Acoustic Inertial Confinement
Thermonuclear Fusion
– Status, Challenges and Opportunities

September 29, 2005

Rusi Taleyarkhan
Arden L. Bement Jr. Professor of Nuclear Engineering
Director, Metastable Fluid Research Laboratory
School of Nuclear Engineering
Purdue University
Purdue University – The Boilermakers
### Purdue University – Fact Sheet

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Established (1874)</td>
<td>39</td>
</tr>
<tr>
<td>Enrollment (Fall, 2004)</td>
<td>68,746</td>
</tr>
<tr>
<td>Degrees Awarded (1874-2003)</td>
<td>477,000</td>
</tr>
<tr>
<td>Alumni (Living)</td>
<td>375,000</td>
</tr>
<tr>
<td>Budget</td>
<td>$1,526,537,034</td>
</tr>
<tr>
<td>Ranking (academic – engr)</td>
<td>Top 10 (US)</td>
</tr>
<tr>
<td>Faculty/Staff</td>
<td>17,812</td>
</tr>
<tr>
<td>Physical Plant</td>
<td>18,275 acres</td>
</tr>
<tr>
<td>President</td>
<td>Martin Jischke</td>
</tr>
</tbody>
</table>
THE ALLURE & CHALLENGES OF NUCLEAR FUSION

• Vast resources (D atoms) - virtually infinite supply in sea water

• Very high energy density (x 10^6 - TNT, Natural gas,...)

• Radioactive byproducts are much lesser/short-lived than from fission

• Requires > 10^7 K plasma that needs to be confined/controlled
  -- X-Treme Rate Dependencies on Plasma Temp.
  -- Dissociation, Ionization, Electron conductivity, Bremmstrahlung,
  -- Confinement (high pressures, D/T atoms, Time)

• Worldwide efforts (>>$B) for over 40y --> ITER / NIF / Z-Pinch/..

• Need for breakthrough in fusion induction, control and scaleup
  --> Acoustic ICF (Bubble) fusion
KINETICS OF FUSION – The Slippery Slope

\[ D + D \rightarrow \begin{cases} \text{\( ^3 \text{He} + n \)}} \quad (\sim \frac{1}{2}) \\ \text{T + H} \quad (\sim \frac{1}{2}) \end{cases} \]

\[
\langle \sigma v \rangle, \text{ m}^3/\text{s} \\
\begin{array}{c}
10^{-36} \\
10^{-33} \\
10^{-30} \\
10^{-27} \\
10^{-24} \\
\end{array} \\
\begin{array}{c}
10^6 \\
10^7 \\
10^8 \\
10^9 \\
10^{10} \\
\end{array}
\]

\[ \sigma v(10^7\text{K}) / \sigma v(10^6\text{K}) \rightarrow \sim 10^9 \]
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1937</td>
<td>Frenzel/Shultes → Photoplates fogged during US cavitation</td>
</tr>
<tr>
<td>1939</td>
<td>“Sonoluminescence” – Harvey (electric charge?)</td>
</tr>
<tr>
<td>1950</td>
<td>Hot Spot Theory (Noltingk and Neppiras) → Compr Htg.</td>
</tr>
<tr>
<td>1960</td>
<td>Extended Hot Spot Theory (Jarman) → Shock Heating</td>
</tr>
<tr>
<td>1962</td>
<td>Timing of SL (Colin West/Harwell – Acustica)</td>
</tr>
<tr>
<td>1992</td>
<td>Single Bubble SL (Gaitan)</td>
</tr>
<tr>
<td>1994</td>
<td>Moss et al. (LASNIX → Can we fire up fusion?; 107K)</td>
</tr>
<tr>
<td>1997</td>
<td>NURETH-7 (Nigmagtulin/Lahey/Embreatchts)→Aperiodic? → Meeting of minds; RPT → formulation of challenge</td>
</tr>
<tr>
<td>2000</td>
<td>Aperiodic forcing enhancement of SL (PRL)</td>
</tr>
</tbody>
</table>
| 1999 | USDOD/Darpa → Search for Acoustic Thermo-Nuclear Fusion?  
| 2005 | “Nature” – Flanigan/Suslick → Plasma states confirmed |
| 2005 | “NED/ANS/NURETH-11” → First successful fusion confirmation |

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SONOLUMINESCENCE
(x 10^{11} Energy Concentrator)

CONVENTIONAL SBSL

Rm/Ro ~ 10
P ~ +/- 1 bar
Tm ~ 600,000 K
(Bremmstrahlung)

Stability Limits

P (bar)
R (\mu m)
SL

+/-1
~7 - 70
~ 50 ps light flashes
Because we can see only the surface of the radiating region

And the interior may be undergoing thermonuclear fusion

Our intriguing little bubble
could actually be

In a JAR!

A Star

Source – L. Crum
BUBBLE FUSION

- MECHANISM FOR INDUCING EXTREME (ULTIMATE) MECHANICAL ENERGY FOCUSING via COLLAPSING BUBBLES

⇒ ~ x \(10^{16}\) to \(10^{20}\)

- IMPLoding BUBBLES REACH CONDITIONS PREVALENT IN THE INTERIOR OF THE STARS

⇒ ~ 1,000 Mbar; \(10^7\)K to \(10^8\)K

- SUFFICIENTLY ROBUST TO FUSE D & D or D & T atoms

- ABILITY FOR THE FIRST TIME IN HISTORY TO USE SIMPLE MECHANICAL ENERGY TO INITIATE & CONTROL NUCLEAR FORCES (Fusion) ⇒ Range of Applications & Uses
TEAM MEMBERS

**ORNL**
- Rusi Taleyarkhan (team leader) → Purdue University
- Colin D. West (retd.)

**ORAU**
- J. S. Cho (Post-Doc)

**Rensselaer Polytechnic Institute**
- R. T. Lahey, Jr. (NAE, Prof/Dean)
- R. C. Block (Prof./A.Dean, previously of ORNL)

**Russian Academy of Sciences**
- Robert Nigmatulin (President, Ufa Branch)
ATTAINING THE HOLY GRAIL OF BUBBLE FUSION

• **AMPLIFY THE ACOUSTIC WAVE PRESSURE** \( \Delta p_i \sim 15-20 \text{ bar} \)
  → On-demand Nucleate Bubbles(50nm) with neutrons
  Grow to Large Sizes \( (5000 \ \mu\text{m}) \rightarrow R_m/R_o \sim 100,000 \)

• **GAS IN THE BUBBLE:** **CONDENSING VAPOR (VAPOR CAVITATION)**
  - Minimizing Effect of Gas Cushioning
  - Higher Kinetic Energy of Convergent Liquid

• **INTENSIFY CONDENSATION** → Enhanced Shock Generation

• **LARGE MOLECULES (ORGANIC) LIQUID**
  - Low Sound Speed in Vapor \( C_G = \sqrt{\frac{\gamma R}{M_G} T} \), where \( M_G \) is molecular weight
  - High Condensation (Accommodation) Coefficient \( \alpha \cong 1 \), for water \( \alpha \cong 0.04 \)
  - High Cavitation Strength (unlike inorganic liquids)

• **CLUSTER of the Bubbles**
OUR APPROACH

- $R_m/R_o \sim 100,000$

- Implode with trillion times greater potential (pdV) energy
  -- vs conventional SBSL (already a strong focusing mechanism)
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~ Refrigeration Packs (thickness ~3-5)

Plastic Wall (~0.6)

Test Cell

To Pump

PMT

PZT

~20

Cavitation Zone

PNG

10

6.25

20
PNG (N-550) – Activation Technology Co.
(~ $5 \times 10^5$ n/s; 200 Hz; L ~20 cm to chamber)
Experimental Sequence of Events

- Neutron burst from neutron generator nucleates bubbles
- Neutron detector gives signal
- Bubbles grow
- Bubble implosions
- Shock waves from bubble implosion reach glass wall and keep ringing for the life of bubble clouds
- Compression and Tension
- Liquid Pressure + -
- Neutron Detector (Scintillator) t=(0 +/- 3*) µs
- First & Later**
- Bubble Implosions
- Bubbles grow
- SL light emissions**
- PMT - Light Detection t=(27 +/- 3**) µs
- Time correlated scintillator flashes** if neutrons are emitted during implosion
- Neutron Detection (Scintillator) t=(27 +/- 3**) µs
- Microphone (on glass walls) detects implosion t>(54 +/- 3**) µs

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“The Sound of Neutrons”
TEST CELL/SYSTEM DEVELOPMENT
&
CHARACTERIZATION

-- Most Time-Consuming Part of Studies (2y)
SYSTEM CHARACTERIZATION (examples)
Variation of PCB Transducer Signal with Frequency

\[ Q \approx 10^3 \]
SYSTEM CHARACTERIZATION
(bubble cloud nucleation to collapse takes ~ 5ms; 0C)
BUBBLES LAST MUCH LONGER @ 18°C

Fig. 9b. Images of bubble nucleation to collapse for tests with Acetone (18°C)
STREAMER EVOLUTION – No BF

$t=0$

$t=1\text{ms}$ (bubble cluster first visible)

$t=3\text{ms}$ (cluster expansion)

$t\approx 35\text{ms}$ (fully established streamer)

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Deuterium + Deuterium → Helium + Tritium + Neutron + Proton

2.45 MeV + 0.82 MeV + 1.01 MeV + 3.02 MeV

50% + 50%
n-γ

EJ-301 Liquid Scintillation Detector

ORTEC 113 Pre-Amp.

ORTEC 460 (amplifier)

ORTEC 552 (pulse shape analyzer)

Canberra 2145 (time-to-pulse height analyzer/single channel analyzer)

ORTEC 427A (delay amp.)

Canberra-PCI MCS/Canberra FMS/Spectrum Techniques UCS-20 MCA

TTL Trigger Pulse

SL
LIQUID SCINTILLATION (LS) DETECTOR
(Extensive Calibrations: Linac TOF, Pu-Be, Co, Cs, PNG)

Diagram showing the response of different sources to the detector channel. The graph depicts the neutron energy (2.5 MeV and 14 MeV) and gamma rays (4.4 MeV and 12 C gamma) in channels.

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NEW LIQUID SCINTILLATION (LS) DETECTOR
(Extensive Calibrations: Linac TOF, Pu-Be, Co, Cs, PNG)
NEW LIQUID SCINTILLATION (LS) DETECTOR
(Conservative Pulse Shape Discrimination)

Gamma & Neutron Time Separation of Co-60 (No PSD)

Gamma & Neutron Time Separation of Co-60 (with PSD)

Pu-Be Gamma & Neutron Time Separation

Background Gamma & Neutron Time Separation (No PSD)

Background Gamma & Neutron Time Separation (with PSD)

Note: Neutron Gating past Channel 63 for

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TIME CORRELATION SIGNALS

Such data not observed for C$_3$H$_6$O or warm C$_3$D$_6$O

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SL TIME SPECTRA (0 to 5000 mic.sec.)

C₃D₆O SL Data (5msec Time Window)

C₂D₆O SL Data (5msec Time Window)

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NEUTRON TIME SPECTRA (0 to 5000 mic.sec.)

C₃H₆O (~0°C)

C₃H₆O Neutron Data (4.8msec Time Window)

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NEUTRON & SL TIME SPECTRA (0 to 100 mic.sec.)

$C_3D_6O (~0^\circ C)$

---

**C$_3$D$_6$O Neutron Data**

- PNG Region
- 1st Collapse Region

**C$_3$D$_6$O SL Data (100microsec Time Window)**

- PNG Region
- 1st Collapse Region

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NEUTRON TIME SPECTRA (0 to 5000 mic.sec.)

$C_3D_6O$ ($\sim 0^\circ C$)

C$D_6$O Neutron Data (5msec Time Window)

Cav. On

Cav. Off

Channel Number
SL-Neutron Time Correlation Spectra (C$_3$D$_6$O; 0° C)

CAVITATION ON

CAVITATION OFF
GAMMAS WILL ACCOMPANY NEUTRONS

But

Quantity & Timing

Are Necessarily Different
GAMMA TIME SPECTRA (0 to 5000 mic.sec.)
C₃D₆O (~0°C)
Neutron vs Gamma Time Spectra (C$_3$D$_6$O; 0°C)

Note: Gammas are Time Separated from Neutrons
Neutron Energy Spectra \((C_3D_6O & C_3H_6O; 0^\circ C)\)

-- 30 Standard Deviation Significance

C\(_3\)D\(_6\)O & C\(_3\)H\(_6\)O Energy Spectrum

Count Difference between Cav. On & Off

Count Difference(%)}

\(< 2.5\) MeV

\(C_3D_6O\)

\(C_3H_6O\)

\(C_3D_6O\)

\(C_3H_6O\)

\(> 2.5\) MeV

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Neutron vs Gamma Changes ($\text{C}_3\text{D}_6\text{O}$, $\text{C}_3\text{H}_6\text{O}$; 0°C)

Gamma emissions ~ 10-15% of neutron emissions --> for $\text{C}_3\text{D}_6\text{O}$

Gamma & Neutron
Count Difference(%) between Cav. On & Off

Gamma emissions are largely 2.2 MeV

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TRITIUM MONITORING

• Liquid Scintillation Counting
  --> LS6500 Beckman (baseline); LS5000/Packard (crosschecks)
  --> Ecolite cocktail (15:1); glass vials
  --> Counts in 5-18 keV window (beta emissions from T)

• Testing with Control Liquid -- C₃H₆O (7h and 12h; 0ºC)
  --> PNG only
  --> PNG + Cavitation

• Testing with C₃D₆O (7h and 12h)
  --> PNG only (0ºC)
  --> PNG + Cavitation (0ºC)
  --> Pu-Be source (5h) --> 0ºC
  --> PNG only (20ºC)
  --> PNG + Cavitation (20ºC)
CONFIRMED TRITIUM GENERATION (New Chamber)

-Beckman LS6500 & LS5000 calibrated counters (5-18 keV);
-Ecolite - Scintillation Cocktail (15:1)
FOR EVERY EXPERIMENT CONDUCTED
WITH $C_3D_6O$
WE CONDUCTED A CONTROL EXPERIMENT
WITH $C_3H_6O$
EVIDENCE FOR NUCLEAR FUSION
~ 150 Referees

- Neutrons (of Correct Energy)?
  YES! --> ~ 5 x 10^5 n/s of 2.5 MeV (30 to 40 SD)

- Tritium?
  YES! --> ~ 6-7 x 10^5 n-t/s (~ 4-5 SD)

- Time Correlation with SL?
  YES!

- Detected gamma rays?
  YES! Time diffused (~ 10+SD); Largely 2.2 MeV

- In Line with Theory & Physics?
  YES!

- Checked with D-Acetone & Control Liquid (H-Acetone)?
  - Only for cavitated D-Acetone
  - Never for H-Acetone
Evidence for Nuclear Emissions During Acoustic Cavitation

R. P. Taleyarkhan, C. D. West, J. S. Cho, R. T. Lahey Jr.,
R. I. Nigmatulin, R. C. Block

8 March 2002, Volume 295, pp. 1868–1873

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Additional evidence of nuclear emissions during acoustic cavitation


1Purdue University, West Lafayette, Indiana 47907, USA
2Oak Ridge Associated Universities, Oak Ridge, Tennessee 37830, USA
3Rensselaer Polytechnic Institute, Troy, New York 12180, USA
4Russian Academy of Sciences, 6 Karl Marx Street, Ufa 450000, Russia

(Received 13 May 2003; published 22 March 2004)

Time spectra of neutron and sonoluminescence emissions were measured in cavitation experiments with chilled deuterated acetone. Statistically significant neutron and gamma ray emissions were measured with a calibrated liquid-scintillation detector, and sonoluminescence emissions were measured with a photomultiplier tube. The neutron and sonoluminescence emissions were found to be time correlated over the time of significant bubble cluster dynamics. The neutron emission energy was less than 2.5 MeV and the neutron emission rate was up to \( \sim 4 \times 10^5 \) n/s. Measurements of tritium production were also performed and these data implied a neutron emission rate due to D-D fusion which agreed with what was measured. In contrast, control experiments using normal acetone did not result in statistically significant tritium activity, or neutron or gamma ray emissions.

DOI: 10.1103/PhysRevE.69.036109

PACS number(s): 89.90.+n
FIG. 1. Spectrum of single bubble sonoluminescence. Top trace (data) is for a bubble driven at 42 kHz in water with 3 Torr of dissolved xenon, taken with a resolution of 12 nm FWHM. These data are fit to blackbody radiation with a temperature of 8000° (top thin line). Bottom trace (data) is for a bubble driven at 1 MHz in water with 600 Torr of dissolved xenon, with a resolution of 70 nm FWHM. The solid line is a fit to bremsstrahlung radiation, with a temperature of $1 \times 10^6$ deg. The fine dashed line is also bremsstrahlung but with a temperature of 65000°. The thick dashed line is blackbody radiation with a temperature of 100000°. The inset is a diagram of the 1 MHz resonator used to generate and trap single bubbles. It consists of two thin ceramic transducers (PZTs) housed inside brass reflectors with a radius of curvature $R = 2.125$ in. The water was contained in a quartz cylinder of diameter $D = 3.1$ in between the reflectors.

Plasma formation and temperature measurement during single-bubble cavitation

David J. Flannigan & Kenneth S. Suslick

Department of Chemistry, University of Illinois at Urbana-Champaign, Urbana Illinois 61801, USA

Single-bubble sonoluminescence (SBSL) results from the extreme temperatures and pressures achieved during bubble compression; calculations have predicted the existence of hot, optically opaque plasma core with consequent bremsstrahlung radiation. Recent controversial reports claim the observation of neutrons from deuterium–deuterium fusion during acoustic cavitation. However, there has been previously no strong experimental evidence for the existence of...
CONDITIONS FOR NUCLEAR EMISSIONS DURING ACOUSTIC CAVITATION

- Liquid was organic ($C_3D_6O$) and deuterated

- Drive pressure amplitude $\sim +/- 15$bar using a PiezoSystems amplifier tied to a resonant acoustic chamber operating $@ \sim 20$ kHz.

- Neutrons (14 MeV) nucleated bubble CLUSTERS ($\sim$25 - 50/sec.)

  ** No cavitation to occur without neutrons **

- Bubble clouds nucleated when tension is greatest; growth
- to $\sim 6$mm prior to collapse

- Liquid was degassed; Chamber under 27”Hg vacuum

- Liquid temperature $\sim 0^\circ$C
Confirmatory experiments for nuclear emissions during acoustic cavitation

Yiban Xu a,*, Adam Butt a, b

a School of Nuclear Engineering, Purdue University, West Lafayette, IN 47907 USA
b School of Aeronautical and Astronautical Engineering, Purdue University, West Lafayette, IN 47907 USA

Received 13 January 2005; received in revised form 14 January 2005; accepted 7 February 2005

Abstract

Confirmatory experiments were conducted to assess the potential for nuclear fusion related emissions of neutrons and tritium during neutron-seeded acoustic cavitation of deuterated acetone. Corresponding control experiments were conducted with normal acetone. Statistically significant (5–11S.D. increased) emissions of 2.45 MeV neutrons and tritium were measured during cavitation experiments with chilled deuterated acetone. Control experiments with normal acetone and irradiation alone did not result in tritium activity or neutron emissions. Insights from imaging studies of bubble clusters and shock trace signals relating to bubble nuclear fusion are discussed.

Published by Elsevier B.V.
Independent Experimentation (2005 NED,ANS,NURETH-11) – Xu/Butt/Revankar; Experimental Apparatus

- Paraffin Blocks
- Freezer
- Chamber
- Pu-Be/Cf-252
- 56.6 cm
- 5 cm

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Confirmation Results (2.45 MeV Neutron) by Xu/Butt/Revankar(2005)

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Diff.</th>
<th>1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3D6O</td>
<td>762</td>
<td>63</td>
</tr>
<tr>
<td>C3H6O</td>
<td>-35</td>
<td>53</td>
</tr>
</tbody>
</table>

(c). Differences of Cav. On and Off

-20
0
20
40
60
80
100

Counts

< 2.5 MeV

> 2.5 MeV

Channels
Confirmation Results - Xu/Butt/Revankar (2005) (Tritium Counting)

**Aggregate Average**

<table>
<thead>
<tr>
<th></th>
<th>DPM/gm</th>
<th>1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_3$D$_6$O</td>
<td>4.1</td>
<td>1.1</td>
</tr>
<tr>
<td>C$_3$H$_6$O</td>
<td>-0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>C$_3$D$_6$O Irradiated</td>
<td>0.0</td>
<td>1.2</td>
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</tbody>
</table>

* Background count rate ~ 40
Conclusions of Confirmation Study  
- May 2005 Nucl. Engr. & Design Journal

- Bubble Fusion Experiments were Conducted with Isotope Radiation Sources with Fast Neutron Measurement and Tritium Counting.
- Statistically Significant (11 SD) Excess of Fast Neutrons and (5 SD) Tritium Emission were Observed in Acoustically Cavitated Deuterated Liquid Only; Never for Control Conditions
IMPLOSION DYNAMICS MODELING/SIMULATION

• Two stage modeling --> HYDRO code
  - Stage 1: Low Mach No. (Rayleigh-Plesset formulations)
  - Stage 2: High Mach No. (Shock modeling; Mie-Gruniesen form of EOS from shock data for acetone)
  - Spatio-temporal neutron generation modeling - LANL D-D data

- Models included effects of conductivity and mass transport at liquid-vapor interface from condensation-evaporation, dissociation, ionization, cluster amplification, electron conductivity

• Simulations evaluated the influence of:
  - Fluid type (low/high $\alpha$)
  - Temperature of operation
Mass, Momentum, Energy Conservation
Differential Equations

\[ \frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( \rho u r^2 \right) = 0, \]

**Mass**

\[ \frac{\partial \rho u}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( \rho u^2 r^2 \right) + \frac{\partial \rho}{\partial r} = 0, \]

**Momentum**

\[ \frac{\partial \left( \rho u \right)}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( \rho u^2 r^2 \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( \lambda T \frac{\partial T}{\partial r} \right), \]

**Energy**

\[ e = \varepsilon + \frac{u^2}{2}, \quad p = p(\rho, T), \quad \varepsilon = \varepsilon(\rho, T), \quad \lambda_g = \lambda_g \left( \frac{T_g}{T_{g0}} \right)^n. \]
INTERFACIAL BOUNDARY CONDITIONS \((r = a(t))\)

Mass:
\[
\rho_g (\partial_t - u_g) = \rho (\partial_t - u) = j \quad \text{ - intensity of phase transition}
\]

Momentum:
\[
p_g = p + \frac{2\sigma}{a} + \frac{4\mu \lambda u}{a}
\]

Energy:
\[
\lambda \frac{\partial T_\lambda}{\partial r} - \lambda g \frac{\partial T_g}{\partial r} = j l
\]

Kinetics of phase transition (Hertz-Knudsen-Langmuir Eqn):
\[
j = \frac{\alpha}{\sqrt{2\pi R_g}} \left( \frac{p_s(T_\lambda)}{\sqrt{T_\lambda}} - \frac{p_g}{\sqrt{T_g}} \right)
\]

\[
T_\lambda - T_g \equiv [T] = 0.45 \frac{j T_S}{\sqrt{2 R_g T_S \rho g}} \quad \text{ - (Labuntsov, 1968)}
\]

\(p_s(T)\) – saturation pressure, \(l\) – evaporation heat
\(\alpha\) – accommodation (condensation) coefficient
MI-GRUNEISEN EQUATIONS OF STATE

\[ \varepsilon = \varepsilon_p + \varepsilon_T + \varepsilon_c \]

\[ p = p_p + p_T \]

\[ \varepsilon_p = \varepsilon_p(\rho), \quad p_p(\rho) = -\rho^2 \frac{d\varepsilon_p}{d\rho} \]

\[ \varepsilon_T = \overline{c}_V T, \quad p_T = \rho \Gamma(\rho) \overline{c}_V T \]

- \( \varepsilon_p \) and \( p_p \) – “cold” or potential internal energy and pressure due to Intermolecular interaction

- \( \varepsilon_T \) and \( p_T \) – thermal internal energy and thermal pressure

- \( \varepsilon_c \) - chemical internal energy

- \( \overline{c}_V \) and \( \Gamma(\rho) \) - averaged heat capacity and Gruneizen Coefficient

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SHOCK ADIABAT (D-u) FOR LIQUID ACETONE
(Trunin, 1992)

\[ D, \text{ km/s} \]

\[ D - \text{Shock Wave Speed} \]

\[ U - \text{Mass Velocity after the Shock Wave} \]

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KINETICS OF FUSION

\[ D + D \rightarrow \begin{cases} \text{\(^3\)He + n} & (\sim \frac{1}{2}) \\ T + H & (\sim \frac{1}{2}) \end{cases} \]

\[ J = \frac{1}{2} n^2 \langle \sigma \nu \rangle, \quad N = \int \int J \, dV \, dt, \]

- \( J \) - neutron emission intensity,
- \( N \) - number of emitted neutrons,
- \( n = \frac{6 \rho_G N_A}{M_G} \) - concentration of D atoms \((\text{CO} \text{(CD}_3)_2)\),
- \( \langle \sigma \nu \rangle \) - averaged product of the cross section times the deuterons thermal velocity,

\[ N_A = 6.02 \cdot 10^{26} \text{ kmol}^{-1} - \text{Avogadro number}, \quad M_G = 64 \text{ kmol}^{-1} - \text{molecular weight} \]

\[ N_D = 6 \frac{N_A}{M_G} = 0.56 \cdot 10^{26} \text{ kg}^{-1} \]
Low Mach Regime

\[ \mathbf{M} = \frac{\mathbf{\alpha}}{C_l} \ll 1 \]

**For GAS (vapor):**

\[ \varepsilon = \bar{c}_{Vg} T, \quad p = R_g \rho_g T \]

\[ R_g = 129.9 \text{ J/(kg·K)}, \quad \gamma = \frac{\bar{c}_{Vg} + R_g}{\bar{c}_{Vg}} = 1.1 \]

**For LIQUID:**

\[ \varepsilon = \bar{c}_{Vl} T, \quad \bar{c}_{Vl} = 2000 \text{m}^2/(\text{s}^2\cdot\text{K}) \]

\[ \rho_l = 858 \text{ kg/m}^3 = \text{const} \]

**Raileigh-Plesset equation**

\[ a \frac{d^2 a}{dt^2} + \frac{3}{2} \left( \frac{da}{dt} \right)^2 = \frac{p_l |_{r=a} - p_l}{\rho_l} \]
Amplification of the Compression Wave in Cluster

Number of bubbles $N = 50$

Maximum microbubble radius

Radius of the cluster

$p, \text{bar}$

$t, \mu s$

$R_0 = 4 \text{ mm}$

$\mu_0 = \mu_{max} = 400 \mu \text{m}$
Spatial distributions of the parameters for subpicosecond thermonuclear stage
Figure 14. Bubble nuclear fusion simulation results for neutron production with (heavy lines) and without (thin lines) inclusion of endothermic chemical energy losses from dissociation and ionization of C$_3$D$_6$O molecules.
Bubble radius evolution for deuterated acetone $\text{C}_3\text{D}_6\text{O}$;

$\omega = 2\pi \cdot 20.5$ kHz, $\Delta p^+ = 40$ bar, $\Delta p^- = 200$ bar, $T_{10} = 273$ K, $\alpha = 1.0$.

"Cold dissociation" because of the "super high pressure" ($10^5$ bar) in liquid needs $10^2$ ns;

"Super high pressure" in liquid (near the bubble interface) takes place 10 ns.
“Non-Equilibrium” ELECTRONS & IONS

\[ T_e \ll T_i \quad \text{(during} \quad 10^{-13} \quad \text{s)} \]

- Per second: **50 effective cavitation cycles initiated by acoustical rarefactions with 200 PNG neutron shots**
  - 50 neutron bursts from 100 acoustical cycles per cavitation cycle
- If: 15 actively collapsed bubbles in cluster
  - 10 neutrons per collapse of one bubble.

\[50 \times 50 \times 15 \times 10 \text{ neutrons per second} \approx 4 \cdot 10^5 \text{ s}^{-1}\]
<table>
<thead>
<tr>
<th>RESULTS OF ANALYSIS</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Bubble Fusion (Ufa Branch of RAS +ORNL+RPI)</strong></td>
<td><strong>Sonoluminescence (Livermore)</strong></td>
</tr>
<tr>
<td>Density: $10-20$ g/cm$^3$</td>
<td>Density: $10$ g/cm$^3$</td>
</tr>
<tr>
<td>Temperature: $10^8$ K = $10$ KeV</td>
<td>Temperature: $10^6$ K</td>
</tr>
<tr>
<td>Pressure: $10^{11}$ bar = $10^2$ Gbar</td>
<td>Pressure: $3 \times 10^8$ bar</td>
</tr>
<tr>
<td>Velocity: 1000 km/s</td>
<td>Velocity: 10 km/s</td>
</tr>
<tr>
<td>Duration: $10^{-13}$ s = $10^{-1}$ ps</td>
<td>Duration: 10 ps</td>
</tr>
<tr>
<td>Radius of the Thermonuclear Core: 60 nm</td>
<td>Radius of the $T = 10^6$ K core: 1-3 nm</td>
</tr>
<tr>
<td>Number of Ions in the Thermonuclear Core: $2 \times 10^9$</td>
<td>Number of Ions in the Core: $2 \times 10^5$</td>
</tr>
<tr>
<td>Production of the Fast Neutrons and Tritium nucleus</td>
<td>$10^5 - 10^6$ s$^{-1}$</td>
</tr>
</tbody>
</table>
FINDINGS and PARADOXES

• COLD LIQUID Effect

• CLUSTER effect

• NON-DISSOCIATION of Liquid

• “COLD” Electrons”

• SHARPENNING:
  
  Node size for Fusion Core
  \[ \Delta r \sim 0.1 \text{ nm} \ll a_* \sim 10 \text{ nm} \ll a \sim 20 \text{ 000 nm} \]

• SHAPE STABILITY
Ability to Utilize Simple Mechanical (Acoustically-driven) Energy to Initiate & Control Nuclear (Fusion) Forces

- Applications?  -- (~ 1,000 Mbar, 10^8K)

---> Non-Power ( ~ 10^6 n/s pulsed neutron-gamma-X-ray-T source)
    - Pulsed neutron/gamma source (on/off)
    - Radiography, therapy, irradiation
    - Explosives detection; Spectroscopy
    - Tritium (SNM) production
    - Materials synthesis (C ->D)
    - Chemical kinetics research at extreme conditions
        - (10^2 -10^3 Mbar; 10^7 K)

---> Optimization/Scalability Potential Research (Phase 2 Focus)
COMMENTS ON THE SHAPIRA AND SALTMARSH REPORT

by
R. P. Taleyarkhan\textsuperscript{a}, R.C. Block\textsuperscript{b(R)}, C.D. West\textsuperscript{a(R)} and R. T. Lahey, Jr.\textsuperscript{b}

(a) Oak Ridge National Laboratory
Oak Ridge, TN; (R)= Retired
(b) Rensselaer Polytechnic Institute
Troy, NY; (R)= Retired

March 2, 2002

Abstract

We have carefully reviewed the data and report of Shapira and Saltmarsh. Our analysis of these data indicates that, contrary to their conclusions, a statistically significant increase of nuclear emissions was actually detected by them during cavitation experiments with chilled deuterated acetone. In particular, the emission rate they measured was $\sim 3$ n/s (compared to about 8 n/s in our measurements). Shapira and Saltmarsh grossly over-estimated the efficiency of their detector. Actually, their detection efficiency for 2.5 MeV neutrons (based on calibration with a Pu-Be source and corrected for distance and shielding), was found to be $\sim 10^{-5}$. Using this value of efficiency their detected nuclear emission rate was $\sim 2 \times 10^5$ n/s, a value which is comparable to that reported by us, and consistent with the results from our tritium measurements. Statistically significant time-correlated neutron emissions during sonoluminescence (SL) bursts was also observed, however their system was poorly designed for coincidence measurements; particularly, for the most energetic bubble implosions subsequent to cavitation.
Figure 2b. Variation of increase in nuclear emissions with cavitation in deuterated acetone for Region D (subsequent collapses of nucleated bubbles)
- Data taken with PD detection system.
Figure 3a  SL time bin correlated neutron emissions for Region D  
- PD Detection System

Note:
1) Average of all counts is 375
2) Increase in Counts for SL Peak Channel is 101
   --> This is a difference of 27% or > 4 Standard Deviations
3) The increase of neutron counts in the SL Peak Channel is greater than that for ALL other SL time bins.