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 sodium iodide detectors in coincidence. A new technique has been developed to measure this coincidence efficiency by detecting the positron prior to its annihilation, and vetoing events in which decay gamma rays other than the 511 keV gamma ray could enter the detectors.

II Motivation

In an inertial confinement fusion reaction a tiny pellet of nuclear fuel is heated by high-powered lasers. In the primary reaction, deuterium and tritium ions fuse releasing 14 MeV neutrons. These neutrons can elastically scatter from other deuterium and tritium ions transferring energy to the ions which then can undergo a secondary fusion reaction to produce even higher energy (20-30 MeV) tertiary neutrons. From these neutrons, information about the fusion reaction, such as the fraction of fuel burned and the symmetry of the compression, can be obtained.

In order to use tertiary neutrons as a diagnostic, one possible technique is to use $^{12}C(n, 2n)^{11}C$ activation, which has a threshold of about 20 MeV and so is not sensitive to primary neutrons. However, 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 ^{11}C decays from $^{12}C(n, 2n)$ activation were counted using NaI detectors in coincidence to detect the gamma rays from the positron annihilation.

In order to determine the absolute number of ^{11}C 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

In order to calculate singles efficiency for the NaI detectors, gamma rays leaving the source in straight lines travel a distance Δ through the detector. Using this distance, the probability that the gamma ray will interact in the detector can be calculated.

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.

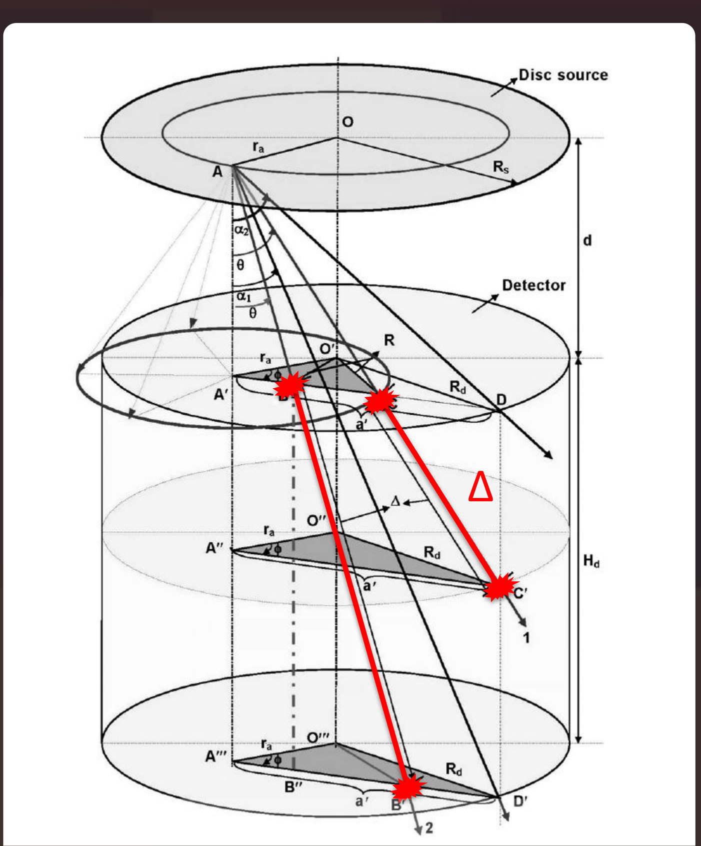
A. Integral Method

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

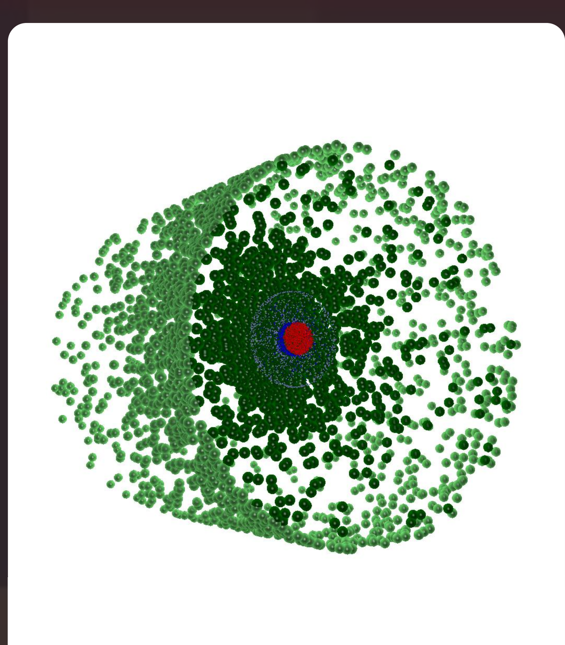
$$\varepsilon = \frac{\int_0^{\theta_1}\left(1-e^{-\frac{\mu H_d}{\cos\theta}}\right)\sin\theta\, d\theta}{1-\cos\theta_1} + \frac{\int_{\theta_1}^{\theta_2}\left(1-e^{-\mu\left(\frac{R_d}{\sin\theta}-\frac{d}{\cos\theta}\right)}\right)\sin\theta\, d\theta}{1-\cos\theta_1}$$

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.



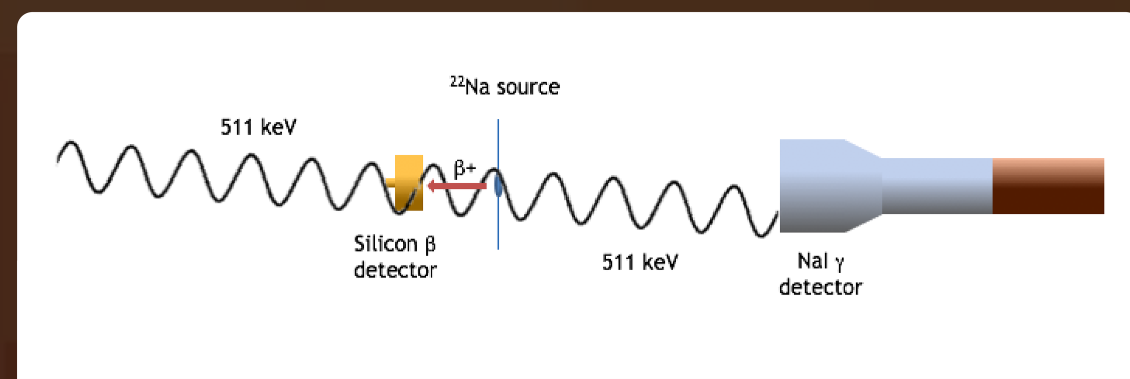
In the Monte-Carlo calculation, gamma rays travel a distance Δ in the detector, giving a probability of interacting $1 - e^{-\mu\Delta}$.



Simulation of extended source with single detector. The Monte-Carlo Method allows for a more realistic source to be placed off center, close to the target. Points mark the entrance and exit from source and detector materials.

IV Preliminary Singles Efficiency

The initial attempt at measuring the efficiency used only one NaI detector with a silicon β detector .

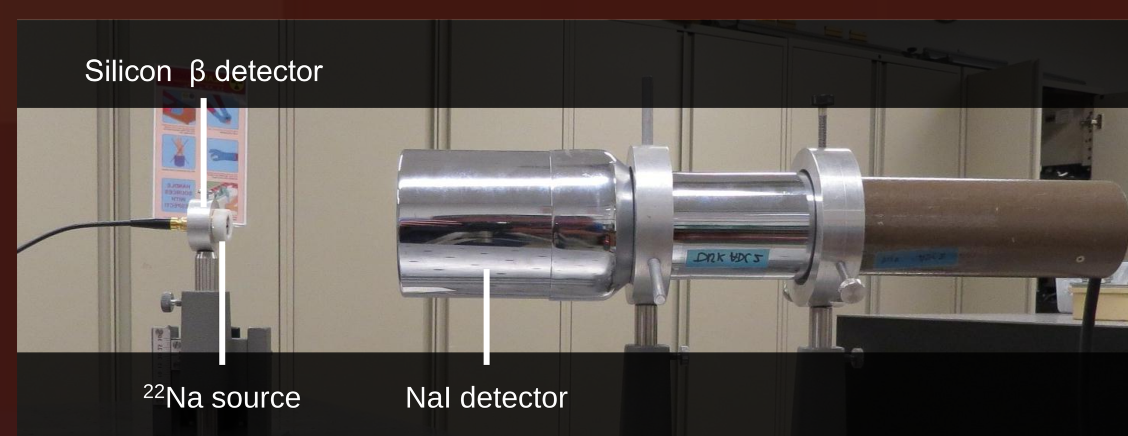


Positrons from ^{22}Na annihilate in the Si detector, emitting back-to-back 511 keV gamma rays in coincidence.

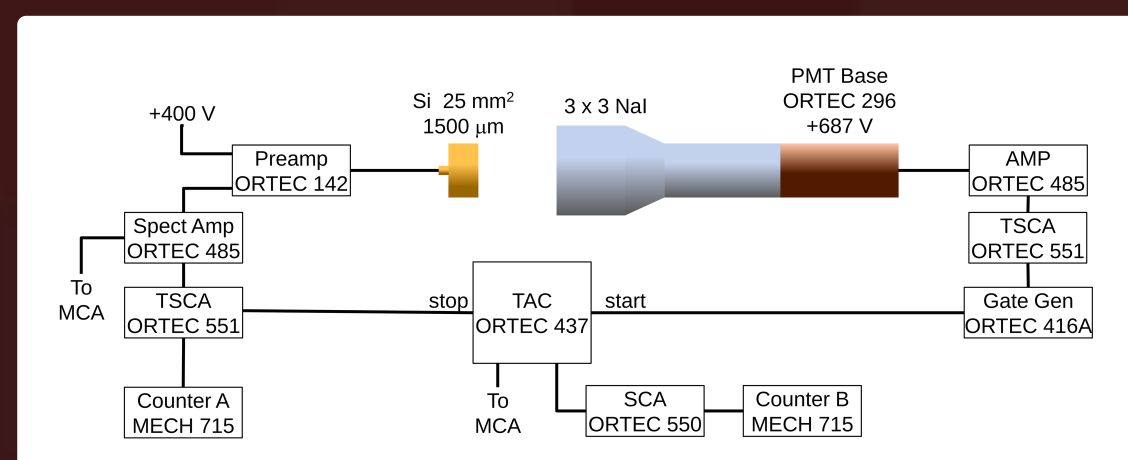
For this experiment, a thin ^{22}Na source emits positrons which then stop in a very thin silicon surface barrier detector. This detector is the source of 511 keV positron annihilation gamma rays that are emitted simultaneously in opposite directions. Because of its high efficiency, a pulse from the Si detector is produced for every pair of gamma rays emitted.

The absolute singles efficiency (ε) is the ratio of the number 511 keV gamma rays detected in coincidence with the silicon detector ($N_{Coincidence}$) to the number of beta particles counted in the silicon detector (N_β).

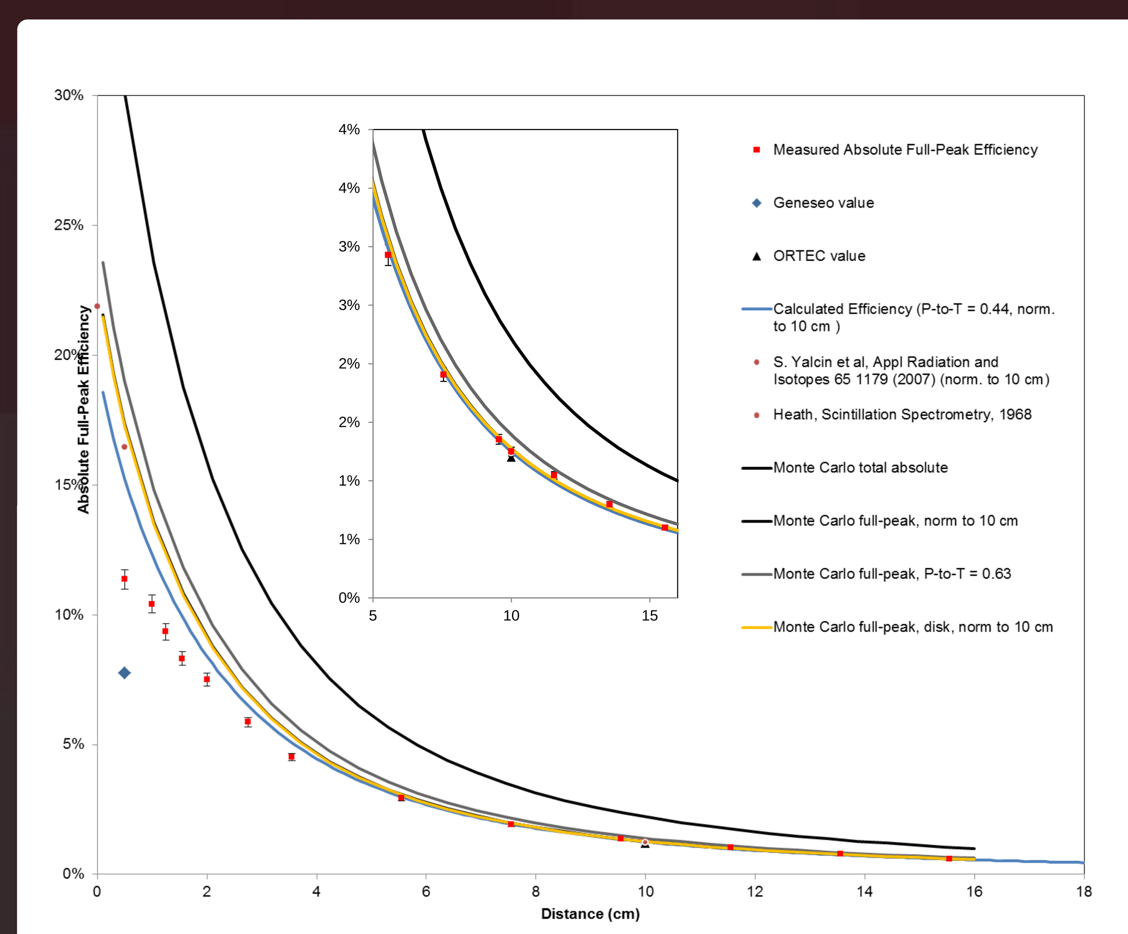
$$\epsilon = \frac{N_{coincidence}}{N_\beta}$$



Singles efficiency experiment, showing the NaI and Si detectors.



Electronic diagram of singles efficiency detector set up, which measures the time difference between the silicon detector and the NaI detector. The timing single channel analyzers are set to only produce pulses for 511 keV gamma rays, good beta events, and events within the coincidence window.

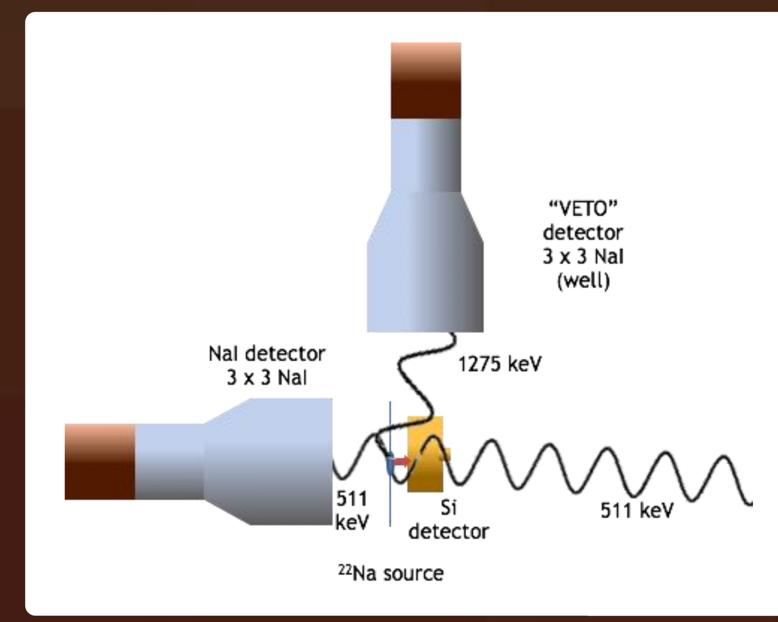


The calculated absolute full-peak efficiency agrees well with the measured values at large distances, but disagrees when the source is close to the detector.

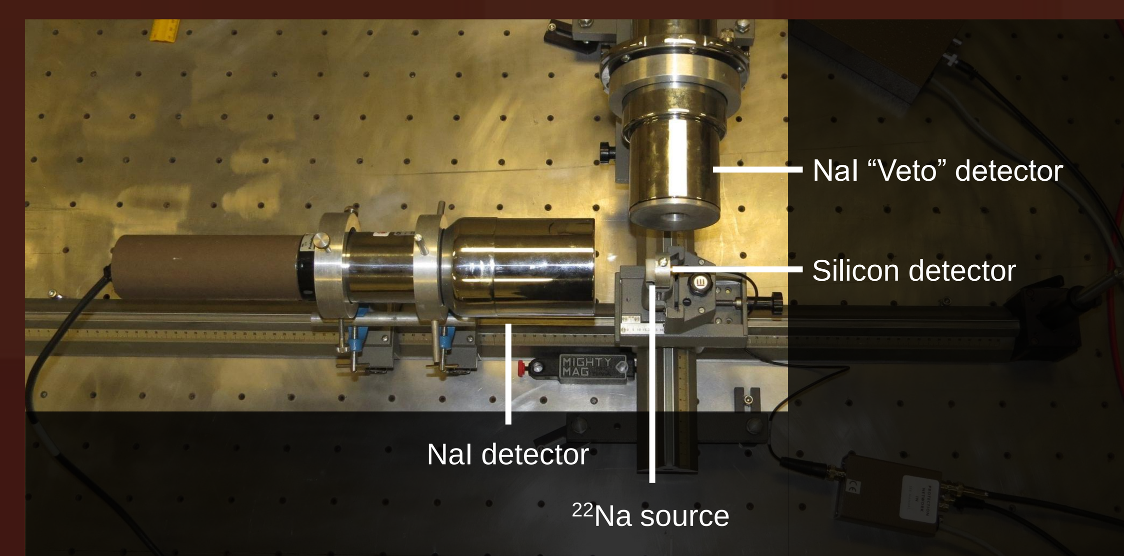
One possible explanation for the disagreement, which we investigated, is that 1275 keV gamma rays from the ^{22}Na are entering the NaI detector at the same time as the 511 keV annihilation gamma rays. This caused the pulse height to be outside of the 511 keV full-peak window.

V Singles Efficiency with Veto

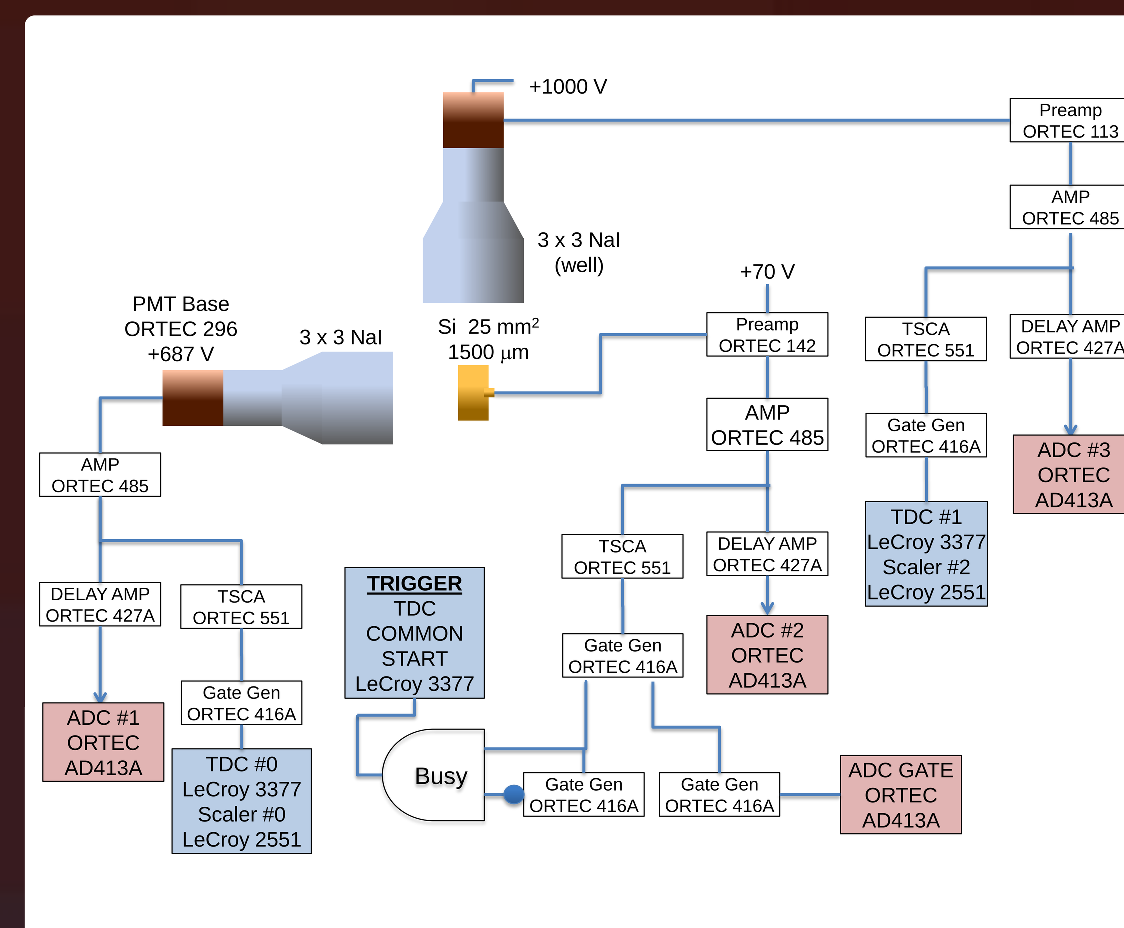
In order to correct for the loss of events due to the 1275 keV gamma rays, another detector was added to the circuit. Only events for which 1275 keV gamma rays enter this detector are counted to make certain no events are counted with a 1275 keV gamma ray entering the NaI detector at the same time as a 511 keV detector. When the "veto" detector triggers, the primary detector did not receive a 1275 keV gamma ray.



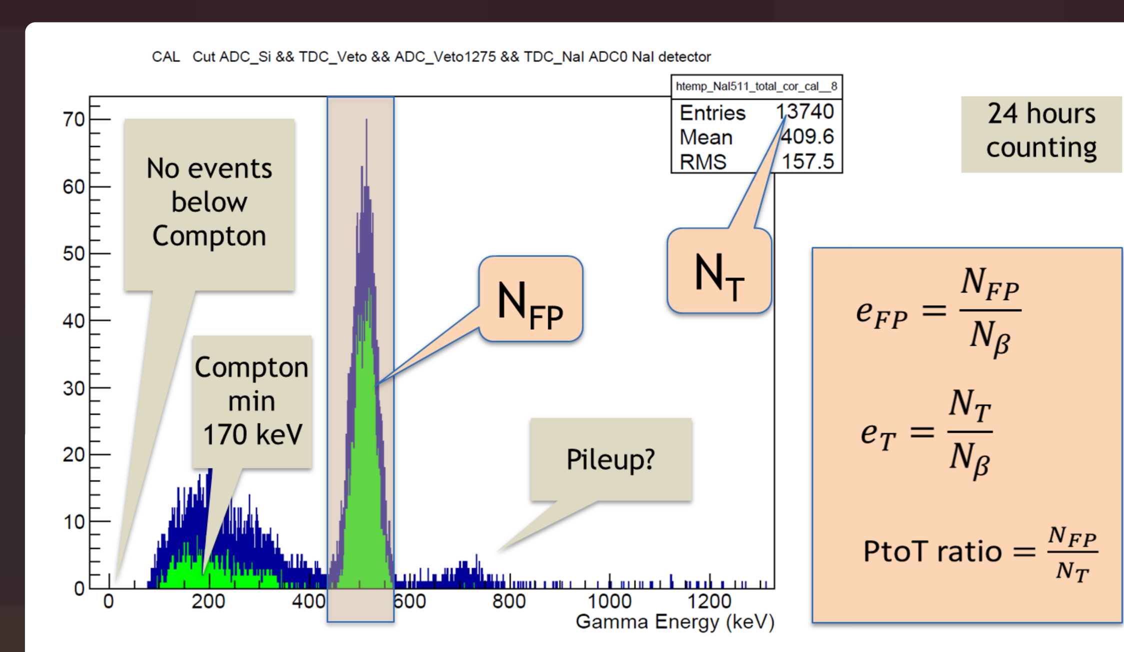
Emitted gamma rays during positron annihilation. The "veto" detector detects 1275 keV gamma rays, ensuring that it did not enter the NaI detector.



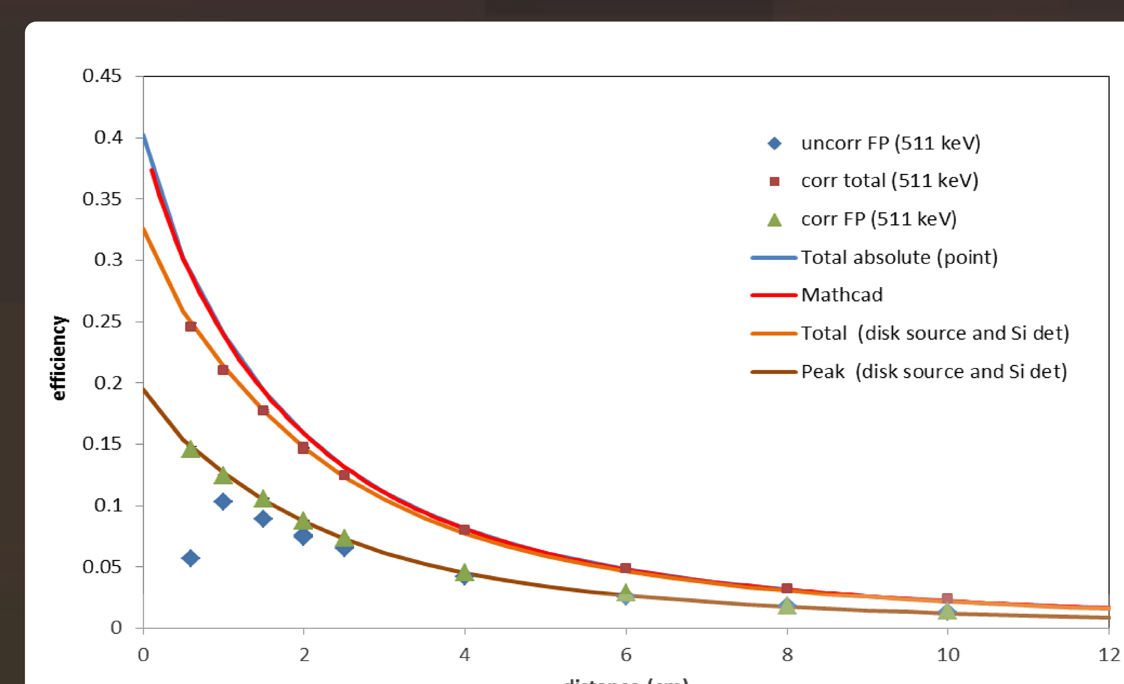
Singles efficiency experiment with "Veto" detector.



Electronic diagram of the singles efficiency detector circuit with "Veto" detector. Because of the complexity of the circuit, it was decided to use a CAMAC data acquisition system to record the pulse height from all three detectors as well as the time differences between the two NaI detectors and the silicon detector.



NaI ADC spectrum for coincidence events with a 1275 keV gamma ray detected by the "Veto" detector and a positron detected in the Si detector. The efficiency ratios are the number of gammas detected (N_{FP} and N_T) to the number of gammas emitted (N_β) excluding events where a 1275 keV gamma enters the NaI detector.



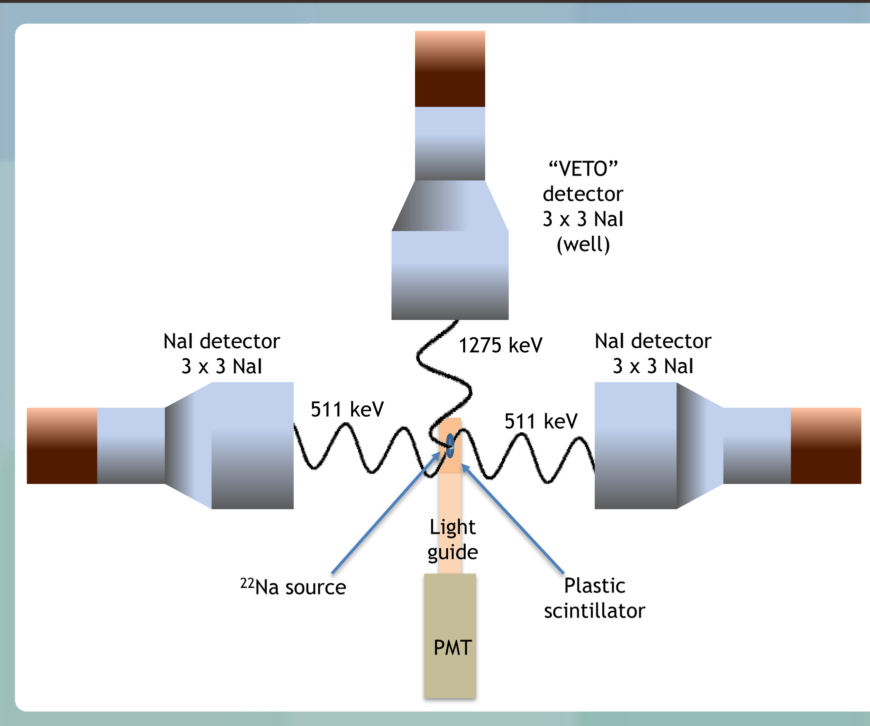
When bad events in which 1275 keV gamma rays enter the NaI detectors are eliminated, good agreement is obtained between the predicted efficiency from the Monte Carlo simulation and the measured efficiency.

VI Coincidence Efficiency

This proposed experiment will correct for 1275 keV gamma rays while measuring the absolute full peak efficiency of two NaI detectors in coincidence. The apparatus for this experiment is currently being built.

The Monte Carlo simulation code has been modified to calculate coincidence efficiencies. These will be compared with the measured values from this experiment, and the results used to validate and fine-tune the Monte Carlo simulation.

Finally, the Monte Carlo code will be used to predict the coincidence efficiency for the more complicated graphite and polyethylene targets used in the $^{12}C(n, 2n)$ measurement, in which the ^{11}C is distributed throughout a solid disc.



Two NaI detectors will be used to determine the coincidence efficiency. The silicon and veto detectors work the same way for the previous singles measurements.