Nuclear Emissions During Self-Nucleated Acoustic Cavitation

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A unique, new stand-alone acoustic inertial confinement nuclear fusion test device was successfully tested. Experiments using four different liquid types were conducted in which bubbles were self-nucleated without the use of external neutrons. Four independent detection systems were used (i.e., a neutron track plastic detector to provide unambiguous visible records for fast neutrons, a BF_3 detector, a NE-113-type liquid scintillation detector, and a NaI γ ray detector). Statistically significant nuclear emissions were observed for deuterated benzene and acetone mixtures but not for heavy water. The measured neutron energy was ≤ 2.45 MeV, which is indicative of deuterium-deuterium (D-D) fusion. Neutron emission rates were in the range $\sim 5 \times 10^3$ n/s to $\sim 10^4$ n/s and followed the inverse law dependence with distance. Control experiments did not result in statistically significant neutron or γ ray emissions.

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Introduction.—Previously, we have provided evidence [1(a),2–4] for 2.45 MeV neutron emission and tritium production during external neutron-seeded cavitation experiments with chilled deuterated acetone, and these observations have now been independently confirmed [5]. Even though the major criticisms associated with our previously published results [1(a)] have been thoroughly discussed and resolved [2], there has been a lingering concern about the use of an external neutron source which strongly suggested the need to demonstrate that thermonuclear fusion could also be attained during acoustic cavitation *without* the use of an external source of neutrons. In addition, it was desirable to demonstrate the ability to attain D-D fusion with alternate deuterated liquids and to measure the emitted neutrons with independent detection systems. In the data presented previously [1(a),2] the neutron measurements were obtained using a NE-213 type liquid scintillation fast neutron detector with pulse-shape discrimination [6–8], and the only test liquid used was deuterated acetone. Our simulations of implosion dynamics indicate that heavy water would not be a good choice [1(b),3] for attaining thermonuclear fusion in imploding bubbles.

In this Letter, we report the results of investigations using independent neutron detection systems and the self-nucleation of bubble clusters in various deuterated liquids including water (without using an external neutron source).

Experimental system.—The experimental configuration is shown in Fig. 1. The test liquid was placed in a cylindrical glass test section which was driven harmonically with a lead-zirconate-titanate (PZT) piezoelectric driver ring attached to the outside surface of the test section. This induced an acoustic standing wave in the test section with a pressure antinode of maximum amplitude ~15 bar. Test-cell operational aspects are described elsewhere [1(a),2,9]. Four independent nuclear particle detection systems were utilized in the new study. This included use of a long-established passive-type track-edge fast neutron detector (i.e., CR-39^{TM} plastic detector from Landauer, Inc.) that is insensitive to γ rays and that is well-known [9–11] to be able to distinguish between neutrons and γ rays, a boron trifluoride (BF_3) thermal neutron detector (TND), a fast rise-time liquid scintillation (LS) detector to ascertain the energy and quantity of any emitted neutrons, and a NaI γ ray spectrum detector.

A unique feature of the present study was the method used for bubble nucleation. In particular, randomly generated (mainly ~4 MeV alpha particles) radioactive decay of dissolved natural uranium was used to nucleate bubble clusters. This completely obviates the need to use an external neutron source and resolves any lingering confusion associated with the possible influence of the previ-

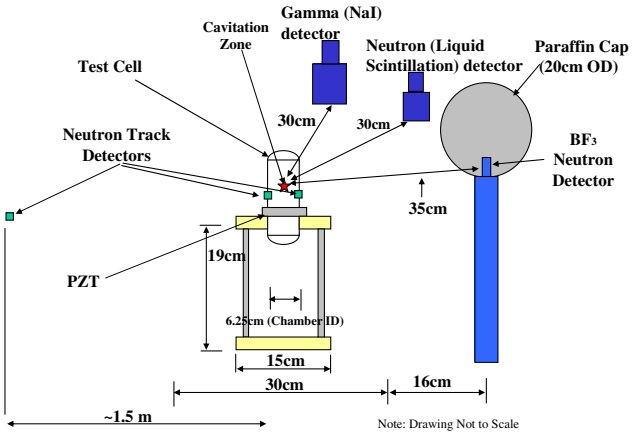

FIG. 1 (color online). Schematic representation of experimental setup.

ously used [1,2] external source neutrons (14.1 MeV) on the emitted neutrons (2.45 MeV).

The test liquids with dissolved alpha emitters were either a mixture of benzene (C_6H_6 or C_6D_6), acetone (C_3H_6O or C_3D_6O), and C_2Cl_4 (an organic liquid which has a significantly lower vapor pressure), or water (H_2O and D_2O). The experiments presented herein did not use external neutrons, rather a uranyl nitrate (UN) salt of natural uranium (99.3% U-238) was used to form a solution [9]. The experiments with benzene-based mixtures were conducted at a temperature of ~7 C (which is a few degrees above the freezing point of benzene), while the experiments for water were run at ~5 C. In contrast with cavitation experiments using fast neutrons and acetone [1(a),2] where we could nucleate ~30 bubble clusters per second, in self-nucleation experiments [9] the rate was much lower at ~1 per second (for benzene-based mixtures) and around 5 per second for water. It is not clear at the present time why this sort of performance reduction takes place; however, the aim of the present experiments was not to optimize D-D neutron emission but to assess if neutron-gamma emissions were at all possible during bubble implosions with deuterated liquids *without* the use of an external neutron source. See Ref. [9] for additional insights.

BF_3 *detector—experimental observations with various test liquids.*—The BF_3 nuclear particle detector (length = 4.5 cm; diameter = 1.25 cm) was used with a 20 cm diameter paraffin ball moderator over it as shown in Fig. 1.

Detector calibration.—The BF_3 detector was calibrated for efficiency of detection using a NIST certified Pu-Be source (emitting $\sim 2 \times 10^6$ n/s) as well as with 1 μCi Co-60 and Cs-137 γ ray sources. Results of pulse height spectra obtained with the Pu-Be source [9] showed a well defined neutron peak above channel 25. At a 10 cm separation the count rate was ~220 c/s which, when corrected for solid angle (0.0054), gives an intrinsic efficiency of ~3% for the detection of fast neutrons in the MeV range. The detector response to γ rays indicated that the majority of pulses would occur [9] below channel 20. The counts collected followed the inverse square law [9], for different separations between the Pu-Be neutron source and the BF_3 detector.

BF_3 *data from self-nucleation experiments with benzene-C_2Cl_4-acetone-UN mixtures.*—Results of control experiments with a C_6H_6-C_2Cl_4-C_3H_6O-UN mixture indicated [9] that there was no statistically significant net change in counts between cavitation on and off. In contrast, the results of experiments with a deuterated C_6D_6-C_2Cl_4-C_3D_6O-UN mixture produced a significant increase (~400%) in neutron counts and ~100% increase of γ ray counts as seen in Fig. 2 and in Table I. Based on the calibrated detector efficiency, the neutron emission rate was estimated to be ~ 5–7×10^3 n/s.

As a cross-check, the distance of the detector from the test cell was roughly doubled from a nominal 35 cm to 65 cm and the experiments were repeated whereby the increase of neutron counts came down by a factor of about 4, commensurate with the inverse square law dependence with distance.

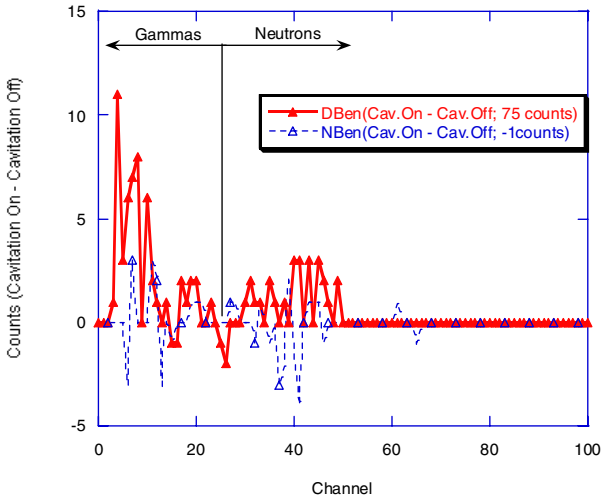

FIG. 2 (color online). Change in counts from Neutron-Gamma Spectra for C_6D_6-C_2Cl_4-C_3D_6O-UN and C_6H_6-C_2Cl_4-C_3H_6O-UN with self-nucleation and BF_3 detector (data collected over 3600 s; Cavitation off counts = 49 and 50 counts for deuterated and nondeuterated liquid tests, respectively).

BF_3 *data from self-nucleation experiments with water.*—Experiments were also conducted by dissolving UN salt in water [9]. Results of experiments with light water (H_2O) and heavy water (D_2O) are shown in Fig. 3 and the raw data are provided elsewhere [9]. For these experimental parameters there was no statistically significant evidence of nuclear emissions with cavitation, for either H_2O or D_2O, which was in accordance with our expectations [1(b),3,9].

LS detector data—experimental observations with various test liquids.—The data obtained with the BF_3 detector system were complemented with data taken with a 5 cm dia × 5 cm LS detector [2] with pulse-shape discrimination between the neutrons and γ rays. Using well-established light curves [6–9], and with the instrument settings used for these experiments, the 2.45 MeV proton-recoil edge corresponded to channel ~120.

LS data from self-nucleation experiments with benzene-C_2Cl_4-acetone-UN mixture.—Raw data from control experiments with C_6H_6-C_2Cl_4-C_3H_6O-UN mixtures and deuterated C_6D_6-C_2Cl_4-C_3D_6O-UN mixtures are provided elsewhere [9]. Net results are shown in Fig. 4 and Table I ,where we see a statistically significant (~17 SD) emission of neutron counts, corresponding to neutron energies of $\leq$ 2.45 MeV.

Neutron track detector—direct visible evidence for neutron emission.—The CR-39^{TM} neutron track (NT) detector was also calibrated and used [9] in our studies for neutron detection; the technology has been utilized for over 40 years [10,11] as a passive means for directly confirming

TABLE I. Count Statistics (above background).

Figure No.	Cav. On Counts	Cav. Off Counts	Difference (On-Off)	SD in Difference	Diff/SD	Detector	Fluid
2	50	49	−1	10	−0.10	BF_3	$C_6H_6 + C_2Cl_4 + C_3H_6O$ + UN
2	124	49	75	13.2	5.7	BF_3	$C_6D_6 + C_2Cl_4 + C_3D_6O$ + UN
3	39	44	−5	9.1	−0.55	BF_3	H_2O + UN
3	37	39	−2	8.8	−0.23	BF_3	D_2O + UN
4	913	923	−10	43	−0.23	LS	$C_6H_6 + C_2Cl_4 + C_3H_6O$ + UN
4	2015	1055	966	55	17.4	LS	$C_6D_6 + C_2Cl_4 + C_3D_6O$ + UN
5	Ref. [9]	Ref. [9]	Ref. [9]	Ref. [9]	<1	Track	$C_6H_6 + C_2Cl_4 + C_3H_6O$ + UN
5	Ref. [9]	Ref. [9]	Ref. [9]	Ref. [9]	14 (Ref. [9])	Track	$C_6D_6 + C_2Cl_4 + C_3D_6O$ + UN
Ref. [9]	16 804	16 906	−102	182	−0.5	NaI	$C_6H_6 + C_2Cl_4 + C_3H_6O$ + UN
Ref. [9]	16 196	15 844	352	178	2	NaI	$C_6D_6 + C_2Cl_4 + C_3D_6O$ + UN

and leaving permanent unambiguous evidence for the presence of neutrons. During each experiment three CR-39 NT detectors were placed as shown in Fig. 1. One CR-39 NT detector was placed approximately 1.5 m away from the test cell to measure the background, whereas two others were affixed to the outside of the glass walls of the test cell.

Experiments were conducted with a deuterated (C_6D_6-C_2Cl_4-C_3D_6O-UN) and control liquid C_6H_6-C_2Cl_4-C_3H_6O-UN. Raw data of the experiments are provided elsewhere [9] and the results are shown in Fig. 5. It was verified that no statistically significant change occurs over background levels without cavitation in deuterated liquid. There were no statistically significant neutron tracks compared with the background sample for the control liquid C_6H_6-C_2Cl_4-C_3H_6O-UN. The average number of preexisting tracks on the background and the test-cell attached detectors (etched for 3 hours each) were both around 13. Significantly, close to a 100% increase [and >5 standard deviation (SD)] in visible neutron tracks were observed for individual samples, only for samples associated with self-nucleation based cavitation experiments in the deuterated liquid C_6D_6-C_2Cl_4-C_3D_6O-UN experiments. On the aggregate, the production of neutron tracks for the deuterated liquid amounted to a ~14 SD change, whereas, for the control liquid the changes were within 0.5 SD. A confirmatory check was also conducted for cavitation experiments with heavy water (D_2O), where it was found that no significant production of neutron tracks was observed (i.e., the changes were within 1 SD). Overall statistics are summarized in Table I. Based on the calibrated efficiency of detection using CR-39 NT detectors we estimate a neutron emission rate of $\sim 5 \times 10^3$ to $\sim 10^4$ n/s which agrees with the results from our other detectors.

Gamma ray spectra data.—Gamma ray spectra were also obtained [9] using a calibrated Harshaw™ NaI (5 cm dia × 13 cm) detector to understand better the neu-

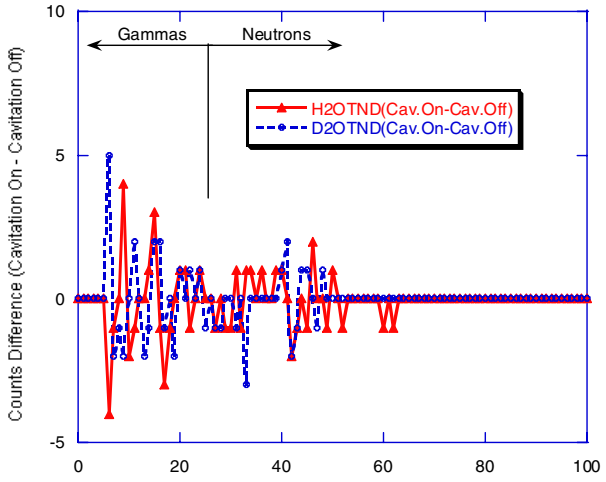

FIG. 3 (color online). Changes in counts from Neutron-Gamma Spectra for D_2O and H_2O with self-nucleation and BF_3 detector (counts for cavitation Off/On = 37/39 for D_2O-UN; = 39/44 for H_2O-UN).

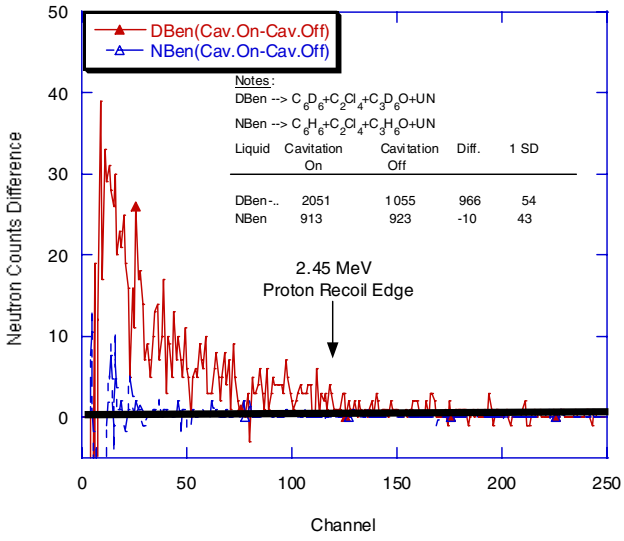

FIG. 4 (color online). Change in counts from pulse height spectra for C_6D_6-C_2Cl_4-C_3D_6O-UN and C_6H_6-C_2Cl_4-C_3H_6O-mixtures with self (alpha recoil nucleation) and LS detector (data taken over 300 seconds).

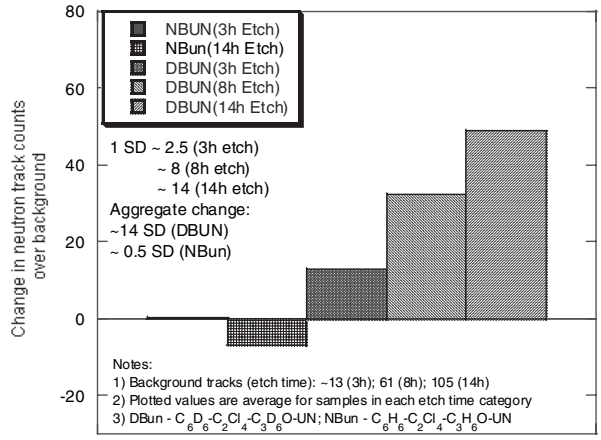

FIG. 5. Variation of neutron tracks for deuterated and nondeuterated test fluids.

tron emission data from the self-nucleation experiments. The results of the control experiments with and without cavitation using C_6H_6-C_2Cl_4-C_3H_6O-UN indicated [9] no statistically significant change between cavitation on and off. In contrast, the results for the experiments with and without cavitation using C_6D_6-C_2Cl_4-C_3D_6O-UN showed a noticeable increase in γ ray emissions above background with cavitation on versus off.

Summary and concluding remarks.—A novel, new technique was used to develop a stand-alone acoustic inertial confinement nuclear fusion device. Statistically significant emissions of 2.45 MeV neutrons were measured with multiple independent detectors during self-induced cavitation experiments in deuterated benzene-acetone mixtures, but not in corresponding experiments with nondeuterated control liquids or heavy water. The measured neutron emissions ($\sim 5 \times 10^3$ to $\sim 10^4$ n/s) obeyed the well-known and expected inverse law dependence with distance. These emission rates are far below break-even levels. As expected, the dissolved emitter did induce cavitation in both D_2O and H_2O, but this did not result in statistically significant changes in the measured neutron counts despite far higher bubble cluster nucleation rates. γ ray emissions were also measured during cavitation experiments with chilled C_6D_6-C_2Cl_4-C_3D_6O-UN. No statistically significant change in neutron or γ ray emissions were observed when there was no cavitation in either deuterated or control liquids.

These data both support and complement the sonofusion data and theoretical predictions that have previously been published [1,2] and clearly demonstrate that thermonuclear conditions can be created during acoustically forced bubble cluster implosions, without the need for an external neutron source.

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