A Figure 9 is referred to, but is not included in this copy.

Using a Neutron detector in SonoLuminescence Experiment - Part II
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1 Introduction

A recent series of experiments conducted by Taleyarkhan et. al.in the Engineering Technology Division has reportedly produced evidence for the emission of "penetrating radiation" in coincidence with light (sonoluminescence) from the collapse of bubbles in Deuterated acetone. The original coincidence experiments were based the observation of concurrent flashes from a light detector (PM tube) and signals from a plastic scintillator + PM tube as viewed on a digital sampling oscilloscope.

An ad hoc review of the experiment concluded that the experiment should be repeated using more sophisticated detection and data acquisition equipment. In particular a liquid scintillator based detector would provide the capability for n-γ discrimination, and multi parameter data acquisition capability would allow better characterization of the detected events. Such equipment was readily available from the Physics Division, as was the necessary expertise to use it.

Table 1 gives the chronology of evaluation experiments performed by the original authors with the help of Physics Division personnel. The work done prior to the July 24 experiment is detailed in part I of this report. The present part deals with the final experiment run on July 24, the analysis of the data acquired then and our recommendations.

Date	Activity
June 8	Agreed to provide Rusi with the neutron detector.
June 10	Detector and electronics assembled and ready to ship.
June 12	Meet with Rusi and Colleen: show detector capabilities.
June 14	It was decided that physics not provide only the detector but also a multi parameter data acquisition system.
June 18	Data Acquisition and neutron detector brought to ETD, set up and tested with a Pu/Be and the neutron generator sources.
June 19	Characterize the background γ and neutron spectra.
June 20	Study relation of detector flash to neutron generator pulse
June 21	Continue the same. Start setup for SL-n/γ coincidences.
June 22	Modified the data acquisition to record SL and neutron coincidences. Try a first run with Deuterated Acetone.
June 23	Fix blocking signal to ensure blocking of n/γ detector during neutron generator pulse on time.
June 25	Run experiments, with and without cavitation and with and without blocking during the neutron generator on cycle.
June 26	Start data analysis - no clear signal for coincidences.
July 3	Try to work on improvements - increase coincidence time to $20\mu s$.
July 5	PMT tube in nγ detector went bad.
July 13	Set up for experiment with coincidence plus singles events . Set up 1MHz counter to time events relative to PNG trigger.
July 24	Final data run with all in place.

Table 1: **Summary of events.**

2 A quantitative study of SL-n/γ coincidences

2.1 Contemplated improvements

Our earlier experiments established that proper estimation of the quasi-random coincidence rates will be crucial in interpreting results. The observed coincidence rates were largely, but perhaps not completely, explained by such random events. The estimation of these rates requires quantitative measurements of the highly time-dependent singles rates seen by both the light detector and the n-gamma detector. Qualitative evaluation is not adequate.

The relevant singles rates must be measured under the actual experimental conditions whenever possible. For example they are sensitive to discriminator thresholds, to the PNG conditions, to the cavitation conditions, probably to the shielding arrangements, possibly to the acetone make-up (ie Deuterated or normal), etc etc. These measurements are made more difficult by the wide dynamic range of rates seen by the n-gamma detector, and the need for time information ranging from 10's of nanoseconds to milliseconds.

2.2 Data acquisition requirements

We need to simultaneously measure the following:

1. The time dependence of n/γ emissions relative to PNG pulse start. These signals may have to be blocked if rates are too high.

2. The time dependence of delayed n/γ signals seen more then 15 μ after the PNG burst.

3. The time dependence of the light flashes seen by the SL monitor relative to PNG pulse start.

4. The time dependence of the the "real" events corresponding to n/γ-SL coincidences relative to PNG pulse start.

5. The relative time between n/γ and SL distributions inside the 20 μs time window allowed for n/γ-SL coincidences.

6. Pulse height spectrum of signals from n/γ and SL detectors. (Rates in individual detectors are known to depend strongly on discriminator settings.)

Fig. 1 presents a rough layout of the physical setup of the experiment. Detector placement and shielding in this type of experiments is an important variable, and our recommendation will address possible improvements that can be made to this layout.

Fig. 2 shows the block diagram for the data acquisition electronics used to accomplish the tasks listed above. The delay time and the full scale time of the TAC were set to accommodate SL-$n\gamma$ coincidences within a time interval of ± 10 μs . To obtain a longer time base measurement of events relative to the PNG start pulse we use a different scheme. Pulses from a 1MHz clock were recorded in a continuously running scaler. The scaler was reset every time the pulsed neutron generator (PNG) fired and read out every time an event occurred. The histogram recorded this way provides the distribution of elapsed time, in μseconds, between the last time the

PNG fired and the occurrence of the event for which the scaler output was recorded. The n/γ - SL coincidence are selected in a four fold logic (LeCroy 365AL) and the logic signal signifying coincidences then feeds a second four fold logic module where SL singles (A), n/γ-SL coincidence (B), and n/γ singles(C) are combined (OR) to determine a valid event. Another four fold logic module implements the blocking of n/γs during the 20μseconds following the PNG trigger. To differentiate between the different event types that can trigger a data readout, logic signals identifying the type of event that occurred are recorded as separate bits in a gated coincidence register. This bit pattern is also recorded for each event.

A full quantitative analysis requires pulse-height calibration of the n/γ detector and the light detector. The detector efficiencies must be known too. Also time calibration of the various time spectra we measure may be required.

3 Third experiment - singles and coincidence data recorded simultaneously

3.1 Brief description of the experiment and snapshots of the data

There were five distinct runs performed:

1. Room background - only neutron detector was turned on (run 115, scale-down factor=8).

2. PuBe source with neutron detector placed at a distance of 42" from the source (run 116, scale-down factor=8).

3. Deuterated acetone with the neutron generator running and with cavitation on and no blocking (run 110, scale-down factor=64).

4. Deuterated acetone with the neutron generator running and with cavitation on and with blocking (run 109, scale-down factor=8).

5. Deuterated acetone with the neutron generator running but without cavitation and with blocking (run 111, scale-down factor=8).

The background rate in the n/γ detector was about 150 counts/sec. Fig. 3 shows neutron and γ energy spectra. The same figure also displays the neutron and γ spectra obtained with the PuBe source as well as neutron and γ energies obtained by running the neutron generator at a lower intensity. The ledge at around channel 3000 corresponds to 14MeV proton recoil energies. The peak in the PuBe gamma spectrum around channel 1800 corresponds to 4.4 MeV electron energy (a 4.43MeV gamma ray from ^{12}C de excitation).

Coincidence runs were performed with and without cavitation. In all cases that we ran, the n/γ separation was marginal because of the high instantenous count rate at the n/γ detector. Even when we blocked out from the data acquisition n/γ signals that arrive at the detector 20μsec after the neutron generator trigger pulse n/γ separation was still poor. The large neutron flux during the PNG pulse reaches the detector and also the pre amplifier and amplifier. The Ortec 572 amplifier used in the experiment probably chokes following the initial pile up of signals and requires several μseconds to recover. Fig 4 has two spectra showing n/γ separation in one of these runs (109). One sees that n/γ separation does improve when we select only events which occur more the 500μseconds after the neutron generator trigger pulse. Fig. 5 and Fig. 6 show the occurrence time clocked for several event types recorded in two runs, one with cavitation (run109) and one without cavitation (run111). These are the n/γ singles, SL light emission singles, and the SL-n/γ coincidences. The SL signals seen more then 500μsec after the PNG pulse are potentially interesting.

3.2 Data analysis

The data rate seen by the electronics during the neutron generator pulse was extremely high ($\geq 10^6$/sec)) and resulted in unacceptable counting losses in the period immediately after the neutron pulse. To avoid this a blocking signal was used to veto all counts from the n-γ detector for 20 μseconds after the onset of the PNG trigger pulse. In addition the event rate from n-γ singles (ie with no SL coincidence) was reduced by only looking at every eighth pulse, thereby reducing the dead time for the computer to below 5% in the worst case.

In a 65 minute long run with cavitation 51 coincidences between pulses from the SL detector and the n-γ detector were observed. To estimate the contribution of random coincidences the time distribution of singles events from the SL and n-γ detectors was analyzed.

Fig. 7 and Fig. 8 show an expanded view of the time distribution of SL, the n-γ and coincidence events relative to the start of the PNG trigger pulse. Time t=0 is at channel 61, and the calibration is 1μsecond/channel. (The clock readout occurs after some processing time delay and the event prompts are also delayed in the electronics), The SL events occur in three regions:

A. During the PNG neutron pulse (ch 61-80) seen in Fig. 7

B. In a 30μsec burst immediately after the PNG pulse (ch 81-122)

C. between 123 and 600μsec there is almost no light activity - but the n-γ rate is significantly higher then normal room background.

D. In a series of short (3μsec fwhm) bursts spaced 52μsec apart appearing beyond ch 600 (Fig. 5).

Note that the channel intervals quoted above are for SL singles but must be shifted down by 10μsec for the nγ singles and coincidences.

The observed singles count rates in the n-γ detector within these three regions are quite different, as can be seen by the nγ singles and SL light singles time spectra shown in Figs. 7 and 8 and must be measured to calculate the expected random coincidence rates within the 20μsec coincidence window. Table 2 shows the results of these calculations. Note that the n-γ events in region A were vetoed by the 20μsec long blocking pulse. In the absence of the blocking pulse essentially 100% of the SL signals in region A would be in coincidence with a n-γ count, increasing the predicted random coincidence events by about 400.

Region	nγ counts/sec	Probability for coinc.	SL events	SL/nγ coin. random	SL/nγ coin. observed
A	89	0.00178	409	0.72	1
B	3915	0.0783	424	33.20	29
C	953	0.01906	47	0.89	1
D	153	0.00306	6983	21.37	20

Table 2: **Estimate of random coincidences**

Thus the measured number of real SL/nγ coincidences is 51-56 or -5±7 which is consistent with zero. Were we to take the average rates recorded during the run, 260.9 nγ/sec and 2.65 SL/sec the estimate random rate would be 40 counts in 3847 seconds which would lead us to interpret the events differently. The time distribution of nγ-SL coincidences summed in 1μsec wide time bins is shown in Fig. 9 and does not show any particular clustering.

We would conclude that there is no evidence of any real coincidences in this experiment. Furthermore there is a substantial random coincidence rate, which must be properly allowed for in any attempt to measure coincidences. As the background rates seen by both detectors are very time dependent, it is essential that these time dependencies be measured at the same time as the coincidences in order to properly evaluate the background rates.

The time dependence seen in the SL detector is fascinating. One must be cautious in interpreting these data however. They represent an integral over many thousands of 5 ms cycles. The interesting gross structure seen between 600 and 2600 microseconds could be a sign that SL bubbles persist for many cycles, but it could also be an integral over a number of single cycle events. This experiment cannot distinguish between these possibilities.

3.3 Recommendations for future experiments

From the original experiment and subsequent analysis we have learned that the effect, if it exists, is small compared with the existing sensitivity (i.e $\leq$ 10 events/hour), and the random coincidence rate ($\approx$ 50 events/hour with blocking in place, and probably $\geq$ 400/hour without blocking).

If it is decided to pursue this line of research a new experimental setup will be required which is far more sensitive (at least two orders of magnitude), and with much lower backgrounds. Furthermore the experiment should be designed to operate automatically for longer periods, and to acquire quantitative counting data without the need for human intervention over long periods of time ($\geq$ a day).

Assuming that the objective is to detect neutrons from d-d reactions coincident with sono-luminescent light then the following options come to mind:

3.3.1 Background reduction.

The backgrounds seen by the scintillation (nγ) detector (mostly γs) include general activity in the room, cosmic rays etc, and prompt and delayed events from the PNG. These sources of background can be reduced using the following:

- Reduce the width of the neutron pulse from the PNG.
- Shield and collimate the PNG to cut down on the sea of neutrons in the room. This will need a careful design of shielding and materials depending on geometry and the detectors chosen.

- Get rid of the general room background. If the room itself is hot (quite possible in Y12) go and do the experiment elsewhere. Store the Pu-Be source elsewhere, or add more shielding.
- Do a careful evaluation of the neutron detector. NE213 scintillator is sensitive to gammas, but could be OK if the n-gamma discrimination is operable. This means reducing the instantaneous rates by shielding etc, and probably reducing the volume to be a better match to 2.45 MeV neutron detection. Other options, such as fission counters, need to be evaluated as well. Again the choice of detector and shielding configuration are inter-twined.
- There is a background from the SL detector, probably due to 14 MeV neutrons hitting the PM tube structure. This detector needs to be shielded from the PNG as much as possible.

3.3.2 Improving the sensitivity.

Increased sensitivity to nγ-SL coincidences can be obtained by increasing solid angle coverage for both neutron and light detection. Using a more efficient light detection system and maybe several neutron detectors will do but that will also increase the singles count rates for nγ and SL. As mentioned before, good rejection of γ rays, or using a detector sensitive only to neutrons with comparable efficiency will help. The SL light detection could benefit greatly by using higher gain photo tube with a photo cathode that is better matched to the emitted light wavelength. If the light spectrum were such that one could clearly separate, by signal amplitude, the noise flashes from true sonoluminescent light we could gain both in background reduction and sensitivity to real events. Focusing mirrors may be a way of substantially increasing the solid angle.

3.3.3 Characterizing the time structure of the SL light.

The data we have already obtained show a tantalizingly complex time structure of the SL light. Further exploration is needed to understand potential dead time effects, particularly when higher efficiency is the goal. Experiments at lower rep rates will show whether the observed large scale (ie ms) time structures persist for longer than 5 ms. Auto-correlation measurements will show whether persistent emission of bubbles (or bubble clusters) over many acoustical cycles is occurring, and also what the dead-time implications might be.

3.3.4 Automation of the experiment.

This experiment to detect neutrons in coincidence with light pulses is akin to typical experiments conducted in nuclear or particle physics. These are low probability coincidence experiments which require long duration experiments with moderate to high singles count rates in the individual detectors. Expertise in these techniques, the statistical analysis of low-level counting data, and the analysis of backgrounds is available at ORNL. It would be advisable to bring in such expertise to help design and operate a new experiment, and to help specify the hardware required.

The current hand-operated vacuum pump should be replaced. If possible the tuning required to sustain cavitation should be automated.

Calibrated light pulser for setting up S/L detector

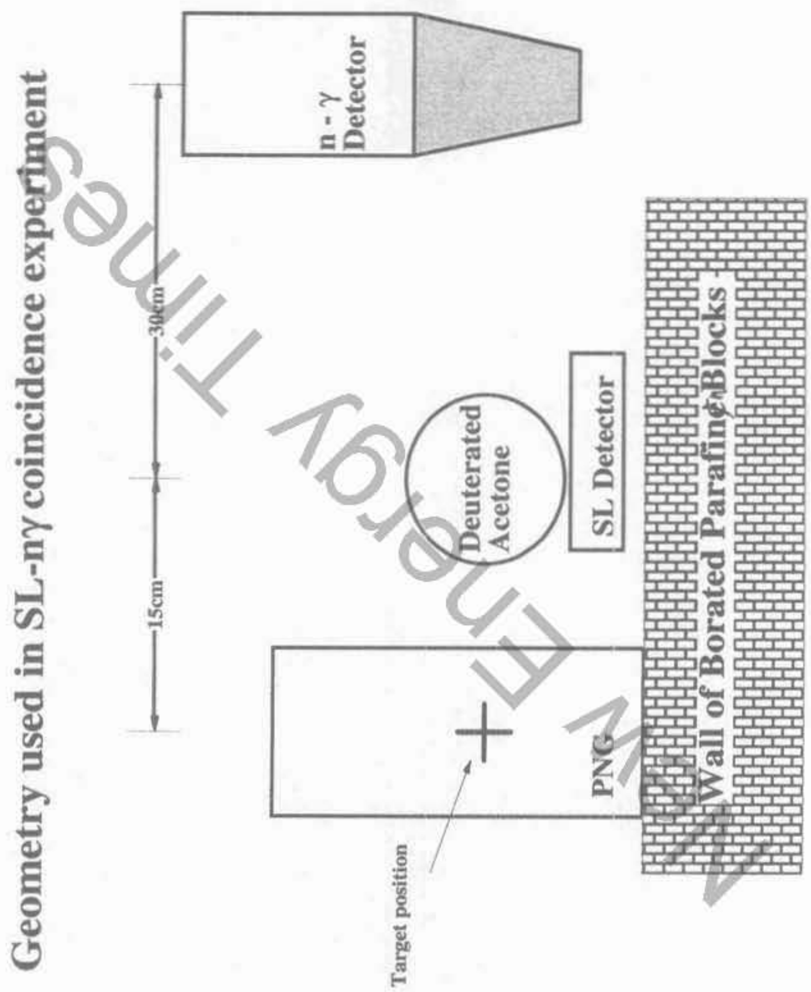


Figure 1: A rough outline of the detector and shielding arrangement used in the experiment

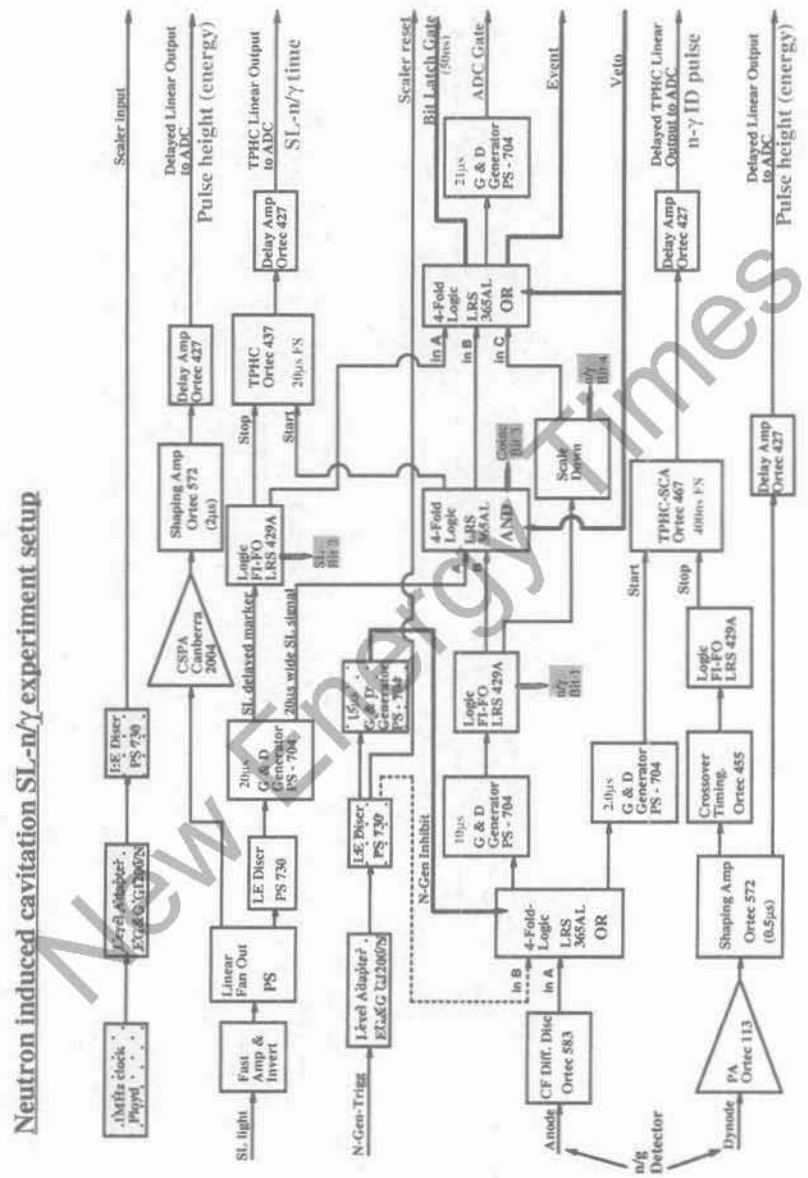


Figure 2: Block diagrams of the improved setup to study the neutron SL-nγ coincidence events

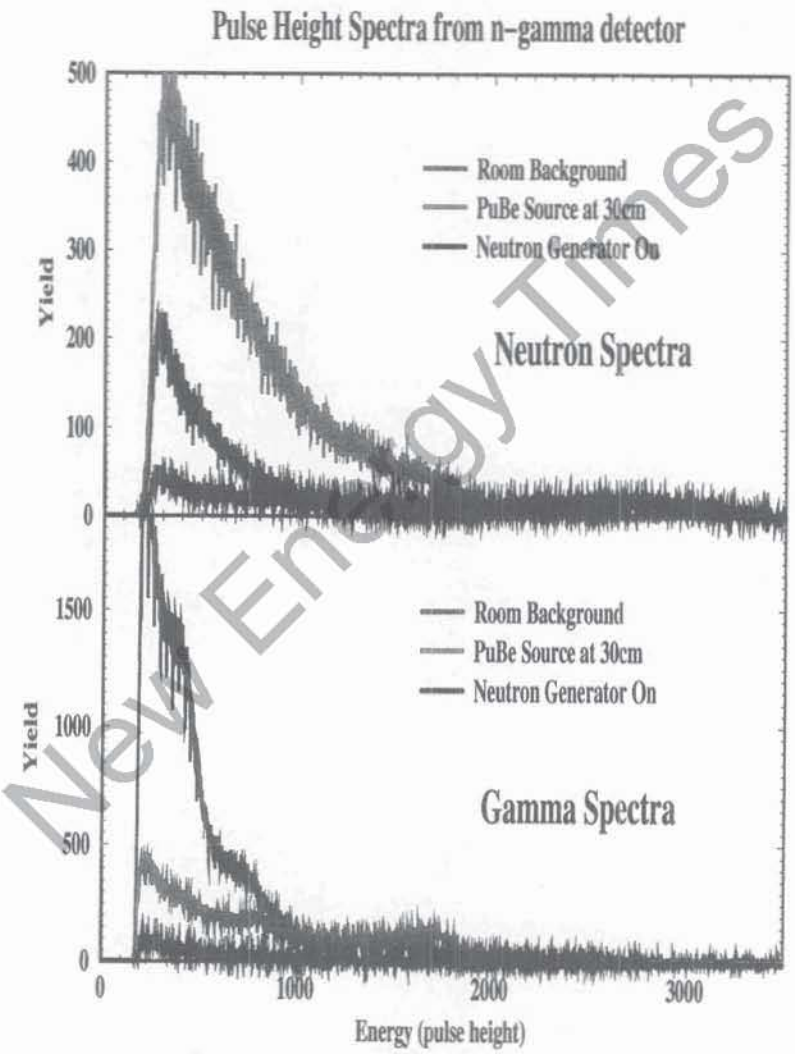


Figure 3: Separated neutron and γ energy spectra from three setup runs: Room background, PuBe and Neutron pulse generator.

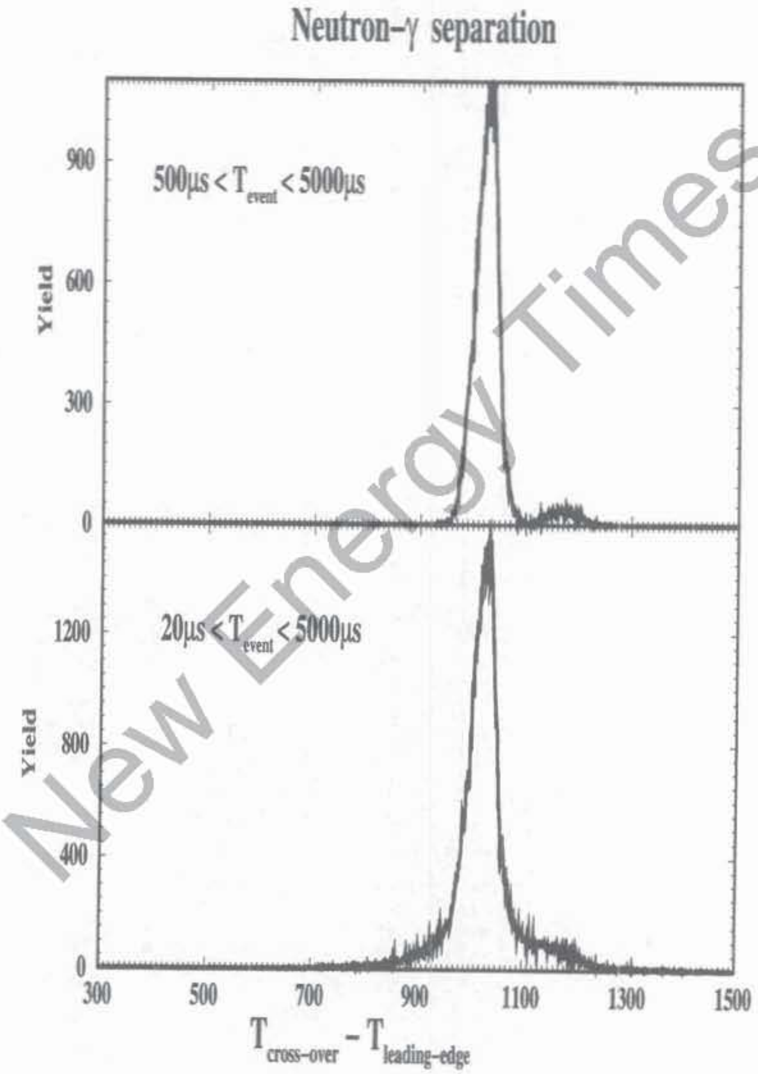
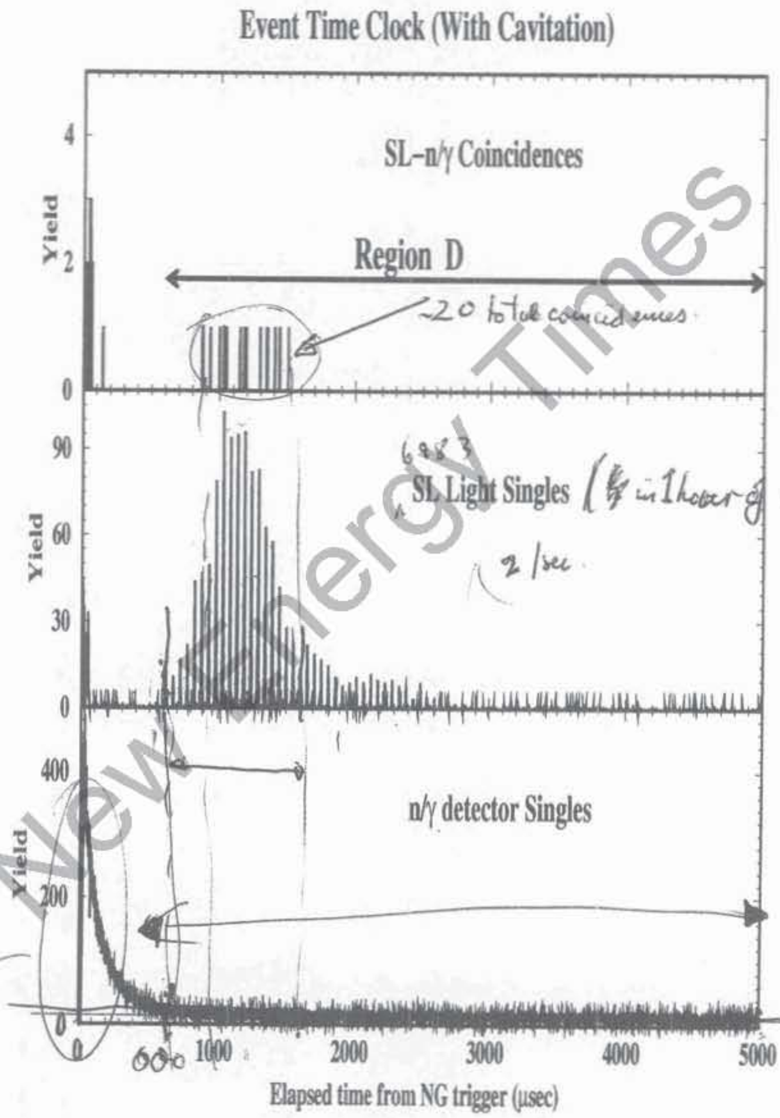


Figure 4: nγ separation during the experiment.



presumably gammas from PNG neutron activations.

Figure 5: Event occurrence time relative to NG trigger time for n/γ singles, SL light emission singles, and the SL-n/γ coincidences recorded in run 109

20μsec block after to.

15·3 × 20 μsec = .00306

1 m sec

400 μsec

400 × 10⁻⁶ × 150

6 × 10⁻²

.006

3×10^? coincs/sec

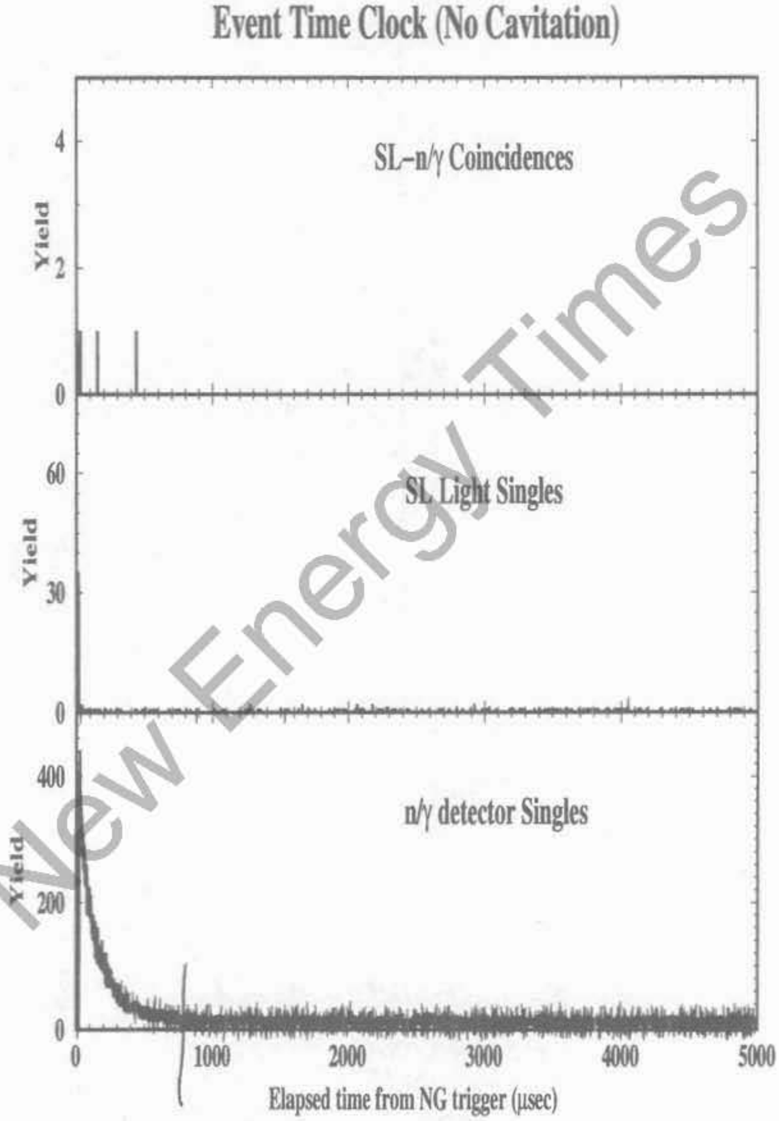


Figure 6: Event occurrence time relative to NG trigger time for n/γ singles, SL light emission singles, and the SL-n/γ coincidences recorded in run 111

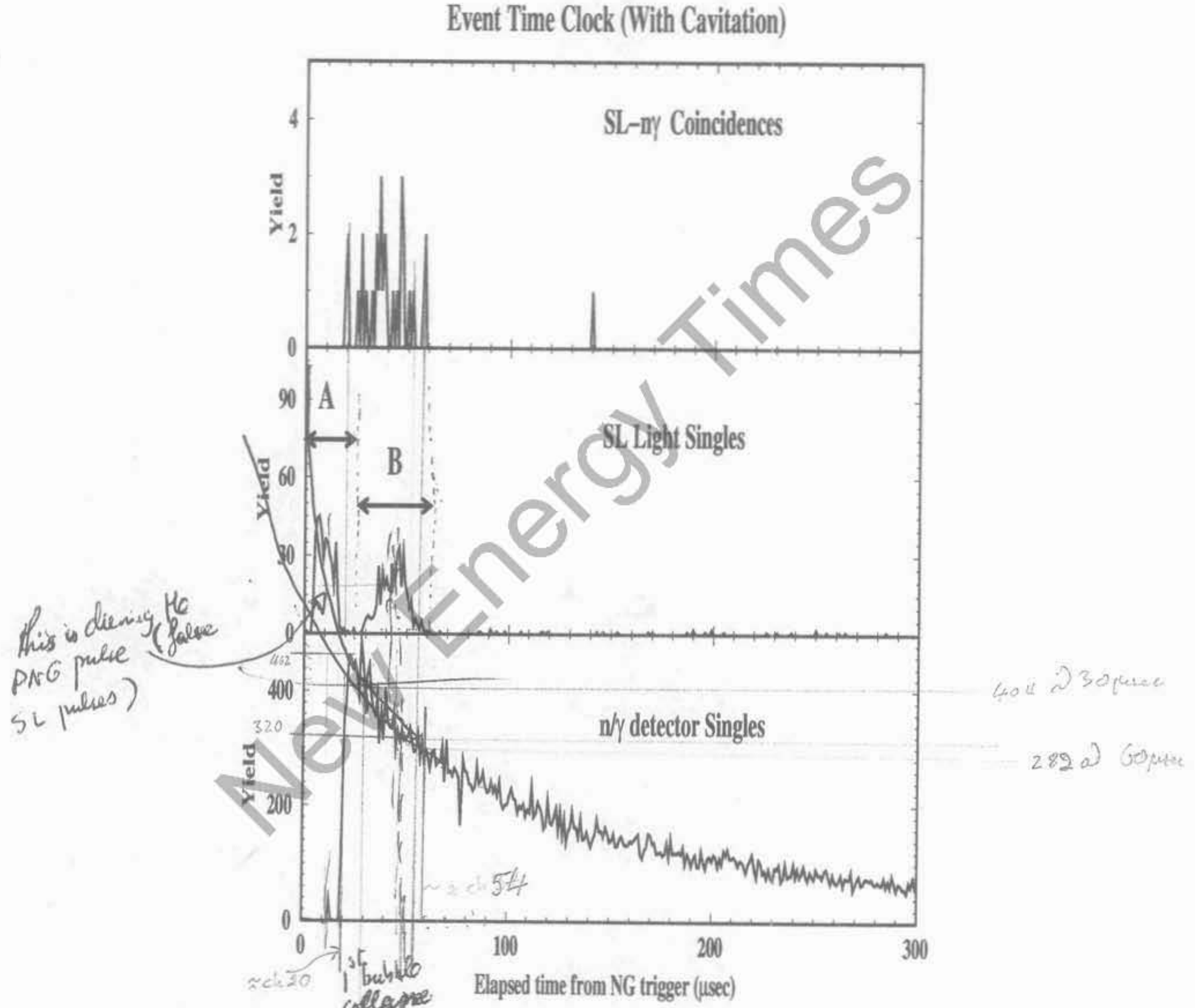


Figure 7: Event occurrence time relative to NG trigger time for n/γ singles, SL light emission singles, and the SL-n/γ coincidences recorded in run 109 expanded time scale

Average between ch 20 & ch 50 = (462+320)/2 = 391   391×8 = 3128

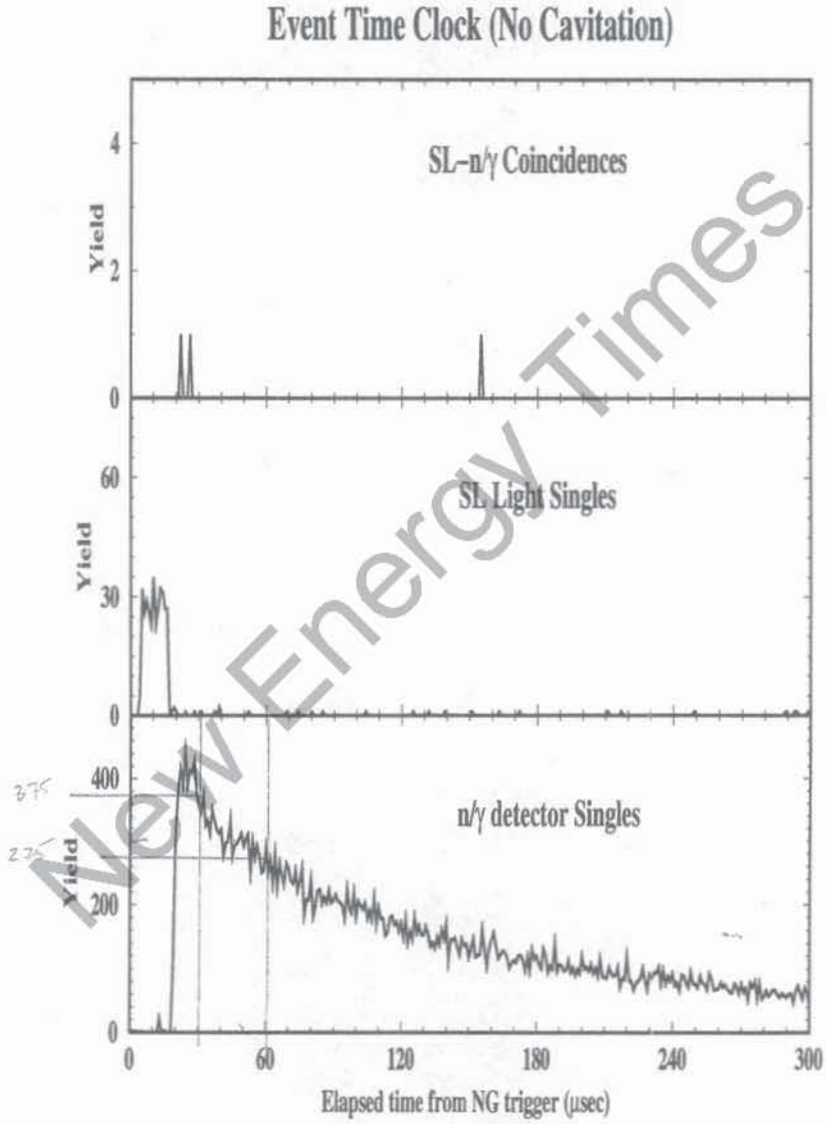


Figure 8: Event occurrence time relative to NG trigger time for n/γ singles, SL light emission singles, and the SL-n/γ coincidences recorded in run 111 expanded time scale