Coincidence Efficiency of Sodium Iodide Detectors for Positron Annihilation

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I Abstract

One possible diagnostic technique for characterizing inertial confinement fusion reactions involves tertiary neutron activation of ^{12}C via the $^{12}C(n,2n)^{11}C$ reaction. Because the cross section for this reaction is not well measured in the energy range of interest, a new measurement was recently made at Ohio University. Part of this experiment involves counting the positron annihilation 511 keV gamma rays from the ^{11}C decay using two sodium iodide detectors in coincidence. A new technique has been developed to measure the coincidence efficiency by detecting the positron prior to its annihilation, and requiring that the 1275 keV gamma ray also emitted by the ^{22}Na be in the full-peak in another NaI(Tl) detector. Measurements and simulation results for the absolute coincidence full-peak efficiencies are presented.

II Motivation

In an inertial confinement fusion reaction, a pellet of deuteron-triton fuel is heated by high-powered lasers. In the primary reaction, deuterons and tritons fuse, releasing 14.1 MeV neutrons. These neutrons can elastically scatter from other deuterium and tritium ions, transferring energy to the ions which then can undergo secondary fusion reactions to produce even higher energy (20-30 MeV) tertiary neutrons. These neutrons reveal information about the fusion reaction, such as the fraction of fuel burned and the symmetry of the compression.

In order to use tertiary neutrons as a diagnostic, one possible technique is $^{12}C(n, 2n)^{11}C$ activation, which has a threshold of about 20 MeV and so is not sensitive to primary neutrons. Using this requires knowing the $^{12}C(n, 2n)$ cross-section, which has not been well-measured.

An experiment was performed using the tandem Van de Graaff accelerator at Ohio university during the summers of 2012 and 2013. In this experiment, graphite and polyethylene targets were bombarded with neutrons, and the ^{11}C decays from $^{12}C(n, 2n)$ activation were counted using two NaI detectors in coincidence to detect the positron annihilation gamma rays.

To determine the absolute number of ^{11}C nuclei produced, and hence the $^{12}C(n, 2n)$ cross section, it is necessary to know the absolute efficiency of the detector system. The current experiment is a measurement of this efficiency.

III Theory

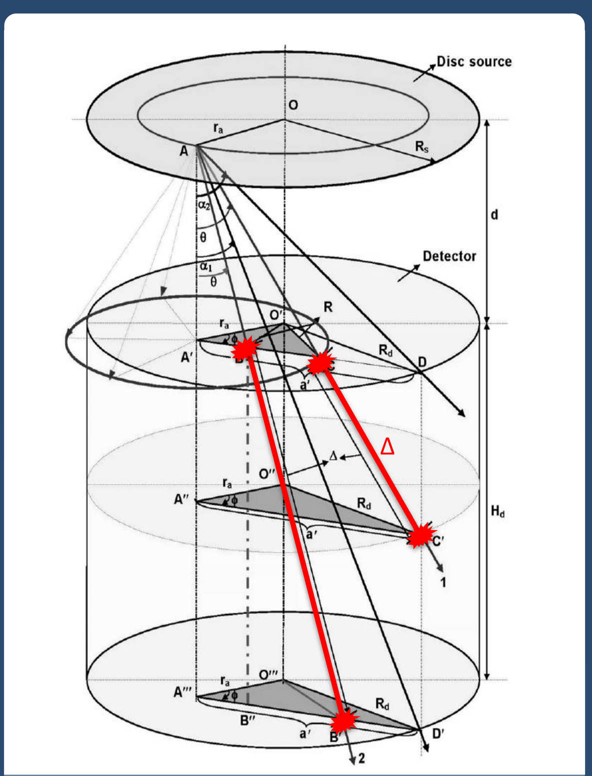
A gamma ray leaving the source in a straight line travels a distance Δ through the detector with attenuation coefficient μ. Using this distance, the probability that the gamma ray interacts in the detector is $1-e^{-\mu\Delta}$.

In this, we assume that all gammas that interact are detected giving us the absolute total efficiency. To determine the full-peak efficiency the peak-to-total ratio is needed.

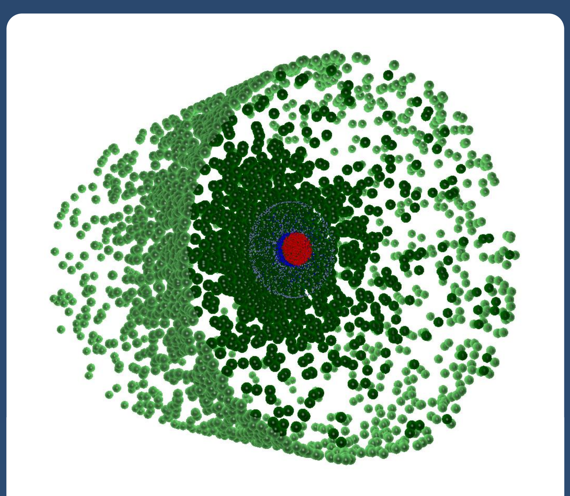
A. Integral Method
The efficiency can be calculated for the simple case of a point source along the detector axis.

$$\epsilon = \int_0^{\theta_1} \frac{\left(1-e^{-\frac{\mu H_d}{\cos\theta}}\right)\sin\theta d\theta}{1-\cos\theta_1} + \int_{\theta_1}^{\theta_2} \frac{\left(1-e^{-\mu\left(\frac{Rd}{\sin\theta}-\frac{d}{\cos\theta}\right)}\right)\sin\theta d\theta}{1-\cos\theta_1}$$

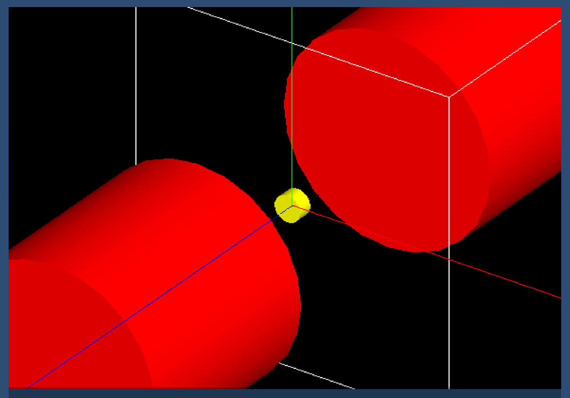
B. Monte-Carlo Method
In the Monte-Carlo calculation, gamma rays are randomly generated and allowed to travel along straight paths through the detector. In addition to the detector, the simulated rays may interact with the source and any surrounding material.

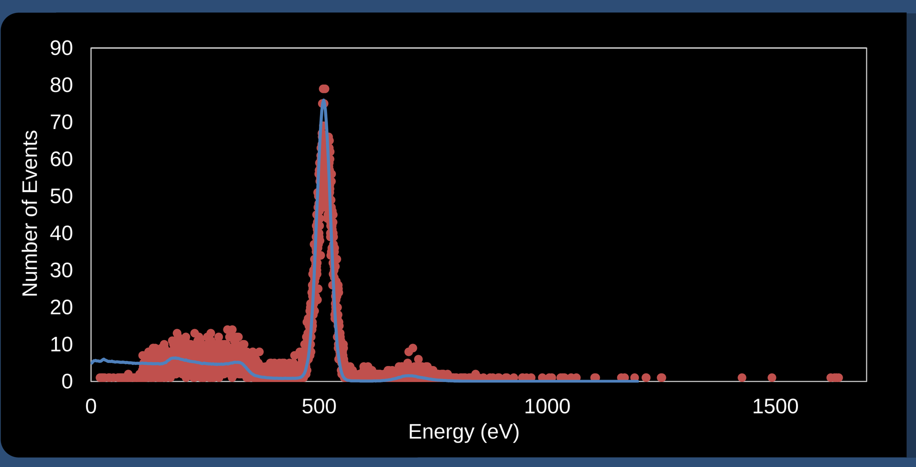


In the Monte-Carlo Method, gamma rays travel a distance Δ in the detector, giving a probability of interacting $1 - e^{\mu\Delta}$.


Monte-Carlo Method simulation of an extended source with single detector. This allows for a disk source to be placed off center, close to the target. Points mark the entrance and exit from source and detector materials.

C. Geant4 Method
Geant4 is a Monte-Carlo code developed at CERN to simulate the passage of particles through matter, allowing for the simulation of Compton scattering in the source and detector-to-detector.


Visualization of the Geant4 simulation of two NaI detectors with a positron source between them.



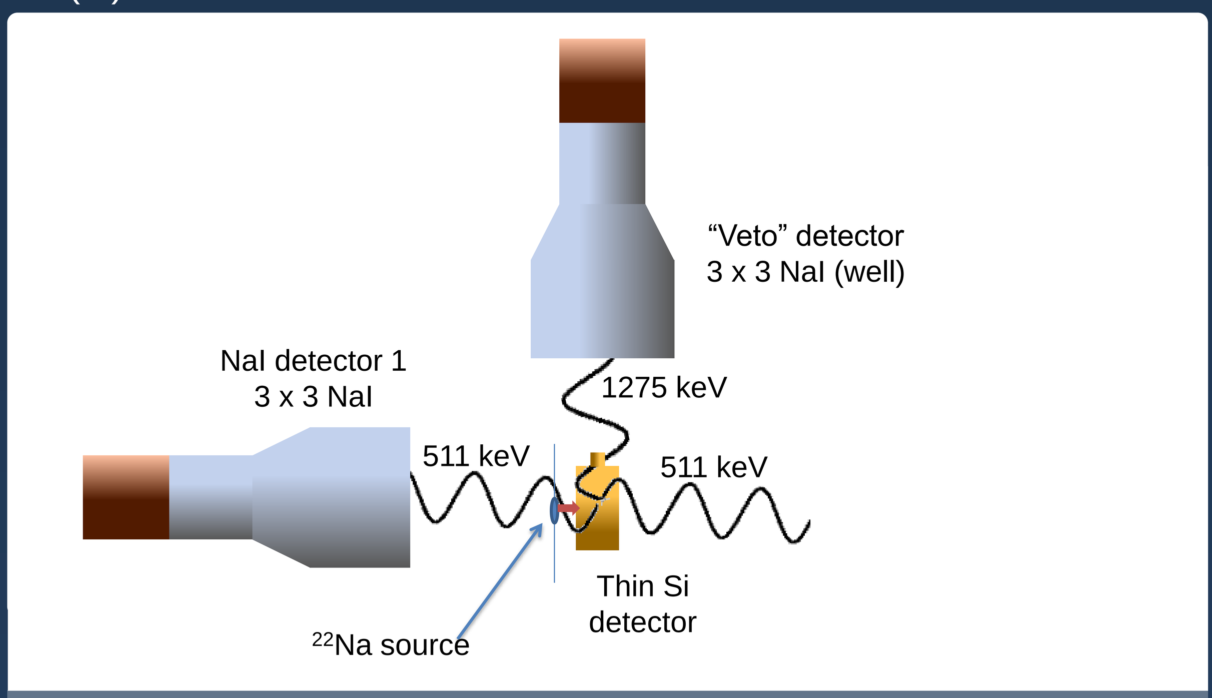
Comparison of the Geant4 simulated singles energy spectrum (blue curve) with the measured coincidence energy spectrum (red circles).

IV Absolute Singles Efficiency

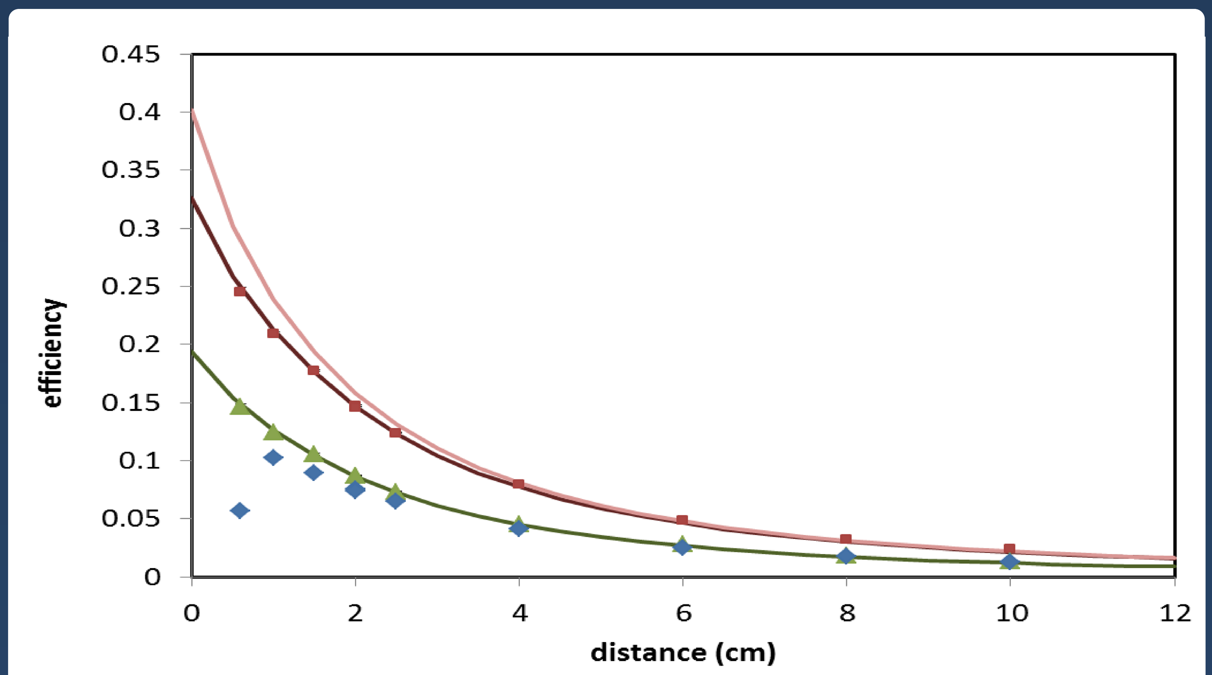
The absolute singles efficiency was measured using two NaI(Tl) detectors and a silicon beta detector. Approximately 1 μC of ^{22}Na was evaporated in a small indentation on a 0.7 mm thick polyethylene disk, adjacent to the silicon detector. Positrons detected in the silicon (N_β) annihilated, creating 511 keV gamma rays which were detected by the NaI(Tl) detector (N_γ). Absolute efficiency (ϵ) is

$$\epsilon = \frac{N_\gamma}{N_\beta}$$

Only events in which a 1275 keV gamma ray entered the "Veto" detector were counted, eliminating 511 keV + 1275 keV sum events from the NaI(Tl) detector.



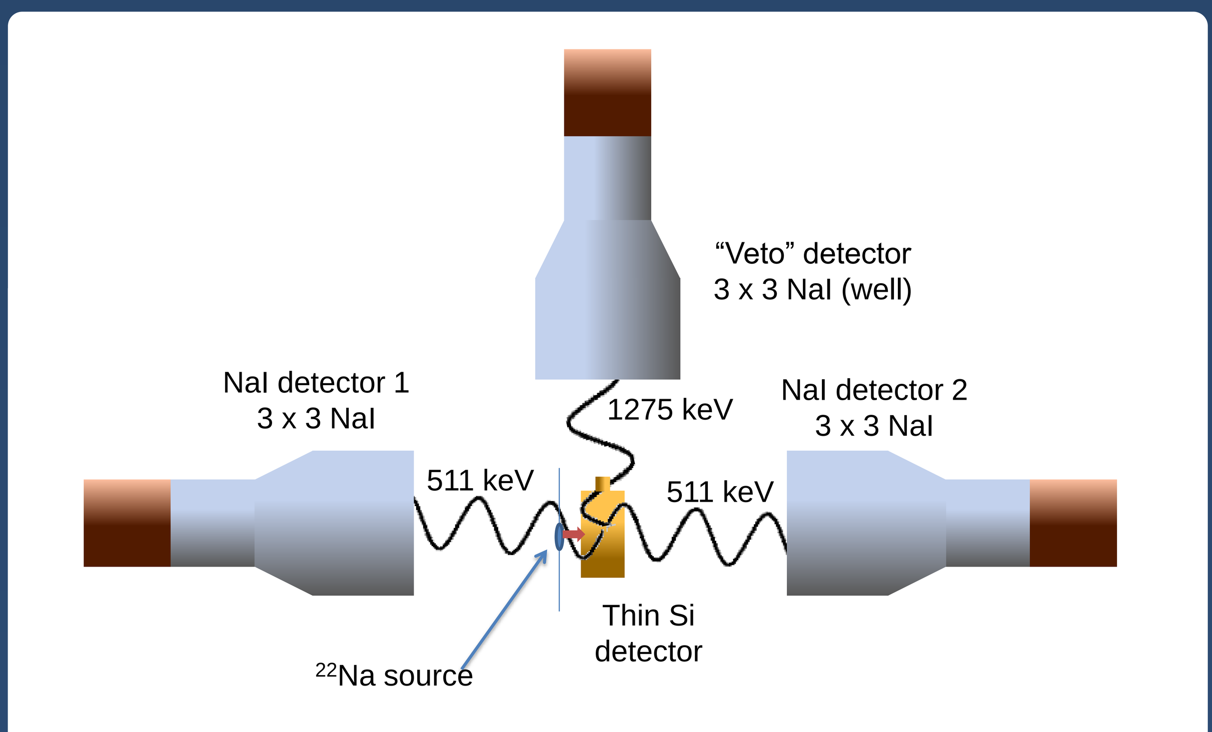
Initial set up for measuring absolute singles efficiency. The "Veto" detector eliminates 511 keV and 1275 keV gamma summing events.



Efficiencies as a function of distance from source to NaI detector. The absolute total (red) and full-peak (green) measured efficiency (symbols) and the Monte Carlo calculation for the extended silicon detector (dark curves) agree well. The Monte Carlo total efficiency for a point source (light red curve) overpredicts the efficiency, and the measured full-peak efficiencies that are not corrected for 1275 keV gamma rays (blue symbols) are below the prediction.

V Coincidence Efficiency

A third NaI(Tl) detector was added to the experiment to measure the absolute coincidence efficiency. Only events in which a 1275 keV gamma ray entered the "Veto" detector at the same time as two 511 keV gamma rays entered both detectors were counted.



Two, back-to-back, 511 keV gamma rays, produced by positron annihilation, are counted in coincidence. Events are only counted if a 1275 keV gamma enters the "Veto" detector.

Unlike the singles efficiency, the theory curve overpredicted measured values for absolute coincidence efficiency. It was hypothesized that the metal casing around the source and silicon detector caused gamma rays to Compton scatter, lowering the count of coincidence events.

VII Conclusion

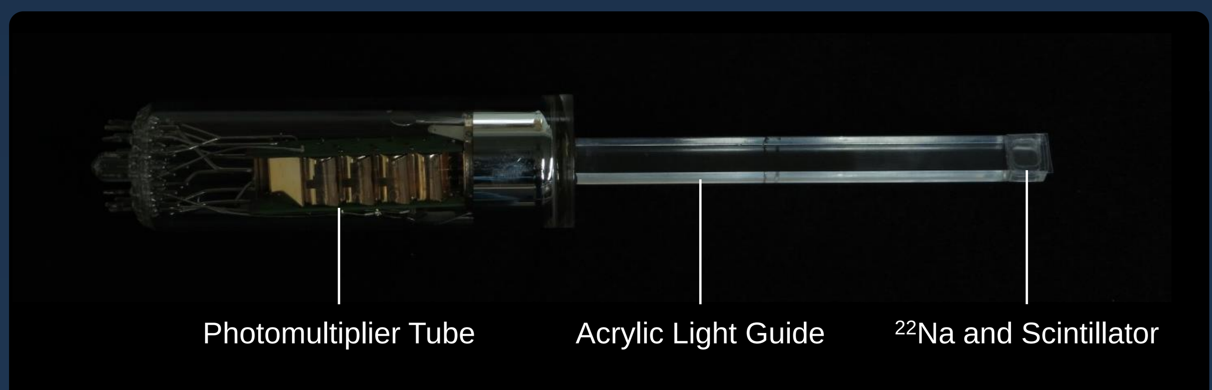
Using the plastic scintillator instead of the silicon detector reduced Compton scattering from material near the source, and improved the symmetry of the setup making it easier to simulate. The difference between measured and predicted coincidence efficiencies was reduced, but not to within error bars. It may be due to scattering from one NaI detector to the other. This effect would depend on the distance between source and detector, getting worse at small distances.

Once our Geant4 code is successfully benchmarked against these experimental efficiency measurements, it will be used to determine the efficiency for the geometry in the $^{12}C(n, 2n)^{11}C$ experiment, allowing the cross section to be determined to better than 5%.

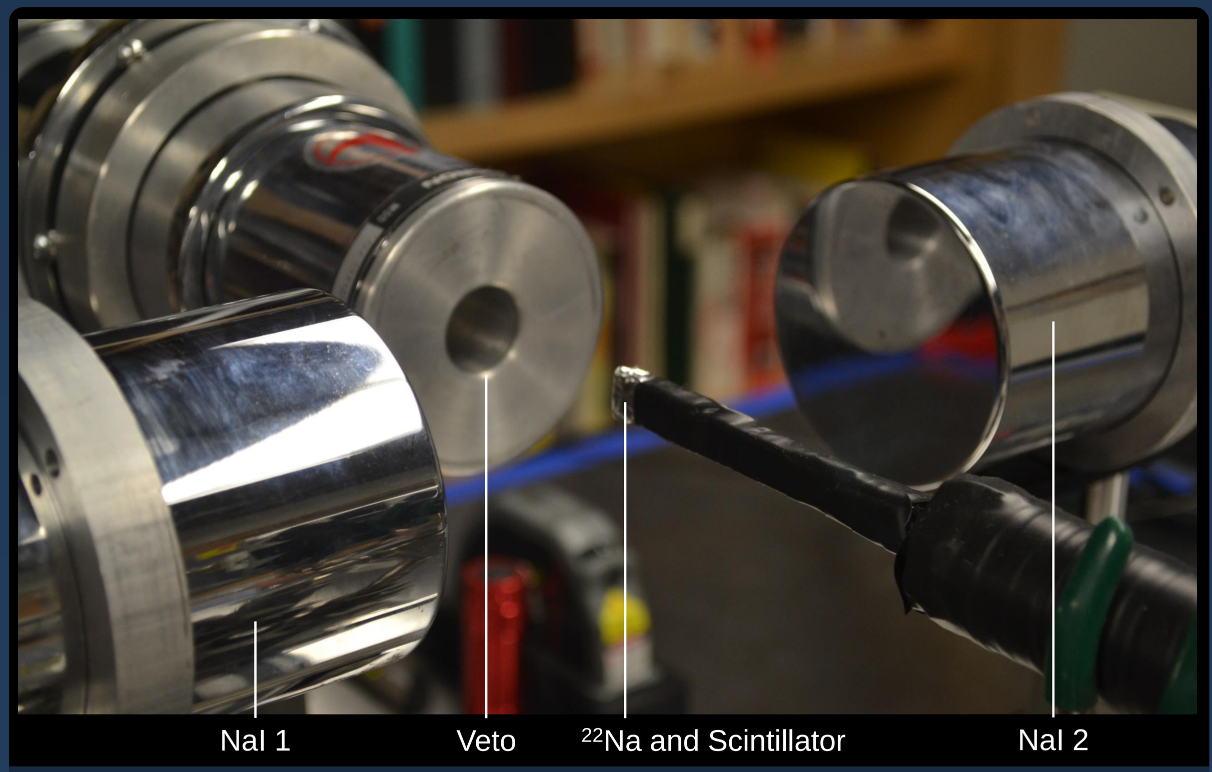
The plastic scintillator and ^{22}Na source will be replaced in future iterations of this experiment with calibrated ^{22}Na and ^{68}Ge sources supplied by NIST.

VI Symmetric Coincidence Efficiency

The metal casing around the source-detector was removed in this redesign to reduce attenuating materials as much as possible. The silicon beta detector was replaced by a scintillator beta detector.



The plastic scintillator and source assembly. ^{22}Na is deposited in two wells, on each side of a small plastic scintillator. Light pulses from the scintillator are detected by a phototube after travelling through an acrylic light guide.



Photograph of the symmetric coincidence efficiency experiment. The plastic scintillator detector reduces material near the source.

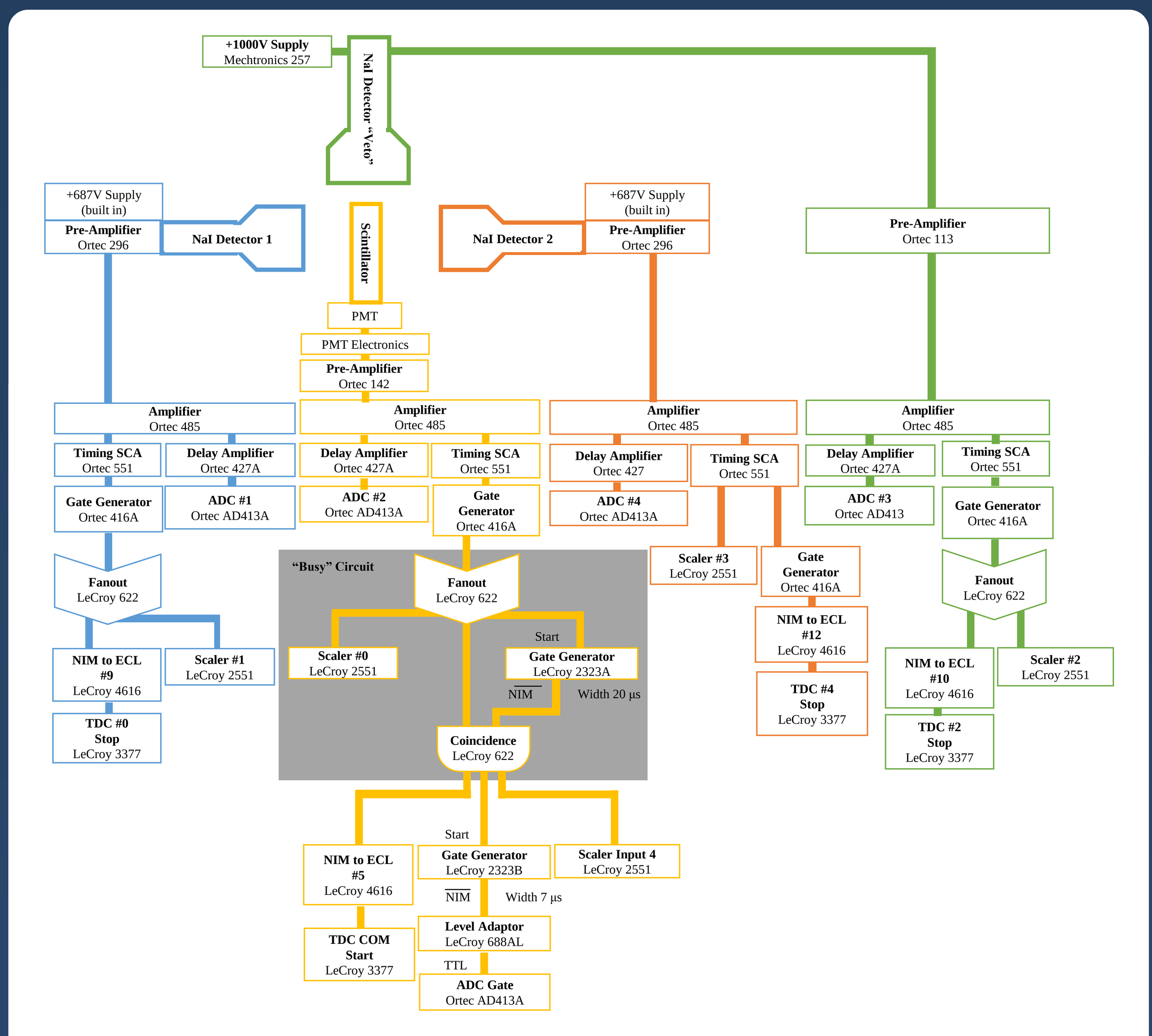
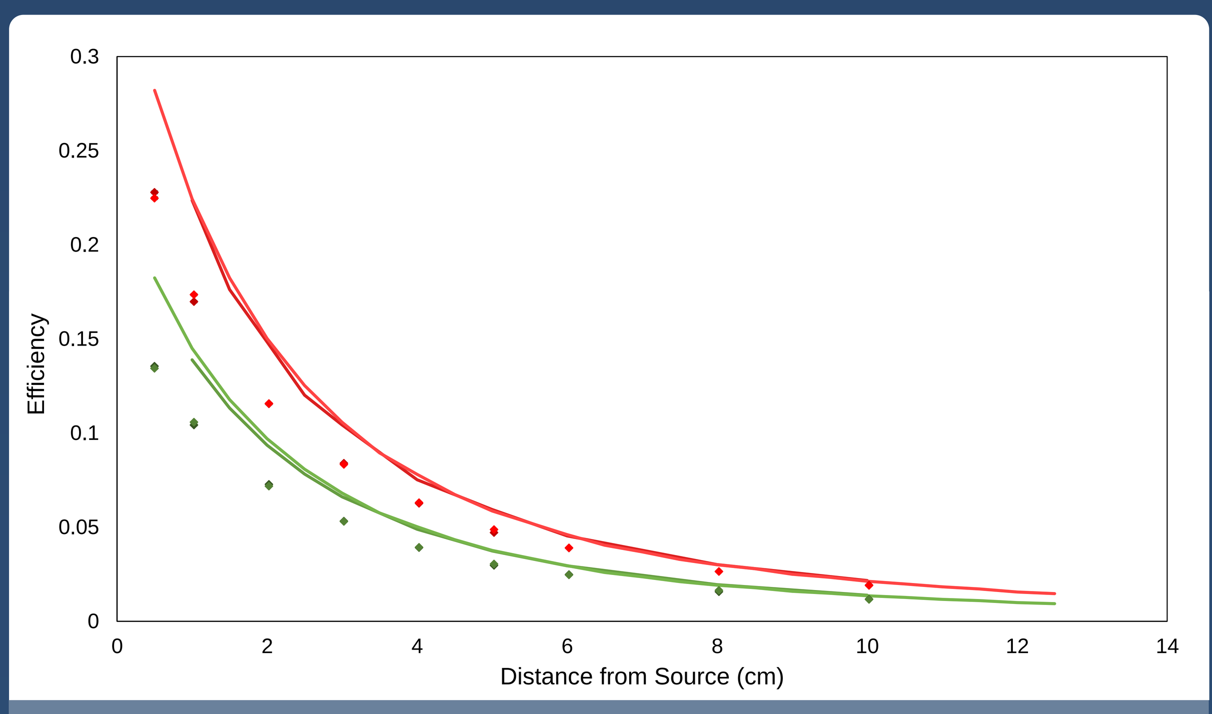
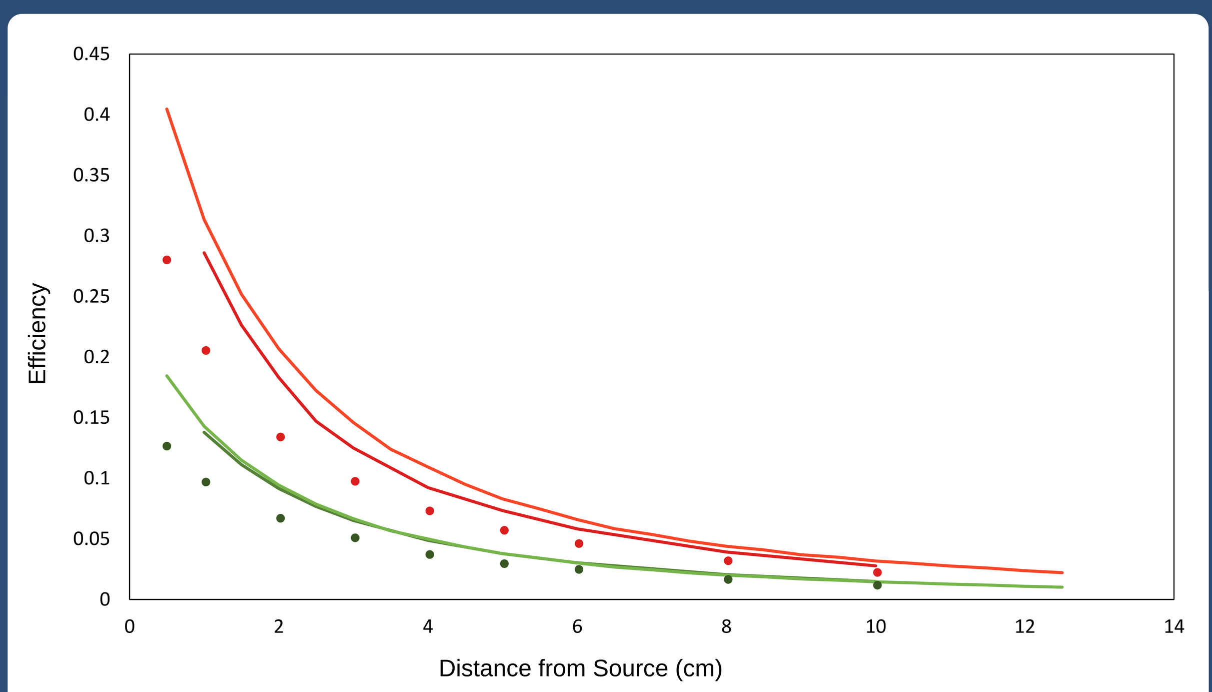


Diagram of the electronics used for the coincidence efficiency experiment. The CAMAC system digitized pulses from each detector and the time difference between the pulses.



Plot of singles efficiency for symmetric coincidence experiment. The absolute total (red) and full-peak (green) calculated efficiencies (curves) for Geant (darker) and the Monte-Carlo (lighter) overpredict the measured efficiencies (points) for both NaI 1 (darker) and NaI 2 (lighter) at all distances. This difference increases at smaller distances.



Plot of coincidence efficiency for the symmetric coincidence experiment. The absolute total (red) and full-peak (green) calculated efficiencies (curves) for Geant (darker) and the Monte-Carlo (lighter) overpredict the measured efficiencies (points) at all distances. The difference is greater at shorter distances.