Toward Temperature-Dependent Spectroscopy in Centrifugally Tensioned Metastable Fluid Neutron Detectors

Connor Hainje
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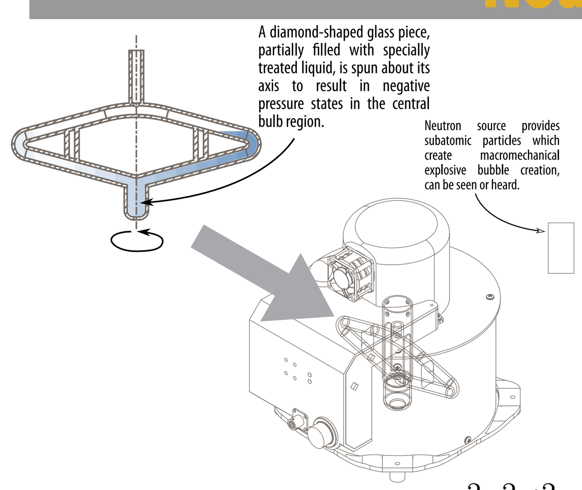
Motivation

The ability to conduct spectroscopy is useful in combating nuclear terrorism [1], as it improves the ability of neutron detectors to more accurately and precisely determine the presence of nuclear weapons, saving countless human lives and immeasureable economic damages. Enhanced fielding of neutron detectors also has industrial applications, as the detectors may more accurately and precisely determine the nuclear radiation that workers may be exposed to, and can allow for improved dosimetry. The centrifugally tensioned metastable fluid neutron detector (CTMFD) is one such neutron detector which uses centrifugal force to put a liquid under negative pressure (in a tensioned state). When in this state, it is sensitive to neutrons. Previous work has shown that temperature has some effect on the sensitivity of the detector, although the extent of this effect is unknown. We desire to find the effect of ambient temperature on the sensitivity of the detector, such that we may perform accurate spectroscopy. If successful, this specific detector may be better used in the prevention of nuclear terrorism and in industrial settings.

Centrifugally Tensioned Metastable Fluid Neutron Detectors



Using centrifugal force, the detector applies negative pressure to the liquid, putting it in a tensioned state (similar to tension in solids) [2], [3].

When in this state, neutrons incident upon the tensioned liquid may interact with the liquid, depositing enough energy to cause a cavitation event.

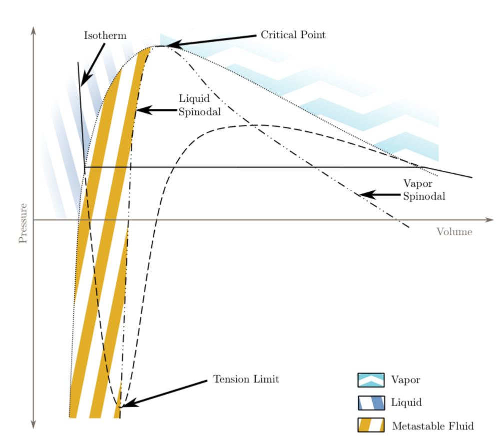
A cavitation event, if of great enough size , will rapidly grow to macroscopic scale, producing a visible bubble and an audible "pop."

$$p_{neg} = 2\pi^2 r^2 f^2 \rho - p_{amb} \qquad [4]$$

This equation may be used to determine the negative pressure in the detector along its central vertical axis.

$$L = \frac{4\varsigma}{p_{amb} - p_{neg}} \qquad [5]$$

This equation is used to find the critical diameter of fluid, within which enough energy must be deposited by a nuclear reaction for a cavitation event to occur.

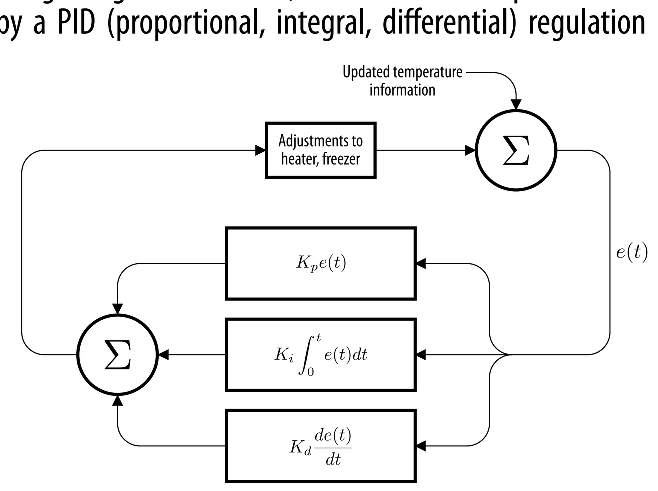


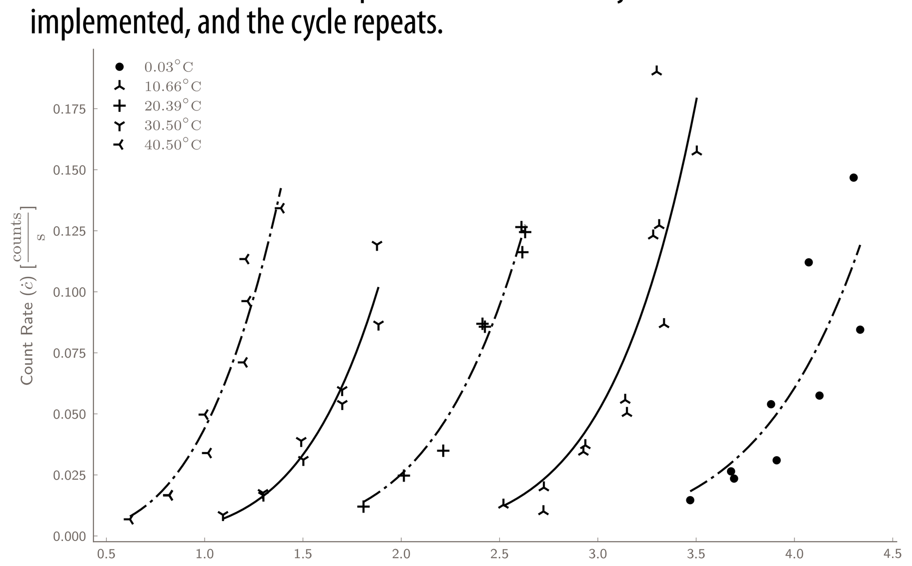
Experimental Set-Up

The precise regulation of temperatures in this experiment required the development of a constant-temperature chamber, inside of which the detector was placed. This apparatus was created using a large chest freezer, inside of which a space heater was placed. The running of the freezer and heater was managed by a PID (proportional, integral, differential) regulation algorithm.

The PID was implemented to the heating and cooling components via Arduino microcontroller. The basic functioning of the PID is summarized by the flowchart to the right [6].

Updated temperature information is taken at regular time intervals, and then the PID calculates the adjustments that should be made to the running of the heating and cooling components in order to attain the desired temperature. These adjustments are implemented, and the cycle repeats.





At each temperature, the CTMFD was placed inside of the constant-temperature chamber, and count rates were found for various negative pressures. Each of these count rate-pressure relationships are represented as curves in the graph to the left. The count rate-pressure curves are shown at different temperatures. The discrepancies between the curves are representative of the varying sensitivity of the detector due to changing temperature.

Proposal

In order to determine the energy spectrum of a neutron source, some relation between the flux of the source, the energy specturm, and the count rate as determined by the CTMFD is desired. First, however, the relationship between a known spectrum and must be determined. Thus, the following equation is proposed.

$$\dot{c} = \Phi \int_V \varphi \Sigma_{cav} dV \qquad [7], [8]$$

This, however, requires the use of a known energy spectrum. To determine the spectrum, we used Monte Carlo N-Particle simulation software in order to simulate the experimental set-up and to determine the spectrum energy that would be incident upon the detector. It also required a definition of the total macroscopic cross-section of cavitation, taking into account all significant nuclear reactions that could deposit enough energy to create a cavitation.

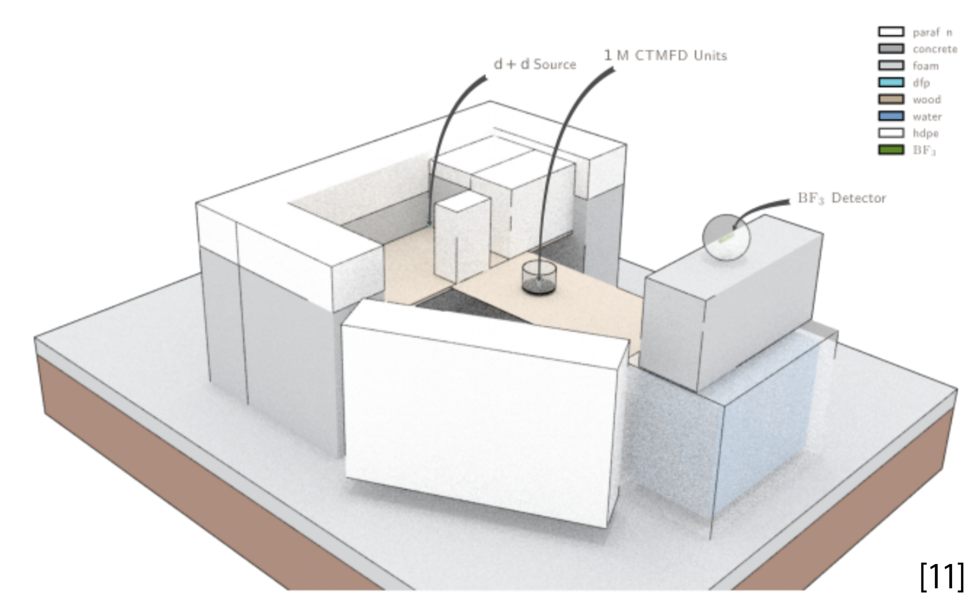
The Φ term is determined by finding the rate of neutron emission from the source (the number of neutrons emitted per second). For the Californium-252 source, the initial rate of radioactive decay, and exponential decay calculations are performed to determine the current rate of neutron emission. For the Deuterium-Deuterium source, the rate of neutron emission is controlled by the electronics of the device, and may be easily known this way.

MCNP Simulation

Simulated Spectrum Determination

Monte Carlo N-Particle (MCNP) simulation software was used to determine the spectrum of energies incident upon the detector [9], [10]. This software operates by repeatedly simulating the random path and events of a particle emitted by some source as it travels through the specified environment. Thus, the energy of a neutron in the detector is simulated by this software.

As the number of simulated particles increases, the law of large numbers indicates that the spectrum of energies incident upon the detector will increasingly mirror the real spectrum of energies.



[11]

The environment, as pictured above and to the right, was recreated in the software. Then, the actions of one billion neutrons were simulated, and the energies of those neutrons that passed into the detector were tallied. The probabilities of these energies were found, and a curve was made. This probability distribution is the spectrum of energies incident upon the detector, which is represented symbolically as φ.

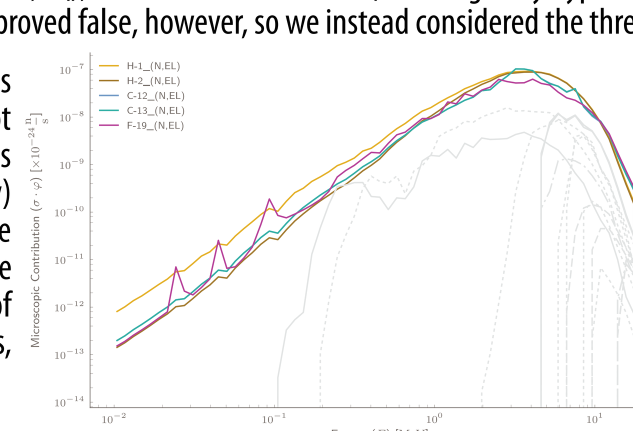
Definition of the Cavitation Cross-Section

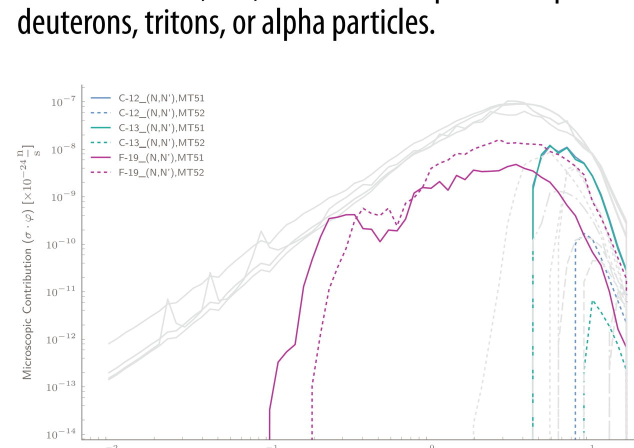
The total cross-section of cavitation is the sum of the macroscopic cross-sections of each individual nuclear reaction that may deposit enough energy to create a cavitation. This is represented mathematically as follows.

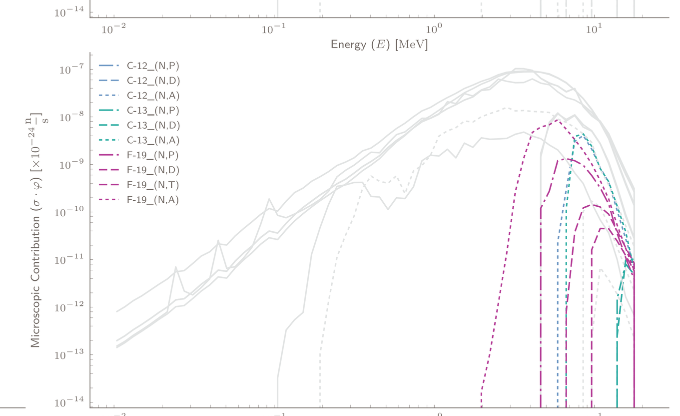
$$\Sigma_{cav} = \Omega \sum^{rxns} \Sigma_{rxn} H(E_{dep} + E_{thermal} - E_{threshold})$$

Thus, the cross-section of cavitation is the sum of the all cross-sections of nuclear reactions (obtained from ENDF nuclear data sheets) [12] where the deposited energy is greater than the threshold energy (the second term, H(), is the Heaviside function). We originally hypothesized that there would be some $E_{thermal}$ term, which represents the thermal energy of the liquid molecules. This proved false, however, so we instead considered the threshold energy to be a function of temperature.

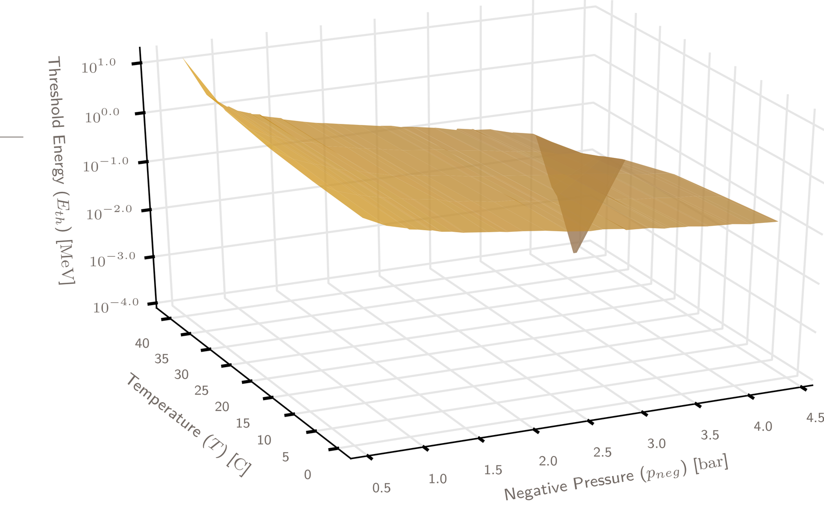
To the right and below are graphs of the contributions of the nuclear reactions that were considered. The plot to the right shows the contributions of elastic reactions in ^{1}H, ^{2}H, ^{12}C, ^{13}C, and ^{19}F. The second plot (below) shows the contributions of inelastic reactions of the first and second excited states for ^{12}C, ^{13}C, and ^{19}F. The third plot (below and right) shows the contributions of reactions in ^{12}C, ^{13}C, and ^{19}F that produced protons, deuterons, tritons, or alpha particles.



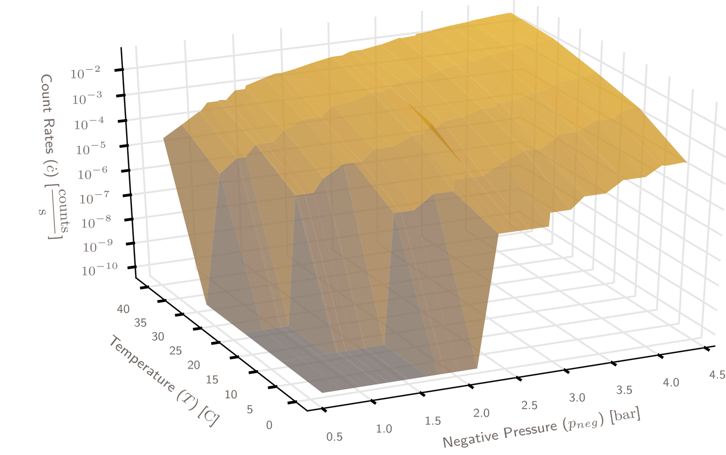




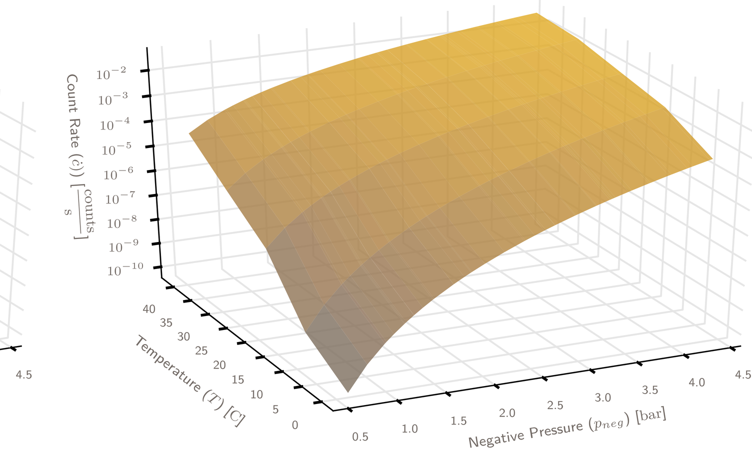
With this relation, the threshold energies that yield the theoretical count rates closest to the experimental count rates were determined as a function of temperature and negative pressure. These threshold energies are shown below.



Results



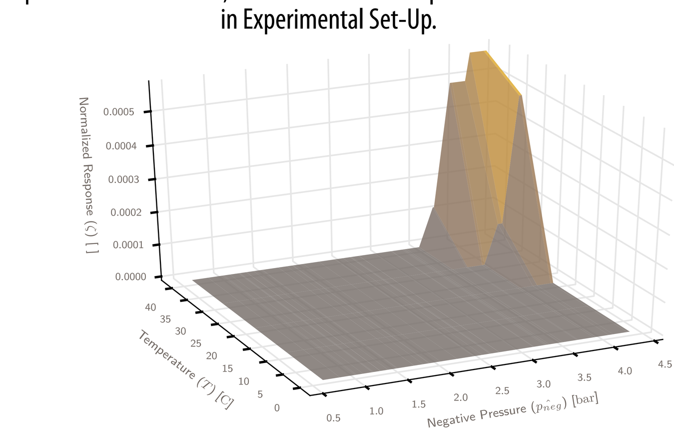
Count rates, calculated from the proposed relation



Expeimental count rates, determined from the power law curves shown in Experimental Set-Up.

The theoretical count rates (above) as determined using the threshold energies match the experimental count rates (above and to the right) quite well.

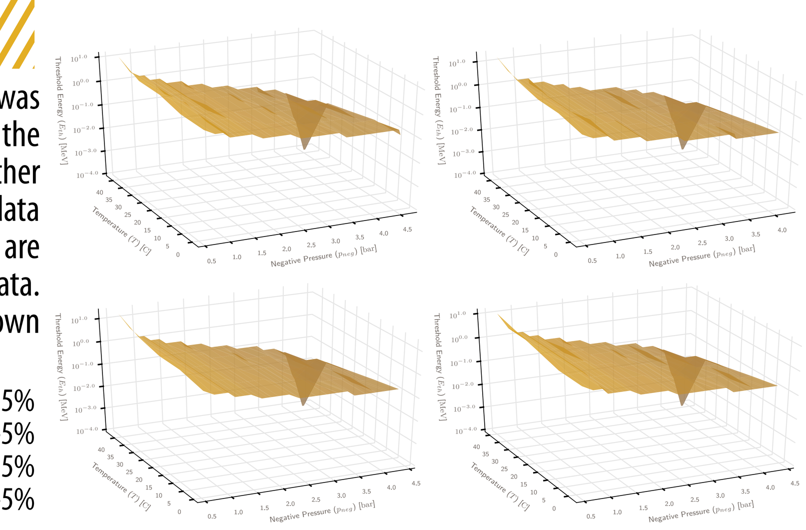
Applying these threshold energies to the spectrum of the deuterium+deuterium neutron source yields a response (to the right), the shape of which matches known phenomena quite well.



Count rates with the deuterium+deuterium neutron spectrum, using the empirically determined threshold energies

Sensitivity Analysis

To test the sensitivity of these results, the data was perturbed and the same simulations were run, and the results show that even with a 5% change in either direction for temperature data or negative pressure data the results stay fairly consistent. Shown to the right are threshold energies calculated with the perturbed data. Note the similarity to the threshold energies shown previously.



Top left: negative pressures +5%
Top right: negative pressures -5%
Bottom left: temperatures +5%
Bottom right: temperatures -5%

Consequences

The determination of a method for calculating the threshold energy of cavitation as it relates to the negative pressure in the CTMFD means that the precise sensitivity of the detector may be more easily known for various temperatures and negative pressures. When this is known, the proposed relation may be used to perform spectroscopy on other neutron sources by first finding the count rates at various temperatures and negative pressures, then using these values to determine the only unknown in the relation: the spectrum.

The development of temperature-dependent spectroscopy with the CTMFD allows for enhanced fielding of these systems. This is useful in combating nuclear terrorism, as these detectors will be able to more accurately and precisely determine the presence of nuclear weapons, saving countless human lives and immeasureable economic damages. Enhanced fielding of CTMFDs also has industrial applications, as the detectors may more accurately and precisely determine the nuclear radiation that workers may be exposed to, and can allow for improved dosimetry.

Further Study

To further the development of temperature-dependent spectroscopy in CTMFDs, experimentation should be conducted to see if the phenomena present when using decafluoropentane as the detection fluid are still present when using other detection fluids (such as acetone). Experimentation should also be conducted at more temperatures, in order to increase the precision of spectroscopy and to determine the range of temperatures for which these results hold true. The experiment should be repeated with other neutron sources, in order to verify the general application of our propsed theory to sources of nuclear radiation. Finally, the results of this experimentation should be used to determine the spectrum of some other neutron source, for which the spectrum is known. This would ensure the validity of our proposed method of spectroscopy in CTMFDs.

References on table below.

Acknowledgements:
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