First Tests on OMEGA of a Bubble Chamber for Neutron Detection

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50th Annual Meeting of the American Physical Society
Division of Plasma Physics
Dallas, TX
17–21 November 2008
The 14-MeV-neutron sensitivity of a freon-based bubble detector has been tested on OMEGA

- The chamber has detected 14-MeV DT neutrons at yields of $\sim 10^{13}$.

- The measured sensitivity agrees with that calculated for neutron–freon bubble formation/growth.

- The sensitivity is too low for neutron imaging on OMEGA, but more than adequate for the higher neutron yields expected at the NIF.
Collaborators

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Neutron imaging can provide data that show why an ICF capsule fails to ignite$^{1,2}$

- Neutron images of ICF capsules provide a direct measurement of the fusion burn region within a compressed target.

- The radiation symmetry can be inferred from a neutron image of the hot-spot fusion region (where the fusion processes occur).

- Bubble chambers are detectors with a high potential in achieving high resolution neutron images$^3$.

The bubble chamber is a fully self-contained platform located in the OMEGA Target Bay

- Neutron interactions in the superheated freon create bubbles that are counted/imaged.

- The bubbles are detected in parallel, monochromatic light.

- For imaging, distribution of bubbles ~ neutron spatial distribution.
The number of observed bubbles inside freon confirmed the theoretical calculations.

- Successive images (21-ms difference) of neutron-induced cavitation inside the BUBDET: about 14 bubbles can be counted in the area not affected by turbulence.
Nucleation occurs inside a bubble chamber when the deposited energy reaches a threshold value

- Thermodynamics of the superheated liquid gives the threshold energy to create a bubble:

\[ W_{\text{bubble}} = \frac{16 \pi \gamma^3}{3(p_v - p_0)^2}, \]

\[ \gamma: \text{surface tension of the active medium} \]
\[ p_v: \text{co-existence phase pressure} \]
\[ p_0: \text{superheated state pressure} \]

- Maximizing the free energy necessary to form a bubble, the critical radius from which a bubble does not collapse but continues to grow is

\[ R_c = \frac{2\gamma}{p_v - p_0}. \]

- Therefore, for a thermodynamically viable bubble, the energy \( W_{\text{bubble}} \) must be deposited over a volume \( \sim R_c^3 \).

- However, the ion-recoil range for \((n, \text{freon}) \rightarrow (n', \text{freon'})\) is \(< < R_c\).

The sensitivity of bubble formation can be understood by examining the details of ion recoil

- Since the recoil-ion range is short, energy must be deposited in a volume $\sim R_c^3$ by energetic (several hundred eV) electrons.

- Furthermore, only a small fraction of the recoil ions have energies $> W_{\text{bubble}}$ ($\sim 2$ keV for freon 115).
The number of bubbles generated per source neutron can be expressed by a simple equation

\[ \text{number of bubbles} = F_n \cdot F_i \cdot F_e \cdot d\Omega. \]

- \(F_n\) is the fraction of the incident neutrons interacting with the superheated liquid.

- \(F_i\) is the fraction of the ejected ions with energy \(\geq W_{\text{bubble}}\).

- \(F_e\) is the fraction of the ejected ions that induce, on scattered electrons, an energy \(\geq W_{\text{bubble}}\) and range \(\sim R_c\), and produce bubbles.
The interaction coefficients from the previous slide can be easily calculated

- \( F_n \) (the fraction of incident neutrons) can be calculated based on the total scattering cross section.

- \( F_i \) (the fraction of the ejected ions with energy \( \geq W_{\text{bubble}} \)) can be calculated based on the differential cross section (>50° for the case of freon).

- \( F_e \) (the fraction of the ejected ions that produce bubbles) can be calculated from the interaction cross section between a recoil nucleus and an electron**

\[
\sigma_{i,e} = 18.74 \times 10^{-21} \frac{Z_e R_h}{W_{\text{bubble}}} \text{ (cm}^2\text{),}
\]

where \( Z_e \) is the number of electrons/molecule and \( R_h \) is the Rydberg energy.

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** F. Seitz, Phys. Fluids 1, 2 (1958).
The number of bubbles/neutron sources can be estimated for the LLE freon bubble detector

- For the case of freon 115 (CCl₂F₅) at 50°C
  - \( F_n = 0.243 \)
  - \( F_i = 0.08 \)
  - \( F_e = 5.719 \times 10^{-5} \)

- Therefore, for the detector’s solid angle

\[
\text{Neutron sensitivity} = \frac{\text{number of bubbles}}{n_{\text{source}}} = F_n \cdot F_i \cdot F_e \cdot d\Omega = 1.33 \times 10^{-12}
\]

- For the set of images shown earlier (subtracting the turbulence area from \( d\Omega \)), the neutron yield is \( y_n = 10^{13} \).

- After subtracting the turbulence area, expected number of bubbles \( \approx 12 \).
Neutron yield at the NIF will be sufficient to obtain a high-resolution neutron image

Penumbral/pinhole imaging with bubble chambers requires at least $10^3$ to $10^4$ bubbles inside the detector for a 4-$\mu$m to 1-$\mu$m resolution of the neutron source image (for a magnification $M = 30$).

<table>
<thead>
<tr>
<th>OMEGA</th>
<th>NIF</th>
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</thead>
<tbody>
<tr>
<td>Source-detector distance – 8 m</td>
<td>Source-detector distance – 16 m</td>
</tr>
<tr>
<td>FOV – 200 $\mu$m</td>
<td>FOV – 200 $\mu$m</td>
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<tr>
<td>Neutron yield $\sim 10^{13}$</td>
<td>Neutron yield $\sim 10^{19}$</td>
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<tr>
<td>No. of bubbles observed $\sim 14$</td>
<td>No. of bubbles expected $\sim 3 \times 10^6$</td>
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</table>

Neutron yield at the NIF will reach $y_n = 10^{19} \rightarrow 10^6$ bubbles can be produced, more than enough for a high-resolution neutron image.
Summary/Conclusions

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