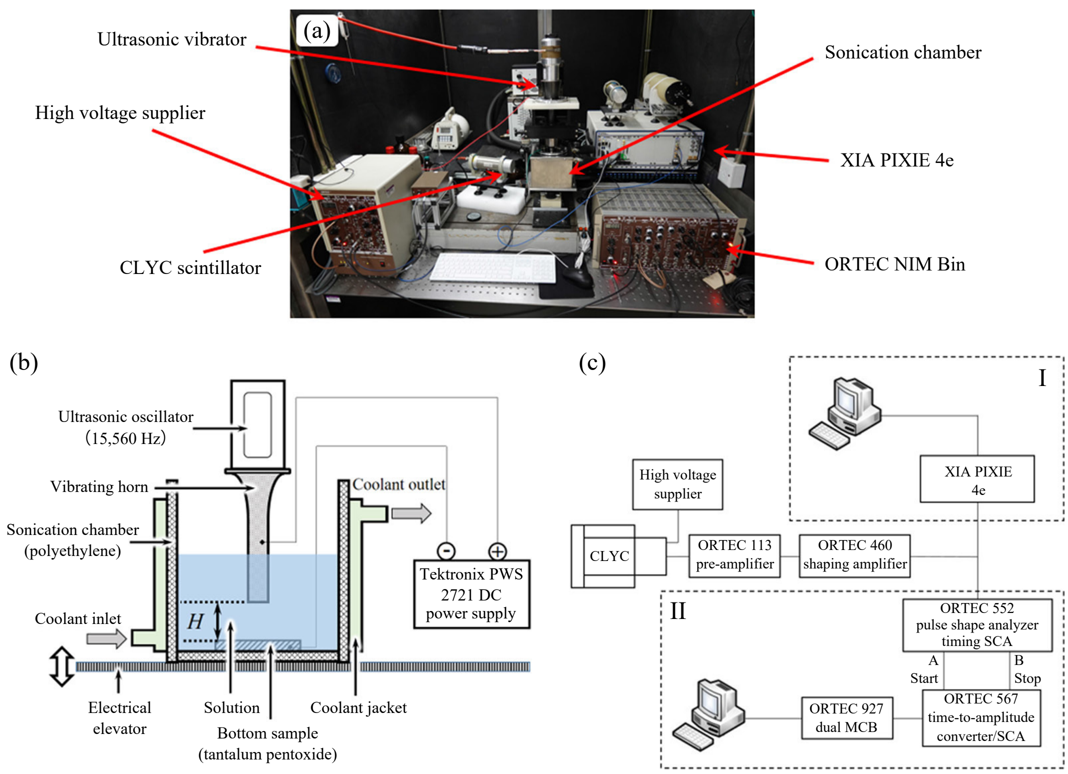

Fig. 1 Experimental setup: (a) arrangement of sonication platform and neutron detection system; (b) schematics of sonication chamber; (c) logic circuit diagram of neutron detection system.

pentoxide, was set to 15 V to impose a static electrical field on the bubbles. The distance between the tip of the horn and the bottom sample, i.e., the dispersing height of cavitation bubbles [36], was set to be 50 μm, which is greater than the amplitude of the horn.

The logic circuit diagram of the neutron detection system based on the CLYC scintillator is presented in Fig. 1(c). The detection system contained one CLYC scintillator cell, which was optically coupled to a Hamamatsu R6231-100 photomultiplier (PMT), and an independent uninterrupted power supply (UPS) was utilized to reduce the electrical interference from the power net. After amplification, one output from the PMT was fed into the XIA PIXIE 4e module, a firmware incorporated with the PSA algorithm. Another output was sent to the RTA logic circuit diagram. In this way, the pulse shape discrimination was applied on the signals captured by the CLYC scintillator.

Before being applied in the controlled experiments, the detection system was exposed to an Am–Be neutron source, and the emitted signals were collected and analyzed with the XIA PIXIE 4e module. The pulse shape discrimination (PSD) variable "slow light/fast light", defined by the ratio of the integrated light in the tail of the PMT signal generated by an event in the scintillator to the integrated light around the signal's peak [37, 38], was employed to discriminate the neutrons from the gamma particles. (See the Electronic Supplementary Material (ESM) for details on the method of pulse shape discrimination.) The PSD spectrum obtained with the XIA PIXIE 4e module is presented in Fig. 2. The scatter density plot clearly shows that the signals can be divided into two regions, i.e., the upper branch with a PSD variable greater than 10 and the lower branch with a PSD variable less than 10. Given that the proton recoils induced by neutrons have longer scintillation decays, the hits in the upper branch represent the neutron events, and the hits in the lower branch are considered gamma ray events. For neutron events, most of their PSD variables are located between 15 and 20, and the energy of these hits exhibits a Gaussian distribution with a peak of approximately 2.8×10^4.

3 Results and discussion

With the sonication system and neutron detection system introduced above, a series of controlled experiments were carefully conducted in normal water and deuterated water, respectively. The volume of the sonication liquid was set to be 200 mL in all experiments, and the duration of each sonication lasted 120 s. The PSA and RTA results are presented in Figs. 3 and 4, respectively.

In Fig. 3, the PSD spectra for sonication in normal water and deuterated water, accomplished with the algorithm embedded in XIA's Pixie spectrometer are presented. Figure 3(a) shows that most of the signals have energies smaller than 2.0×10^4 on the chart, and the number of signals with PSD values ranging from 0 to 5 is obviously the highest. Otherwise, only a few signals with energies greater than 2×10^4 and PSD values greater than 10 are found, and these signals are randomly scattered on the chart. However, as shown in Fig. 3(b), when sonication is induced in deuterated water, the number of signals with PSD values smaller than 10 increases drastically, and the energy of these lower PSD signals also rises, mostly up to 2×10^4. Importantly, signals with PSD values ranging from 15 to 20 and energies greater than 2×10^4 are densely scattered, as shown in Fig. 3(b), and this distribution pattern is in accordance with the neutron events shown in Fig. 2. This difference between Figs. 3(a) and 3(b) indicates that neutron events were captured by the detection system from the sonicated deuterated water.

When sonication was performed in normal water, the collapse

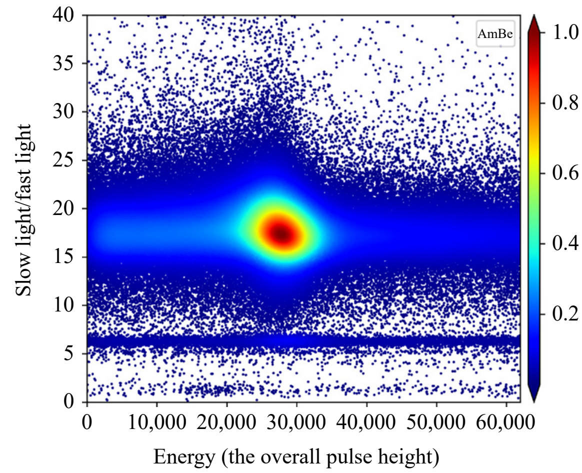

Fig. 2 Scatter density plot of signals captured by detection system exposed to Am–Be neutron source.

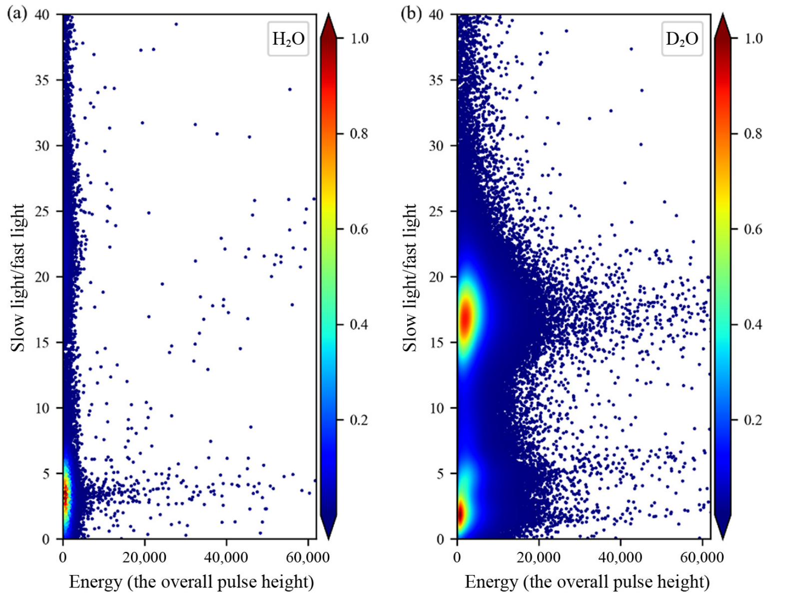

Fig. 3 Pulse shape analysis of signals: (a) sonication with normal water; (b) sonication with deuterated water.

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of the cavitation bubble would generate high temperature and high pressure inside the bubble and then induce the transitions of electrons between different energy levels of atoms, in which gamma ray particles could be emitted. Nevertheless, as in deuterated water, the extremely high physical condition inside the bubbles, resulting from the collapse of cavitation bubbles, could reach the level of deuterium–deuterium thermonuclear fusion, which emits considerable amounts of neutrons and gamma ray particles. The whole physical process was so fierce that visible luminance could be obviously observed during the sonication. (See the video in the ESM for details on the experimental process.) Accordingly, the detected spectrum in Fig. 3(b) presents two major concentrated regions, respectively corresponding to neutron events and gamma ray events, while only one major concentrated region is found in Fig. 3(a). Moreover, an extra detection system based on the ^{3}He proportional counter was established to double examine the neutron emission phenomena during the sonications, and the collected spectrum with deuterated water displays a similar profile with the calibration spectrum when exposed to an Am–Be neutron source, which strongly proof the emission of neutrons. (See the ESM for details on Helium-3 based neutron detection system.)

Using the information of the rising time of the scintillation light pulse, Fig. 4 displays the RTA results from sonication with normal water and deuterated water, respectively. In Fig. 4(a), only one peak at approximately 1,200 is observed, which indicates that only one kind of particles are captured by the scintillator. In contrast, in addition to the same peak located in Fig. 4(a), another peak on larger channels, between 1,400 and 1,500, is found in Fig. 4(b), and obvious separation of these two peaks could be identified here. Since the proton recoils induced by neutrons have longer scintillation decay, the rising time of signals induced by neutron events should have a larger value than that of gamma ray events. Thus, the two peaks in Fig. 4(b) undoubtedly correspond to the gamma ray events and the neutron events, respectively. Accordingly, the comparison of the RTA results in Fig. 4 also confirms that neutrons were detected when the sonication was generated in deuterated water, which provided positive evidence of the occurrence of deuterium–deuterium thermonuclear fusion in this work.

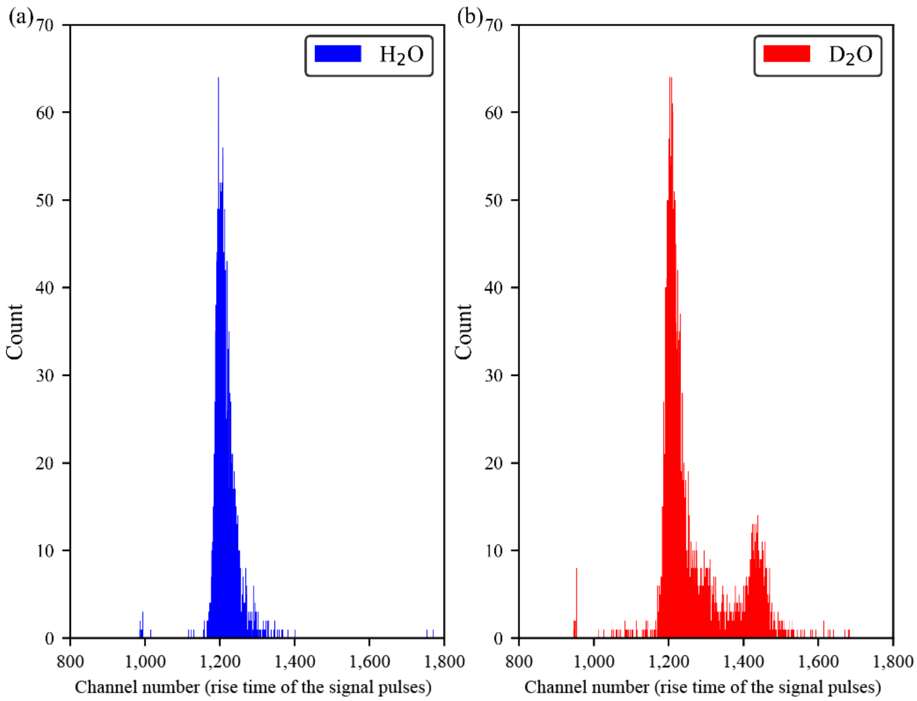

Fig. 4 Rise time analysis of signals: (a) sonication with normal water; (b) sonication with deuterated water.

4 Conclusions

In this work, intense cavitation, induced by an ultrasonic vibrating horn within a limited region, was performed respectively in normal water and deuterated water, and the particle emission behavior caused by collapsing cavitation bubbles was investigated with a detection system based on a CLYC scintillator. The pulse shape discrimination procedures applied on the collected signals, which were carried out with pulse shape analysis and rise time analysis, implied that only gamma ray events were captured during sonication with normal water, while obvious separation of neutron and gamma ray events was identified during sonication with deuterated water. The detection accomplished here indicated that deuterium–deuterium fusion was achieved when sonication was conducted in deuterated water. This study proposes a feasible approach to achieve controllable nuclear fusion and provides useful guidelines for the future application of fusion energy.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. The author Shuai Chen is the Youth Editorial Board Member of this journal.

Electronic Supplementary Material

Supplementary material is available in the online version of this article at https://doi.org/10.26599/FRICT.2025.9441083.

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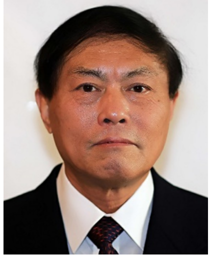

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