Sonoluminescence and the Search for Sonofusion

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Introduction

- Sonoluminescence involves the repetitive generation of extremely short (~100 ps) light flashes during the implosive collapse of acoustically-forced gas/vapor bubbles.
  - This phenomena has been known for more than 70 years and has been widely used by chemists for the study and use of high temperature chemical reactions (i.e., Sonochemistry).
  - Nevertheless, the “Holy Grail” is the achievement of thermonuclear *Bubble Nuclear Fusion* (i.e., Sonofusion),and this will be the focus of my talk.

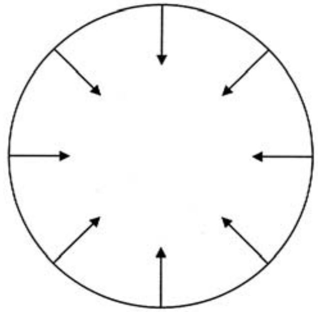


Figure-1a
Start of the Bubble Implosion
($Ma_g < 1$)

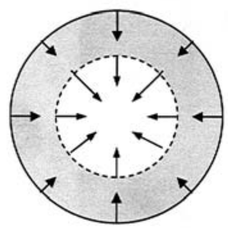


Figure-1b
Shock Wave Formation
($Ma_g \geq 1$)

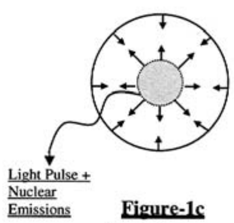


Figure-1c
Shock-Induced
Super-Compression and
Gas/Plasma Heating

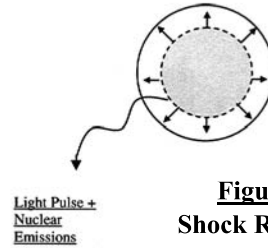


Figure 1-d
Shock Reflection,
$R(t)=R_{min}$

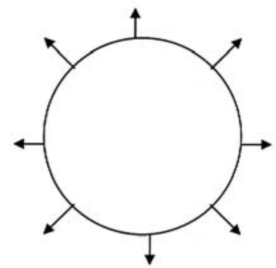


Figure-1e
Onset of
Bubble Expansion

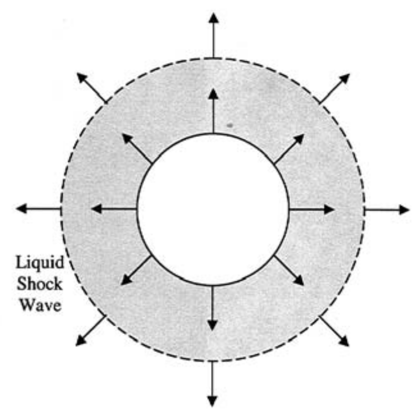


Figure-1f
Shock Wave Formation in Liquid

BUBBLE IMPLOSION SCENARIO

Discussion - Experiments

- There has been a renaissance in sonolum-inescence research since Gaitan (re)discovered (~1990) how to achieve single bubble sonoluminescence (SBSL).
  - A typical SBSL experiment involves an acoustically-forced, noncondensible, gas bubble in which $R_{max}/R_0 \sim 10$. It is important to note that R_{max} and Δp_I are limited by fundamental issues associated with rectified diffusion, interfacial/ shape instabilities and the polarity of the Bjerknes force). This, in turn, limits T_{max}, p_{max} and ρ_{max}.

- In order to overcome these limitations a completely different experimental approach was taken in the sonofusion (SF), or bubble nuclear fusion, experiments performed at Oak Ridge National Laboratory (ORNL).

  - A well-degassed deuterated liquid hydrocarbon (i.e., D-acetone, C_3D_6O) was subjected to large amplitude acoustic excitation (Δp_I= 15 to 40 bar), creating high liquid superheats prior to 14.1 MeV neutron-induced cavitation (PNG, 6μs at FWHM; ~10^6 n/s)

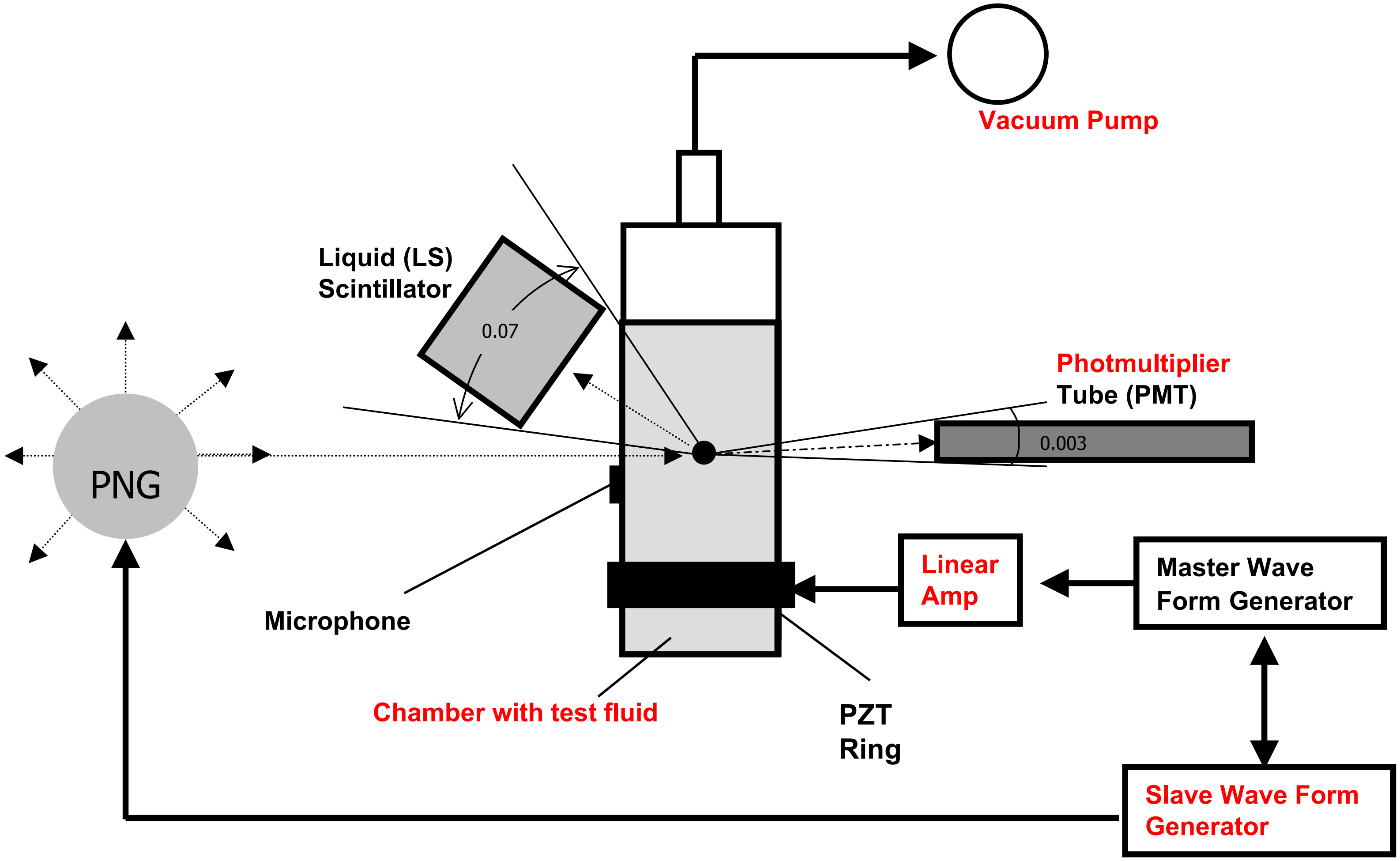
- The vapor bubbles within the resultant bubble cluster achieved $R_{max_{SF}}/R_{max_{SBSL}} \sim 10\,(V_{max_{SF}}/V_{max_{SBSL}} \sim 10^3)$ prior to implosive collapse.

- The interfacial velocity, $\dot{R}$, towards the center of the bubbles was also much higher, thus the kinetic energy in the liquid $(\propto R^3\dot{R}^2)$, which ultimately compresses the bubble, was about 10^4 times higher in SF than in SBSL experiments.

Bubble Nuclear Fusion Research Team

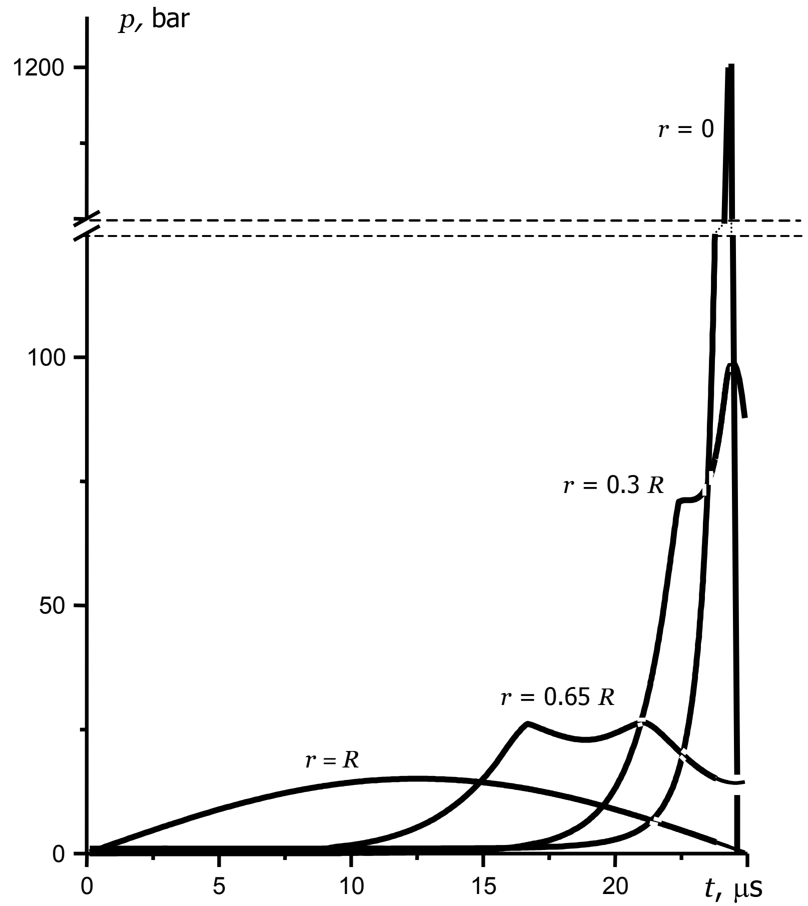
ORNL (USA)	RPI (USA)	Institute of Mechanics: Russian Academy of Science – Baskortostan (Russia)
Rusi Taleyarkhan†	*Richard T. Lahey, Jr.*	*Robert Nigmatulin**
Jong Cho	Robert Block	Iskander Akhatov*
Colin West	Song Bae**	Raisa Bolotnova
	Gerardo Delgadino**	Andrew Topolnikov
	Don Steiner	Nelya Vakhitova
	Francisco Moraga	

† Currently holds the Bement Chair in Nuc. Eng. at Purdue University; * Visiting scholars at RPI; ** Ph.D. students-RPI.

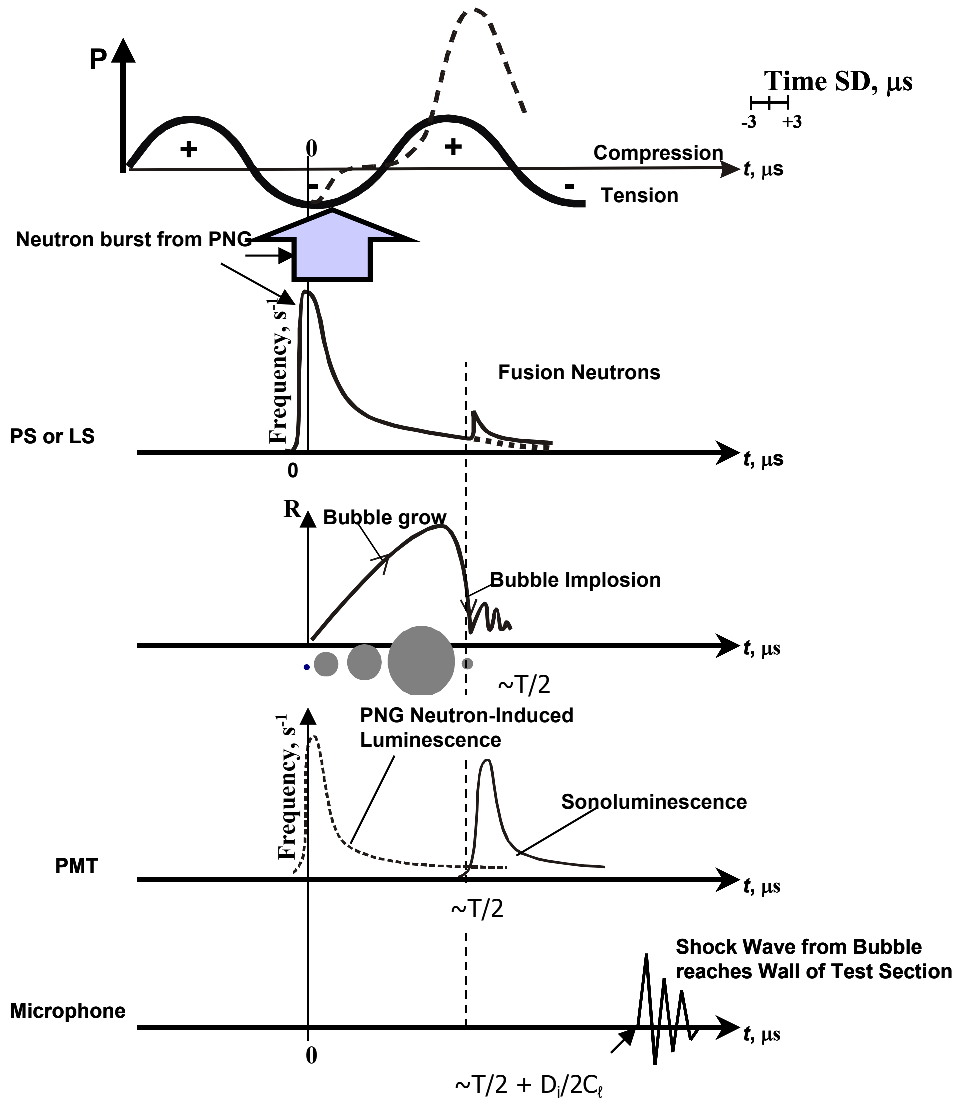


Vacuum Pump
Liquid (LS) Scintillator
0.07
Photmultiplier Tube (PMT)
0.003
PNG
Microphone
Linear Amp
Master Wave Form Generator
Chamber with test fluid
PZT Ring
Slave Wave Form Generator

- It is important to note that the liquid pressure within the bubble cluster can greatly intensify during the implosion process.
    - The interior bubbles (~15 out of the ~1,000 original cavitation bubbles) may achieve thermo-nuclear conditions.



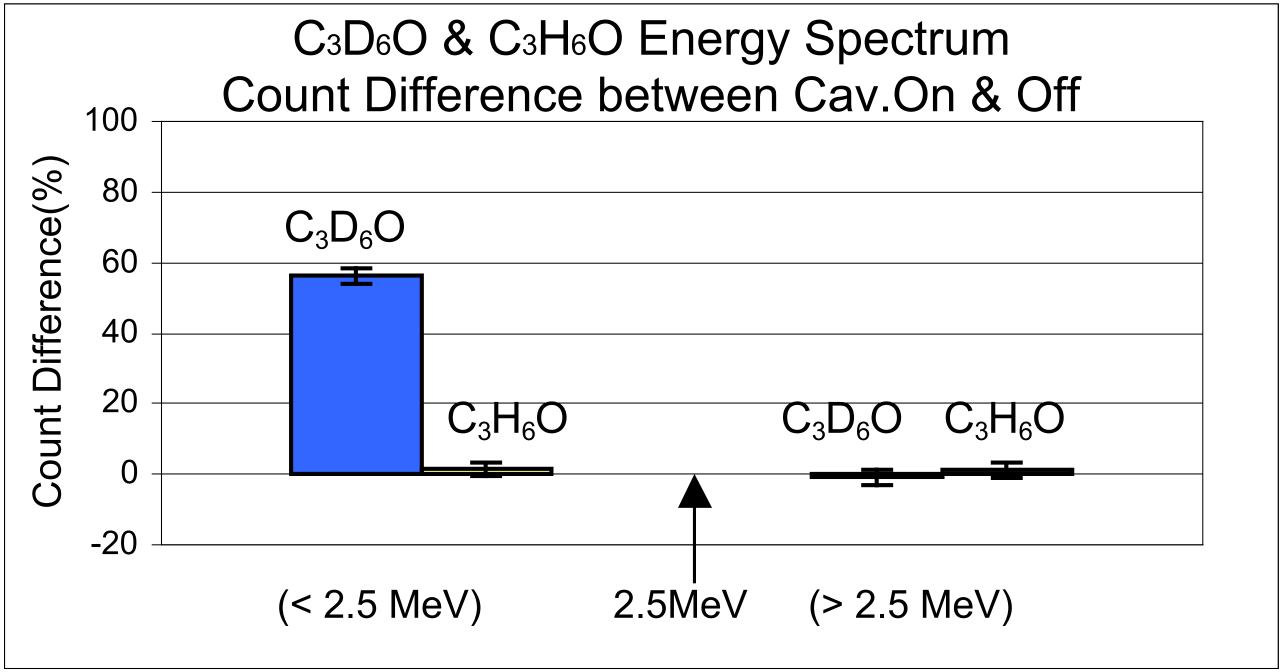
PRESSURE INTENSIFICATION WITHIN AN IMPLODING BUBBLE CLUSTER



P
Time SD, μs
-3
+3
0
+
+
-
-
Compression
Tension
t, μs
Neutron burst from PNG
Frequency, s-1
Fusion Neutrons
PS or LS
0
t, μs
R
Bubble grow
Bubble Implosion
t, μs
~T/2
PNG Neutron-Induced
Luminescence
Frequency, s-1
Sonoluminescence
PMT
t, μs
~T/2
Shock Wave from Bubble
reaches Wall of Test Section
Microphone
t, μs
0
~T/2 + Di/2Cℓ

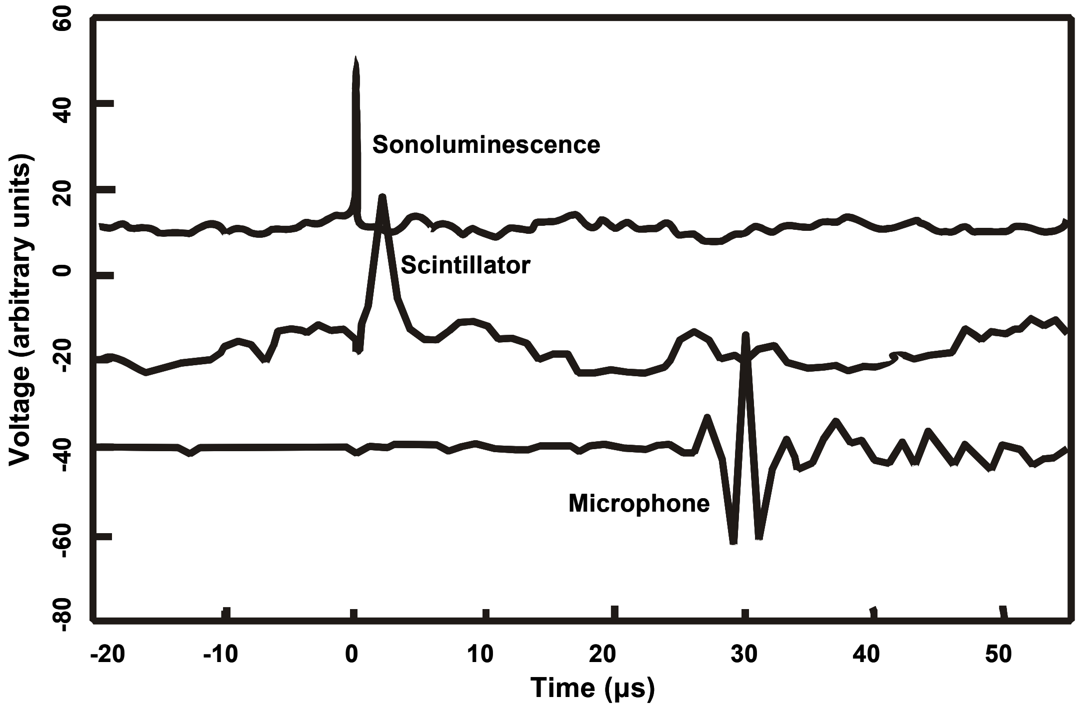
- Using pulse shape discrimination (PSD) techniques (to differentiate between the emitted neutrons and gamma rays), and a multichannel analyzer, it was found that 2.45 MeV D/D fusion neutrons were emitted from cavitated D-acetone.

    - Correcting for neutron absorption & scattering, the solid angle of the detector and its in situ efficiency $\left(\eta_D \sim 10^{-3}\right)$, the measured rate was: <u>~4×10⁵ neutrons/ sec</u>.

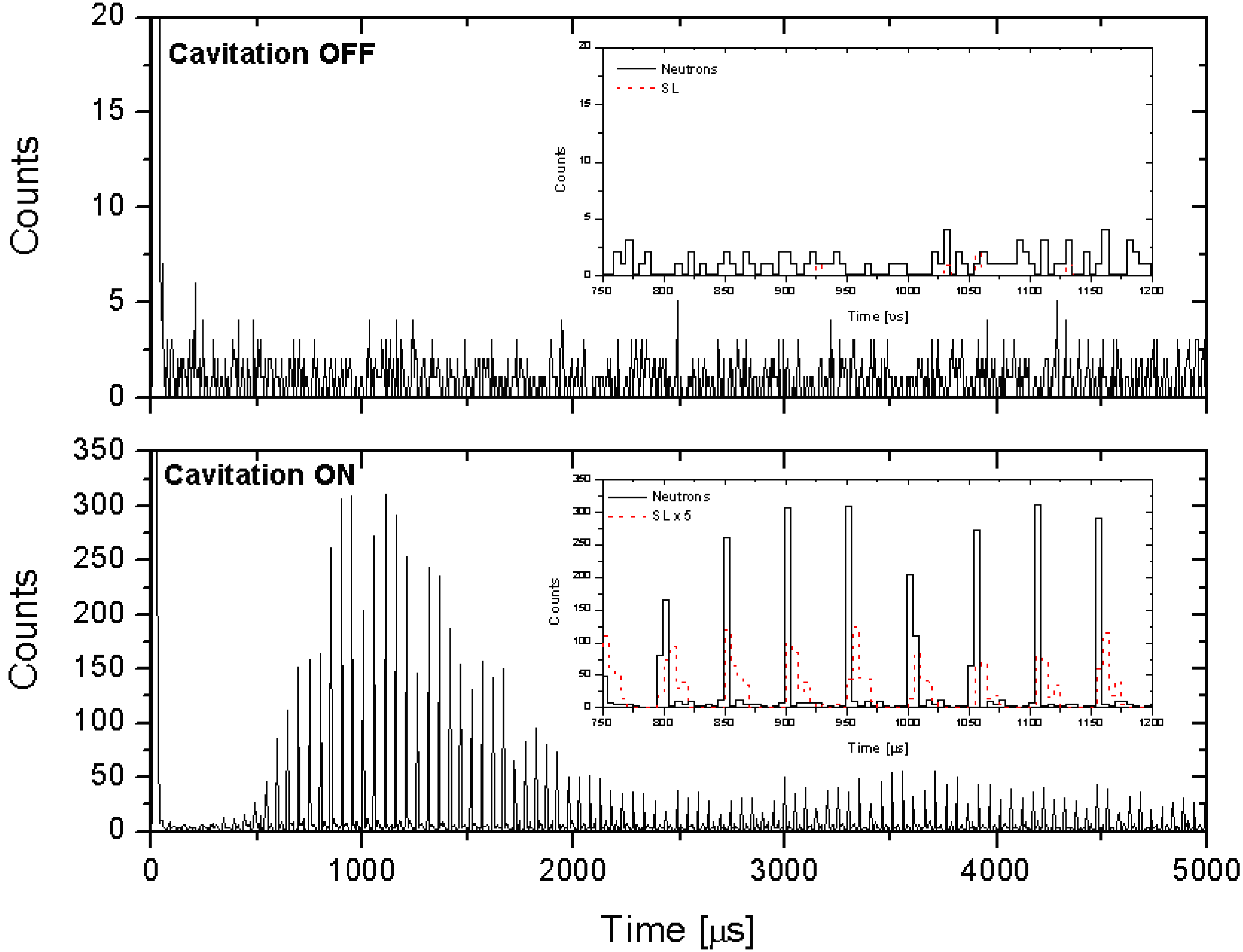


Binning by neutron energy

- The D/D neutrons were found to be coincident with the SL light pulses, and these coincidences were always followed $\left(D\,t\ ;\ \ D_{i}/2C_{l}\right)$ by a shock wave which hit the wall of the cylindrical test section.
- Significantly, no coincident fusion events were observed <u>unless</u> the D-acetone was <u>chilled</u> (i.e., ~0˚C).



Coincidence Measurements



(Note the ~50 energetic bubble cluster "bounces" after the initial implosion.)

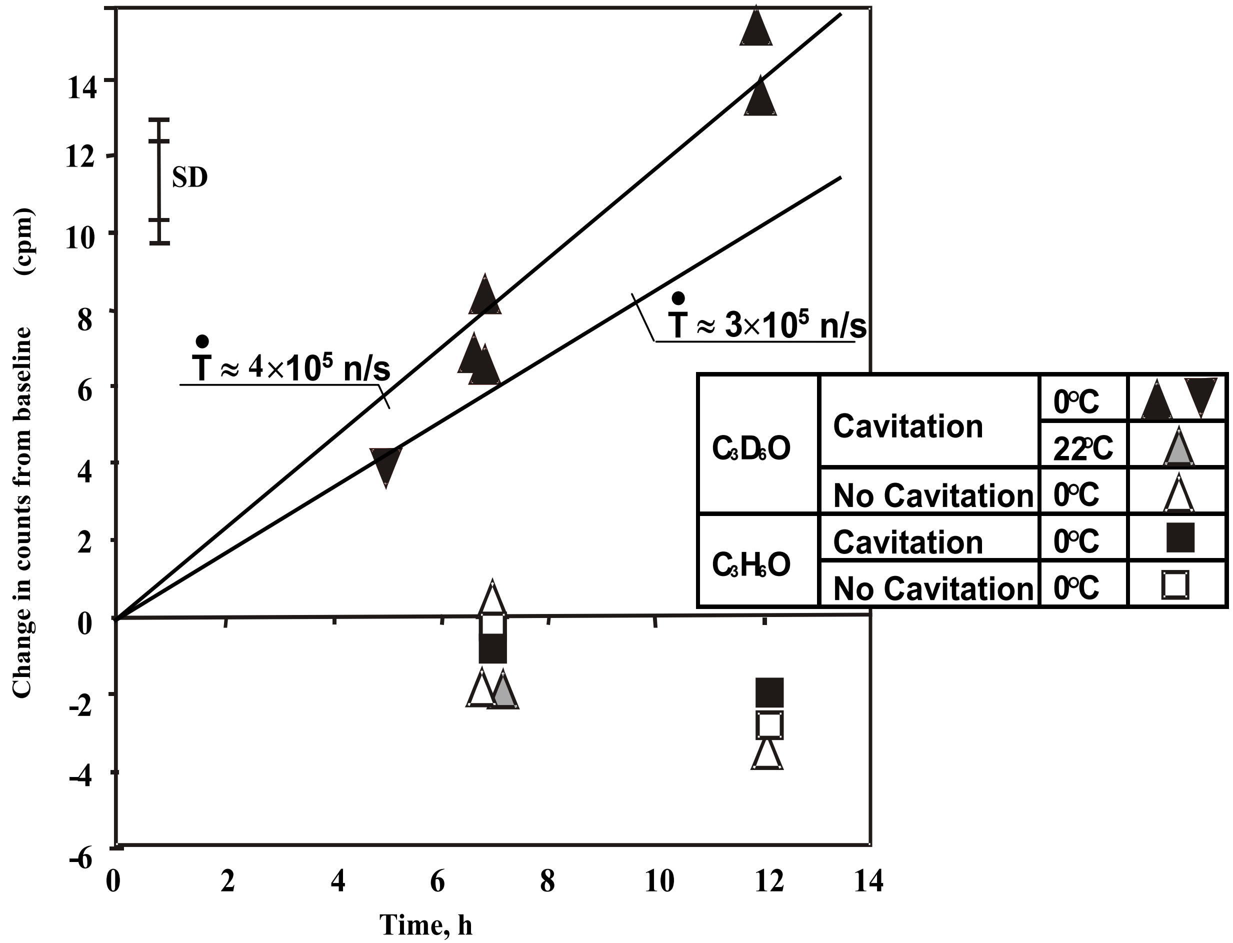
- A D/D fusion reaction has two possible outcomes (with about an equal probability):

$$D + D \text{ ® } {}^{3}He + n\left(2.45MeV\right) + 3.3MeV$$

$$D + D \text{ ® } T + H + 4MeV$$

- Thus tritium ($T \equiv {}^{3}H$) measurements were also made to independently confirm the occurrence of D/D fusion reactions.

  - These data indicated a monotonic buildup of tritium in irradiated, chilled D-acetone (only).
  - The D/D neutron count rate was consistent with the tritium measurements inferred from the neutron measurements ($\sim 4\times10^{5}$ n/s).



Tritium Counts

Discussion-Analysis

- A detailed analysis was performed to explain and confirm these experimental results.

  - Assuming that <u>spherical</u> bubble compression effects (e.g., plasma formation dynamics, shock waves, etc.) lead to the sonoluminescence and sonofusion, the phenomena can be analyzed using:

(1) A modified Rayleigh equation

- Low Mach number $\left(Ma_g \equiv |\dot{R}|/C_g\right)$ stage

(2) A HYDRO code

- High Mach number stage

- The modified Rayleigh equation is [Nigmatulin et al, *JFM*, 2000]:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \left(p_{l_i} - p_I\right)/\rho_l + \frac{R}{C_l \rho_l}\frac{d}{dt}\left(p_{l_i} - p_I\right) \qquad (1)$$

where R(t) is the instantaneous bubble radius

- This equation is valid for $Ma_g \equiv |\dot{R}|/C_g \le 0.1$, where the bubble expansion and compression process is essentially isothermal and homobaric.

- For the high Mach number stage of the bubble implosion process, the detailed phasic conser-vation equations in spherical coordinates must be used:

<u>Mass Conservation</u> ($k = v, l$)

$$\frac{\partial \rho_k}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho_k u_k r^2\right) = 0 \tag{2a}$$

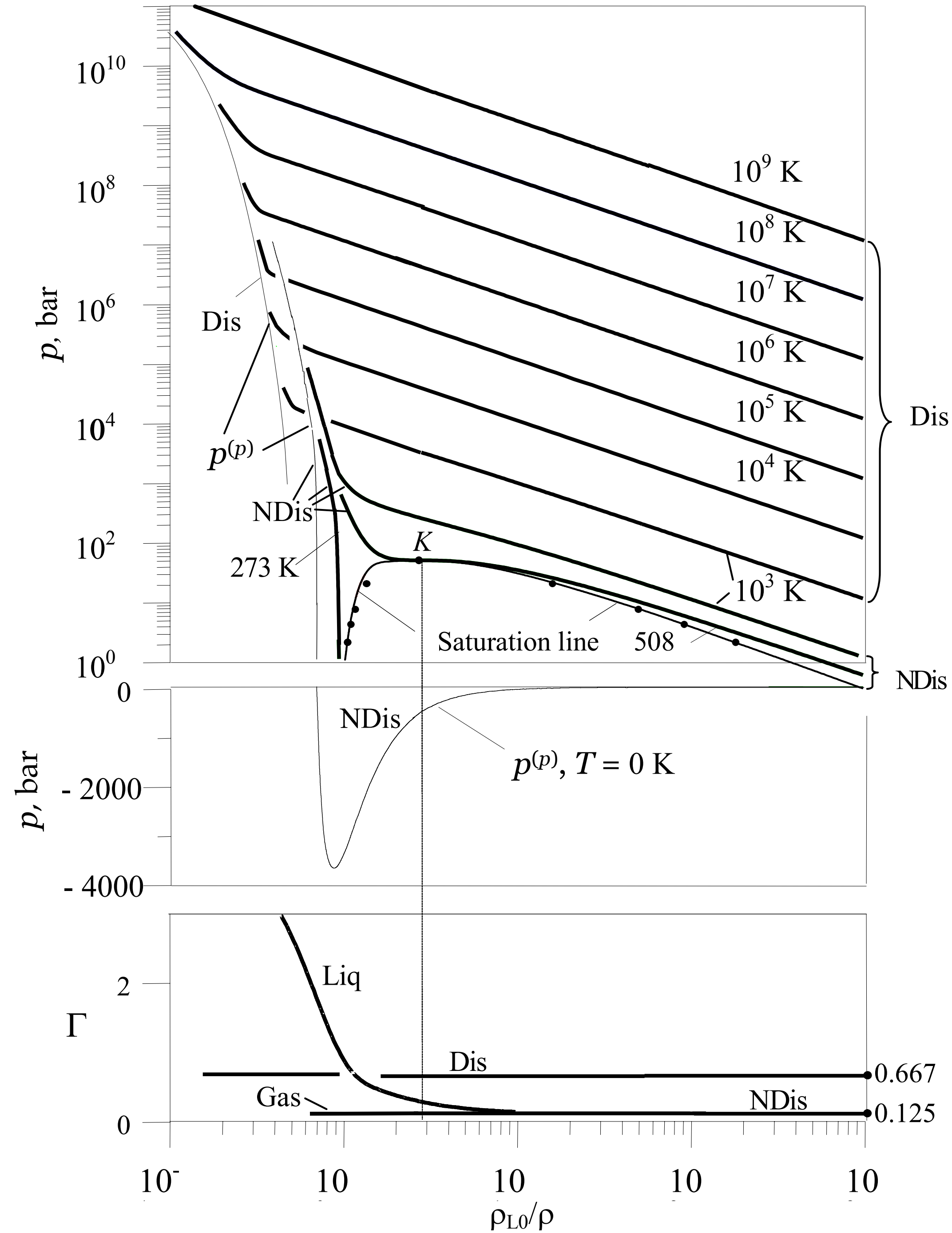
Momentum Conservation ($k = v, l$)

$$\frac{\partial (\rho_k u_k)}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho_k u_k^2 r^2\right) + \frac{\partial p_k}{\partial r} = 0 \tag{2b}$$

- Energy Conservation (k = v, l)

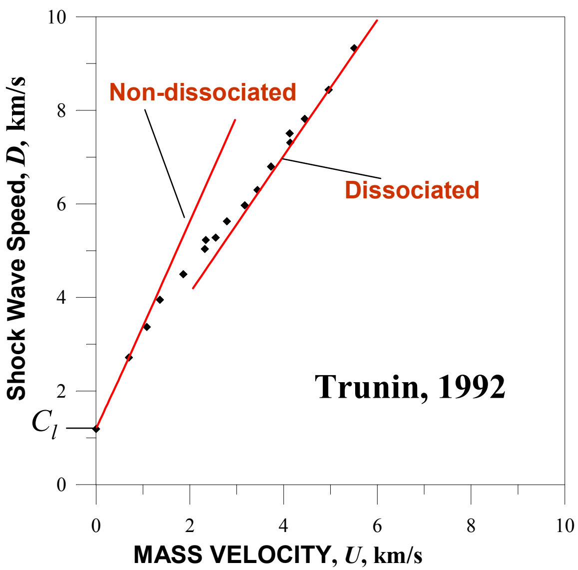
$$\frac{\partial e_k}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left[u_k r^2 (e_k + p_k)\right] = \frac{1}{r^2}\frac{\partial}{\partial r}\left[\kappa_k r^2 \frac{\partial T_k}{\partial r}\right] \qquad (2c)$$

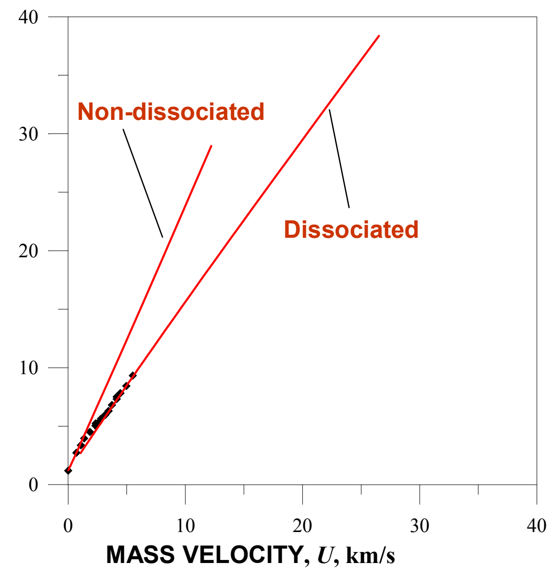
  - We note that different phases can take place <u>only for subcritical conditions</u> (i.e., $p<p_{crit}$, $T<T_{crit}$)
- <u>Closure</u> is achieved by specifying κ_k and the appropriate equations of state (EOS) for the liquid and vapor/plasma within the bubble.
  - The Mie-Gruneisen EOS ($p_v=p_p+p_T$; $e_v=e_p+e_T+e_c$) and Born-Mayer potentials (p_p, e_p)were used [Nigmatulin et al, *Phys. of Fluids*, 2005].



10^9 K
10^8 K
10^7 K
10^6 K
10^5 K
10^4 K
10^3 K
Dis
NDis
p, bar
Dis
p^(p)
NDis
273 K
K
Saturation line
508
NDis
p^(p), T = 0 K
p, bar
Liq
Dis
Gas
NDis
Γ
0.667
0.125
ρL0/ρ

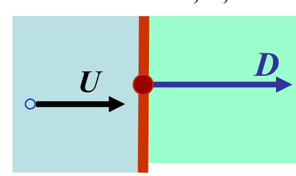
- It should be noted that due to the rapid implosion process ($\Delta t < 10$ ns) <u>liquid dissociation</u> does not have time to occur, thus the liquid remains "stiff," which greatly strengthens the shock wave in the vapor/plasma.





D – **Shock Wave Speed**

U – **Mass Velocity after the Shock Wave**



- Also, due to the shock-wave-induced method of heating during plasma formation (which is quite different from laser-induced inertial confinement fusion), the electron temperature will be much less than the ion temperature during the implosion process.

  - Thus the effective plasma temperature during the thermonuclear fusion events will be essentially the ion temperature. Moreover, the radiation energy losses associated with the electrons (e.g., line losses, bremsstrahlung, etc.) will be relatively small.

- To model the (ion-ion) thermal conductivity in an ionized vapor, κ_v, was given by:

$$\kappa_v = a_1 T_v^m + a_2 \qquad (3a)$$

$$\tau_{ii} \frac{\partial q'}{\partial t} + q' = -\kappa_v \nabla T_v \qquad (3b)$$

where $m = ½$, q' is the heat flux and τ_{ii} is the time constant ($\sim 10^{-13}$s) for the ion-ion energy transfers. This model is expected to give a reasonable estimate of the non-radiative heat loss.

- The well-known Hertz-Knudsen-Langmuir model for the phase change flux was also used:

$$\dot{m}''_v = \frac{2\alpha}{(2-\alpha)} \left[\frac{p_{sat}(T_i) - p_{v_i}}{\sqrt{2\pi R_v T_i}} \right] \qquad (4)$$

where α is the phase change (i.e., accommodation) coefficient and R_v is the gas constant.

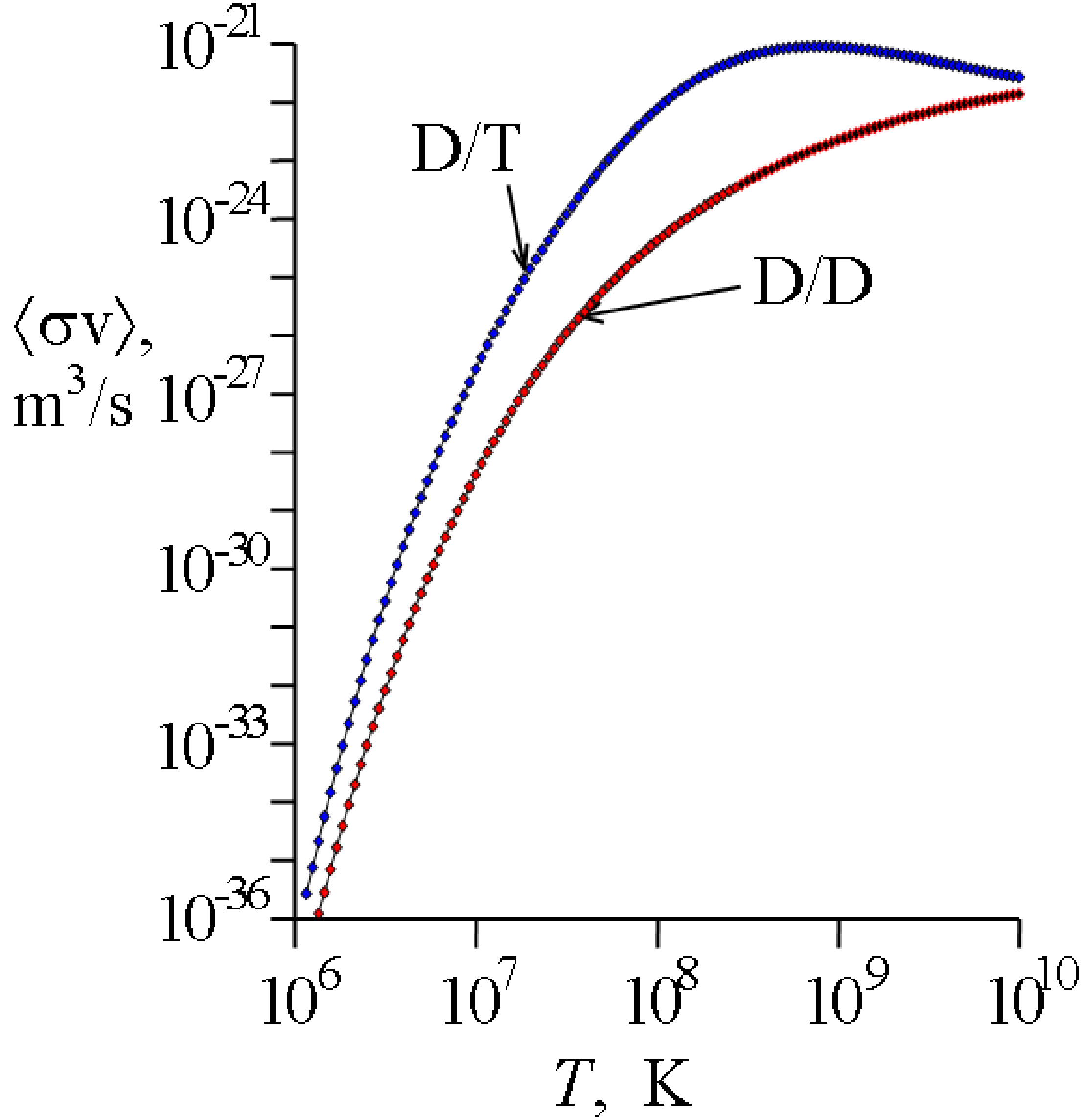
- In order to evaluate the production rate of D/D fusion neutrons a neutron kinetics model, and the weighted cross sections (<σv>) for the thermonuclear fusion reactions, can be used in conjunction with HYDRO code evaluations of the local, instantaneous thermal-hydraulics:

$$\dot{n}_n''' \equiv \frac{dn_n'''}{dt} = \frac{1}{2} < \sigma v > \left(n_D'''\right)^2 \qquad (5)$$

where n_n''' is the neutron density and n_D''' is the deuterium ion density.

- Thus,

$$n_n = \int_{V_{bubble}} \int_{o}^{1/\phi} \frac{dn_n'''}{dt} dt\, dv = \int_{o}^{R} \theta(r)\, dr \approx \left(n_D'''\right)^2 \langle \sigma v \rangle R^3 \Delta t \qquad (6)$$



10^{-21}
10^{-24}
10^{-27}
10^{-30}
10^{-33}
10^{-36}
D/T
D/D
⟨σv⟩,
m³/s
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
T, K

- Typical numerical results for the ORNL sonofusion experiments indicate ultrahigh pressures and temperatures. These conditions are predicted to yield about <u>ten</u> (10) neutrons/implosion for each highly compressed bubble.

Global Check

	Typical SBSL Results [Moss et al, 1994]	Typical Sonofusion Results [Nigmatulin et al, 2005]
R_{core}	~2 nm	~60 nm
Δt_*	$\sim 10^{-11}$ s	10^{-13} s
ρ_*	$\sim 10^{4}$ kg/m^3	$\sim 10^{4}$ kg/m^3
p_*	$\sim 10^{9}$ bar	$\sim 10^{11}$ bar
T_{i_*}	$\sim 10^{6}$ K	$\sim 10^{8}$ K
<σv>	$\sim 10^{-37}$ m^3/s	$\sim 10^{-25}$ m^3/s

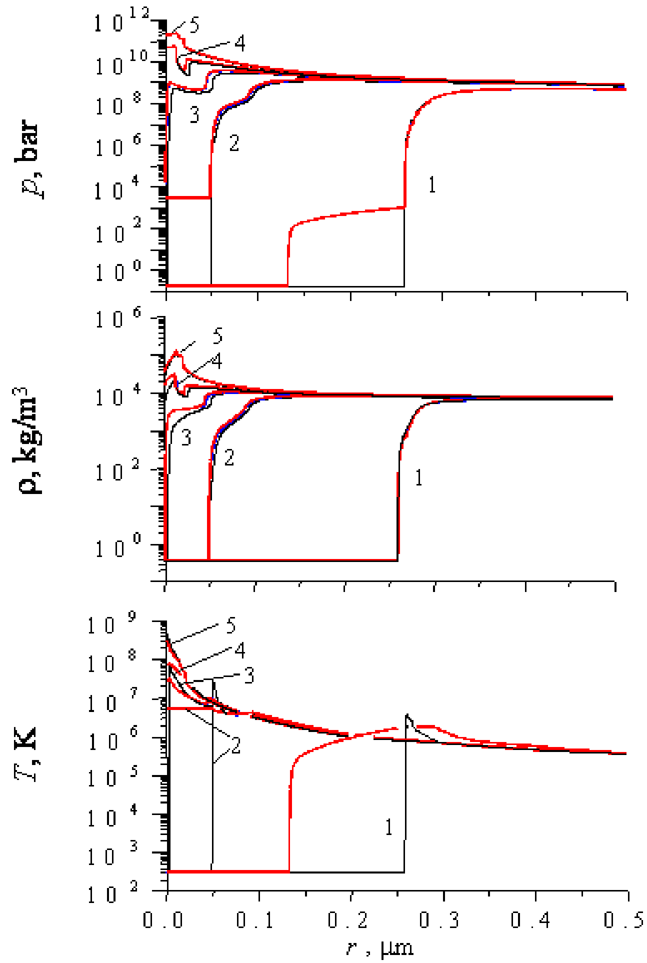
- Thus Eq. (6) implies:

$$n_n \sim (n_{D'})_*^2 \langle \sigma v \rangle_* R_{core}^3 \Delta t_* = \begin{cases} 10 \text{ neutrons / implosion / bubble - } \mathbf{SF} \\ 0.0 - \mathbf{SBSL} \end{cases}$$

- Since we expect about 15 highly compressed bubbles within the bubble clusters, and each cluster experienced up to 50 implosions/sec and 50 energetic "bounces" at the acoustic frequency, we predict a D/D fusion neutron yield of about,

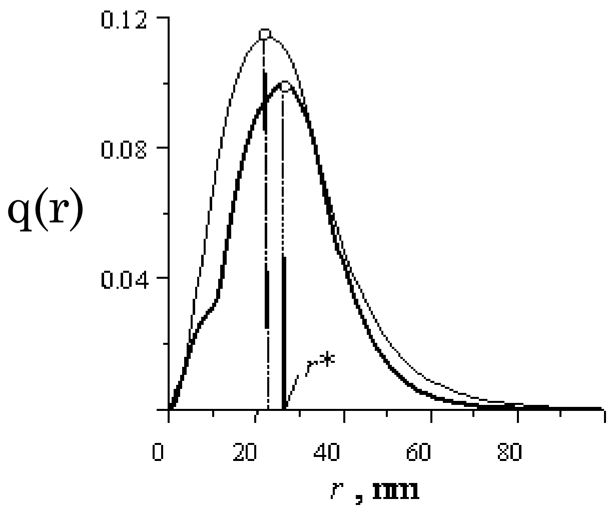
$$\dot{n}_n = (10\,\text{neutrons / bubble})(15\,\text{bubbles})\left(50\,\frac{\text{clusters}}{\text{s}}\right)(50\,\text{bounces/cluster}) \approx \underline{4 \times 10^5\,\text{neutrons / sec}},$$

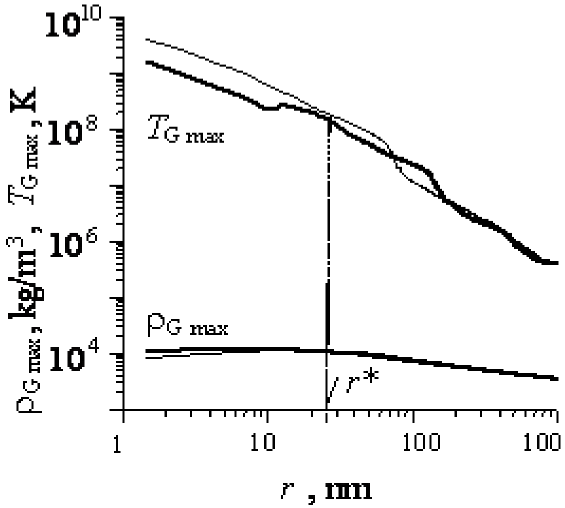
which is in very good agreement with the measured neutron rate (~4 × 10^5 neutrons/sec) and that inferred from the tritium measurements (~4 × 10^5 neutrons/sec).



The high Mach number phase of bubble implosion (thin line, κ_v = Eq. (3a); thick line, κ_v = constant).

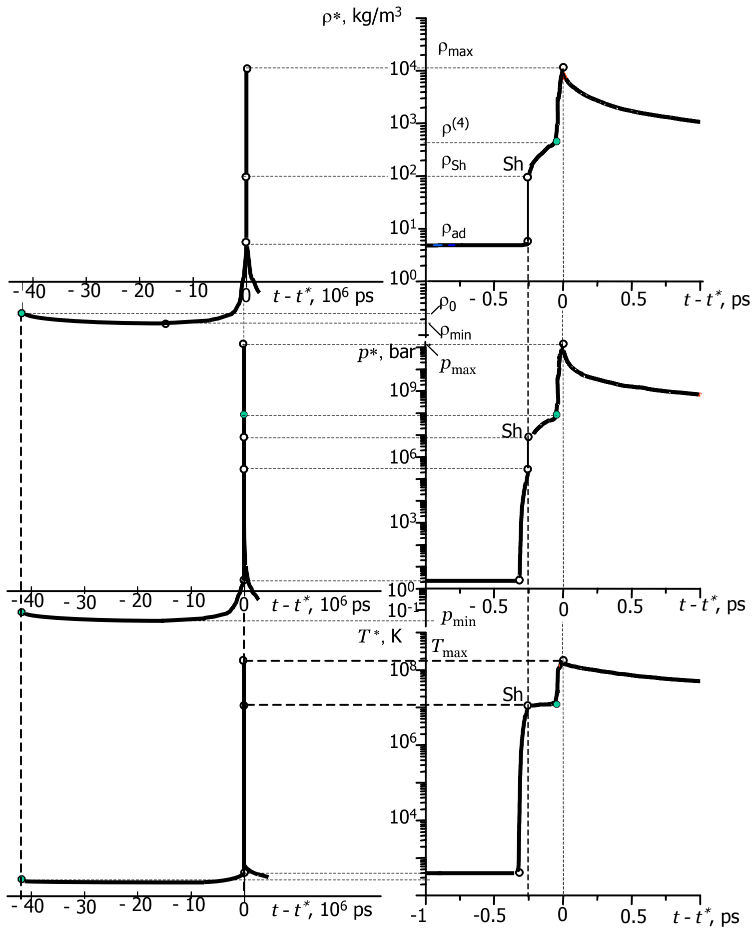
- Unlike in SBSL, endothermic “chemical reactions” play a minor role (~5%) in Sono-fusion experiments.





(Note: The thick line involves endothermic “chemical reactions” while the thin line ignores these reactions.)

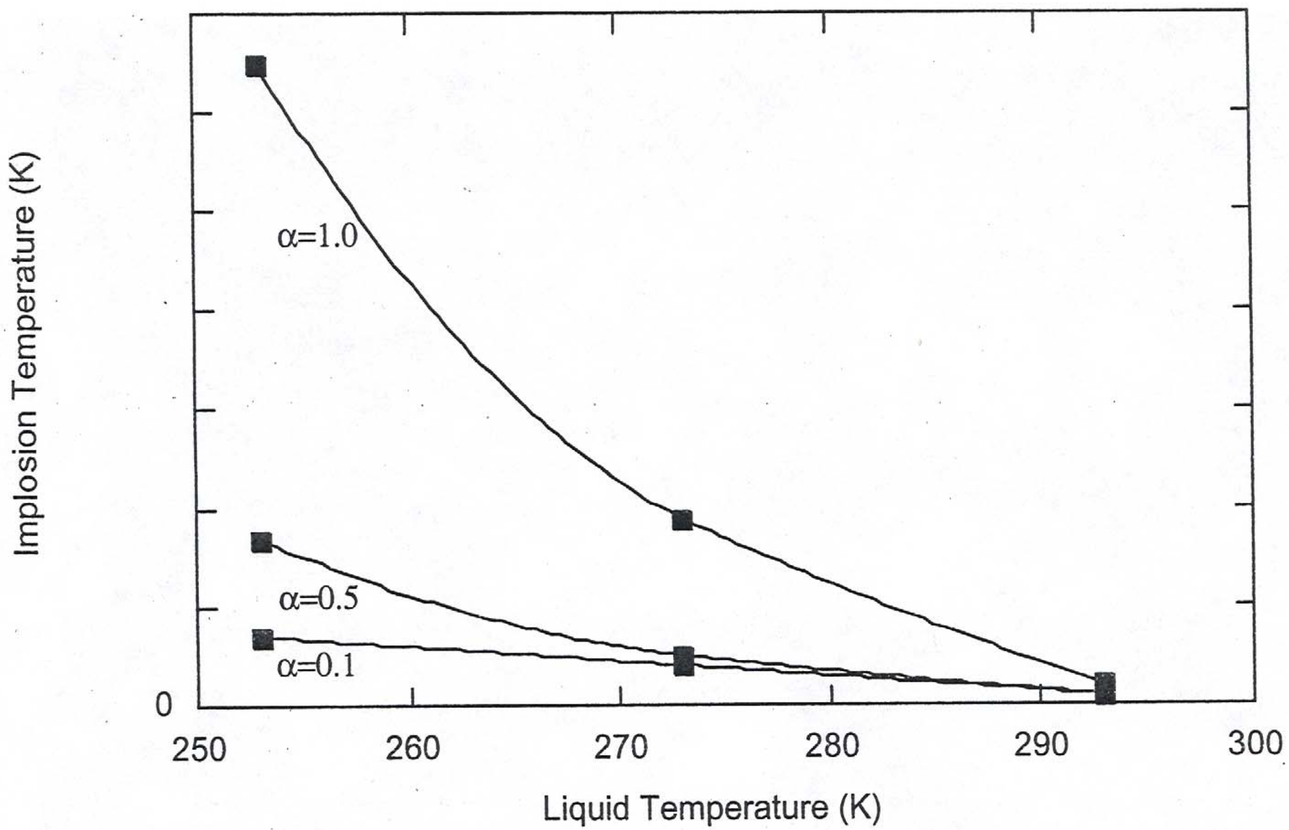
- The interactions of the shock and compression waves at r = r* is quite complicated.



- Parametric calculations show that the "peak" implosion temperature increases as the liquid pool temperature, T_0, is decreased and the phase change coefficient (α) is increased.
    - Reducing T_o decreases the vapor pressure (i.e., for D-acetone, $p_s(T_o = 293K) \simeq 3.5 p_s(T_o = 273K)$), and thus reduces the evaporation rate during bubble expansion.

- Both low T_0 and high α promote vapor conden-sation, which, in turn, minimizes vapor "cushioning" during bubble implosion.

  - Interestingly C_3D_6O has α @1.0 while D_20 has $\alpha \leq$ 0.075. Thus D-acetone appears to be a better test fluid than heavy water.



The Effect of Liquid Pool Temperature on

Bubble Implosion Temperature

- Also, detailed neutron/ion transport and nucleation analyses indicate that high energy neutrons can produce <u>bubble clusters</u> (~1,000 bubbles in D-acetone) that may experience bubble nuclear fusion, while pulsed lasers lead to a few <u>large</u>, <u>non-spherical</u> vapor bubbles which do not achieve thermonuclear conditions during implosions.

Conclusions

- D/D fusion was achieved at ORNL during sonofusion experiments.
  - The process is repeatable and can be predicted using a state-of-the-art HYDRO code.

- The next step is to work on <u>scale-up</u> of the process (to increase neutron yield) including the use of other test liquids and the creation of a nuclear chain reaction (i.e., criticality).

  - <u>IF</u> successful, sonofusion has the potential to revolutionize the way energy is produced worldwide.
    - *However, we still have a long way to go…*
    - *Stay tuned!*