Efficiency Calibration for Measuring the $^{12}C(n, 2n)^{11}C$ Cross Section

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I Abstract

One possible inertial confinement fusion diagnostic involves tertiary neutron activation via the $^{12}C(n, 2n)^{11}C$ reaction. A recent experiment to measure this cross section involved coincidence counting annihilation gamma rays produced by the positron decay of ^{11}C. This requires an accurate value for the full-peak coincidence efficiency of the NaI detector system. The GEANT 4 toolkit was used to develop a Monte-Carlo simulation of the detector system which can be used to calculate the required efficiencies. For validation, simulation predictions have been compared with the results of three experiments. In the first, full-peak coincidence positron annihilation efficiencies were measured for ^{22}Na positrons that annihilate in a small plastic scintillator. In the second and third, NIST-calibrated ^{22}Na and ^{68}Ge sources were placed between copper and graphite disks. A comparison of calculated with measured efficiencies, as well as $^{12}C(n, 2n)^{11}C$ cross sections, are presented.

II Motivation

In an inertial confinement fusion reaction, a pellet of deuterium-tritium 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 isotropy of the compression.

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

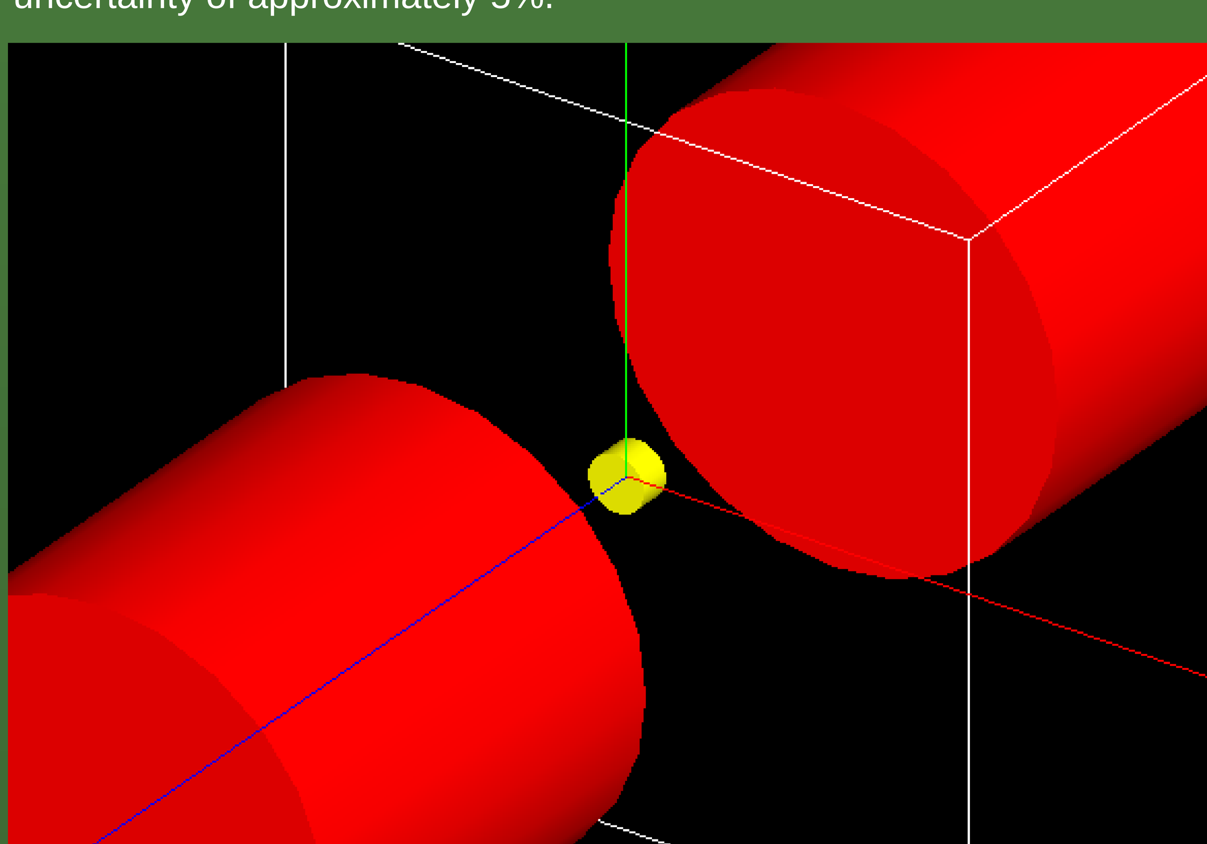
An experiment to measure the $^{12}C(n, 2n)$ cross section was performed using the tandem Van de Graaff accelerator at Ohio university during the summers of 2012 and 2013. In this experiment, graphite and polyethylene targets were bombarded with neutrons, and the ^{11}C decays from $^{12}C(n, 2n)$ activation were later 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 gamma counting detector system. The current experiment is a measurement of this efficiency.

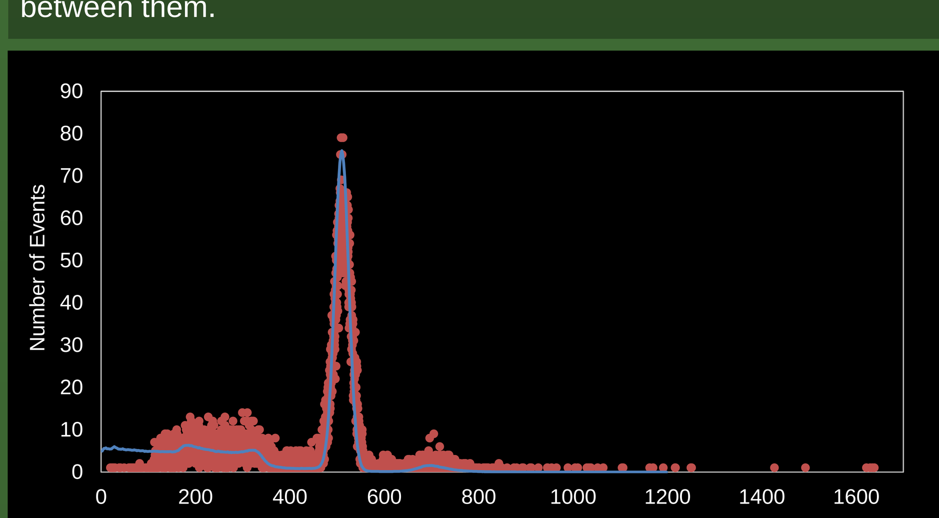
III Theory

GEANT is a Monte-Carlo toolkit developed at CERN to simulate the passage of particles through matter, allowing for calculations to include Compton scattering in the source and from detector-to-detector. In the simulation, realistic gamma rays are randomly generated and may interact with the source, the detectors, and any surrounding material.

GEANT calculations were compared to measurements of absolute full-peak coincidence efficiencies for the three experiments, which verified the accuracy of the simulation to within 5%. These efficiencies were used to determine the number of ^{11}C present in the polyethylene and graphite targets, and hence the $^{12}C(n, 2n)^{11}C$ cross section to an uncertainty of approximately 5%.



Visualization of the GEANT simulation for 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).

Previous measurements

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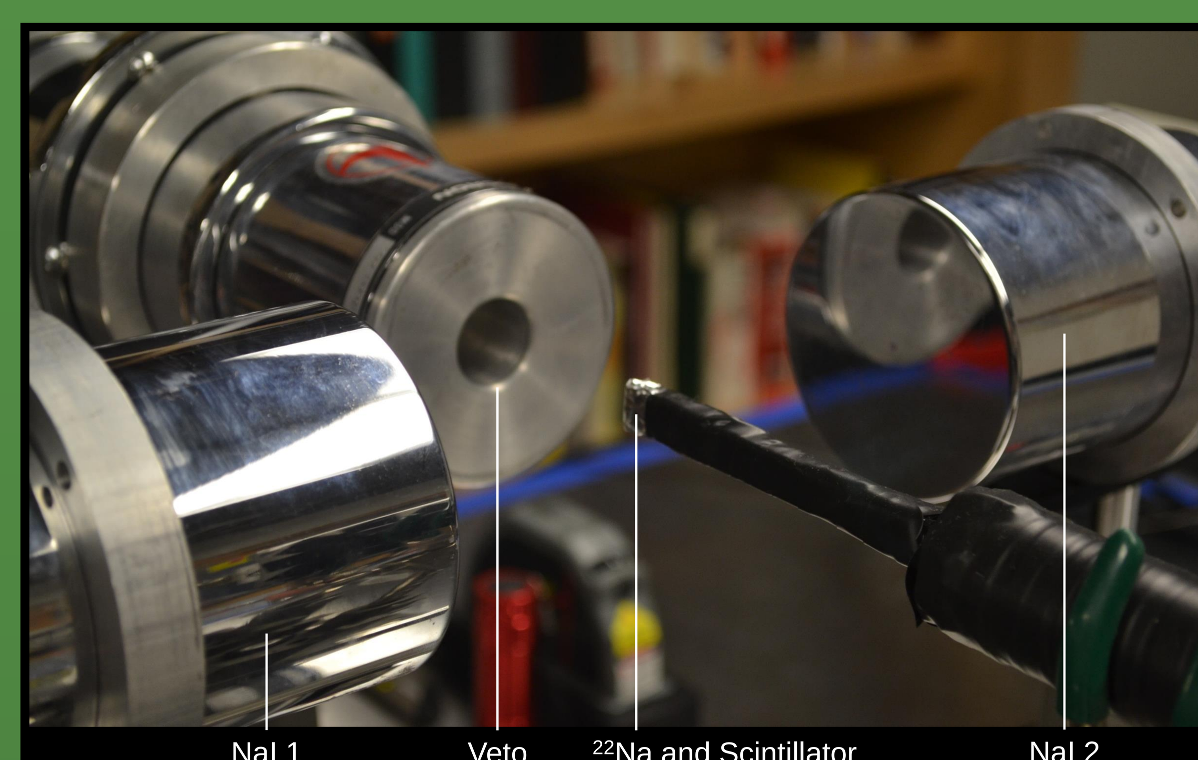
IV Experiment One

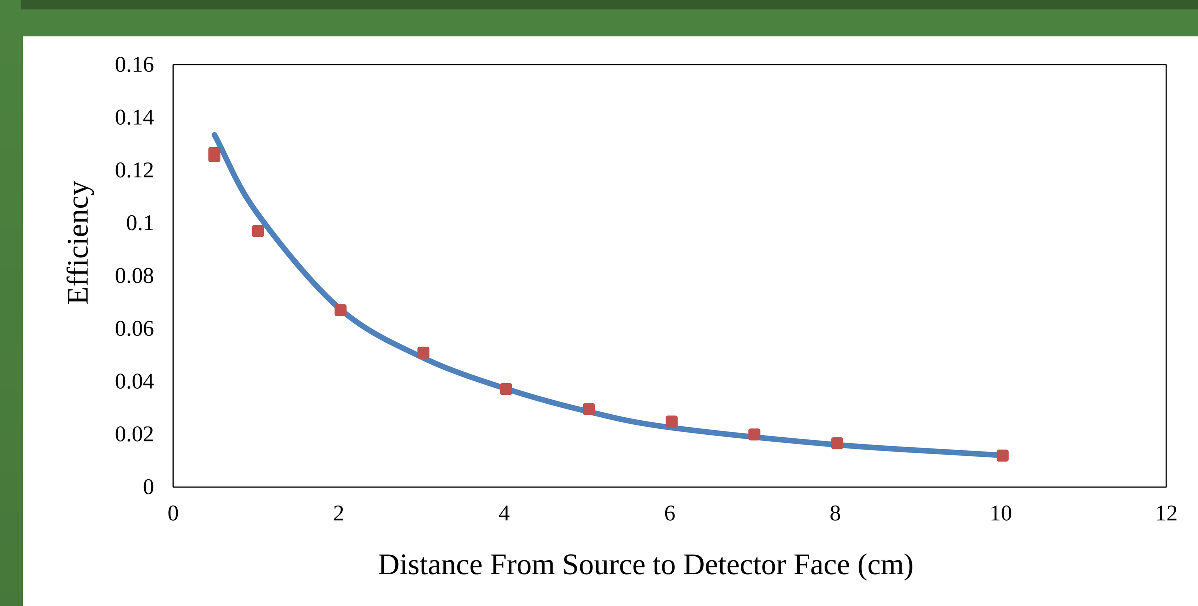
To measure the efficiency of the NaI detectors, 0.5 μC of ^{22}Na was evaporated onto a small plastic scintillator affixed to a photomultiplier tube (PMT) by an acrylic light guide. Positrons from ^{22}Na decay that stopped in the plastic scintillator produced an electronic pulse from the PMT. These positrons annihilated in the plastic producing two back-to-back 511 keV gamma rays. A pulse from the plastic scintillator signaled a positron annihilation event.

The gamma rays produced by the annihilation were detected by the two NaI detectors placed coaxially on either side equidistant from the ^{22}Na. A third NaI detector ("Veto") was placed at 90 degrees to the axis of the other detectors. This was used to detect the 1275 keV gamma rays released by the de-excitation of the daughter ^{22}Ne. If these gamma rays entered the other NaI detectors, they could sum with the 511 keV gamma rays and create an anomalous sum-peak reducing the measured full-peak efficiency. The efficiency was

$$\varepsilon(\text{coincidence}) = \frac{N(\text{NaI1} \cdot \text{NaI2} \cdot \text{plastic} \cdot \text{veto})}{N(\text{plastic}) \cdot \text{branching ratio}}$$



Photograph of Experiment 1. Positrons created by the decay of ^{22}Na were detected by the plastic scintillator. Back-to-back 511 keV annihilation gamma rays were detected in NaI 1 and NaI 2. The Veto detector ensured that 1275 keV gamma rays did not sum with 511 keV gamma rays.

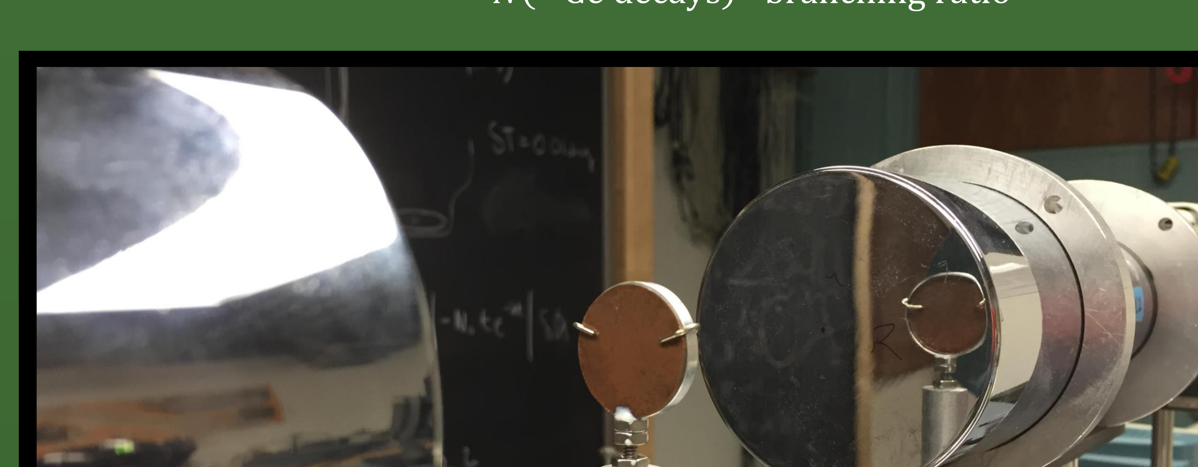


Full-peak coincidence efficiency as a function of the distance between the source and NaI detectors. GEANT calculations (blue curve) agreed with measurements (red squares) to better than 5% at close distances.

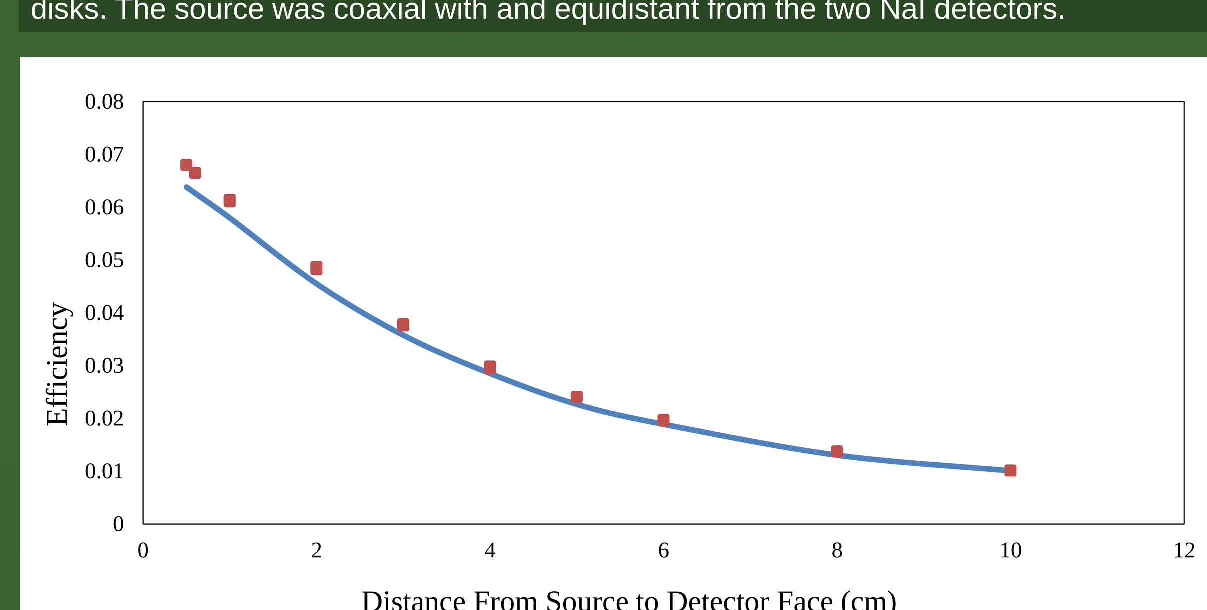
V Experiment Two

Using calibrated ^{22}Na and ^{68}Ge sources provided by NIST, two further tests of the GEANT calculation of efficiency were performed. In each test, the sources were placed in the same location as the ^{22}Na in Experiment 1. The scintillator detector was no longer needed since activity for both sources was known. The "Veto" detector was not needed for the ^{68}Ge measurement because the source did not produce significant de-excitation gamma rays. Each source was sandwiched between copper disks of appropriate thicknesses to stop all positrons.

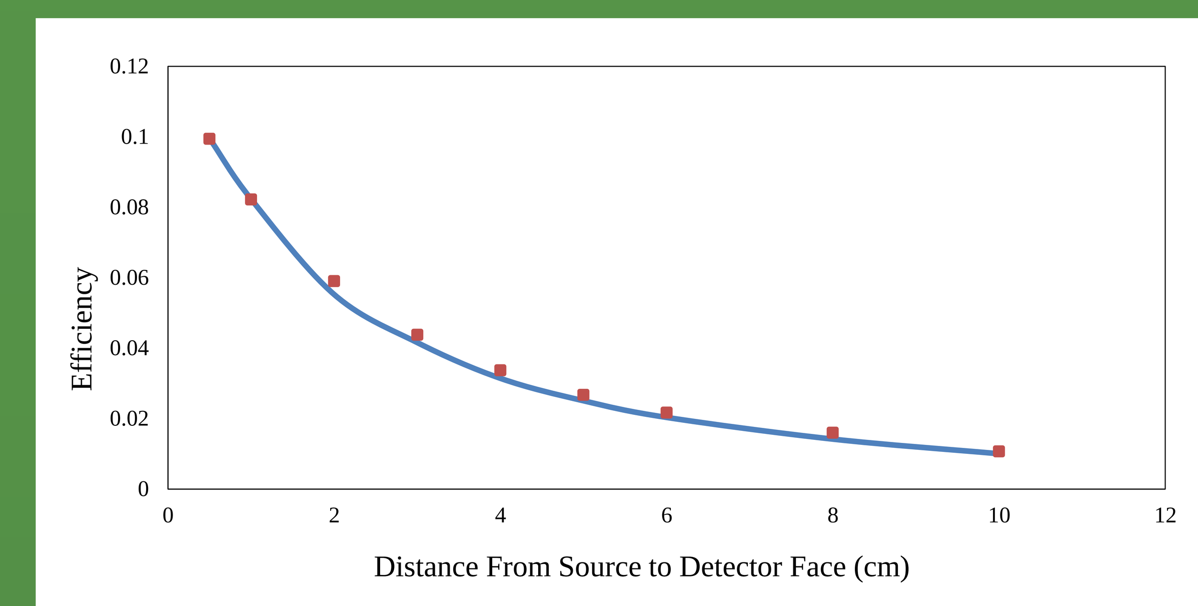
$$\varepsilon(\text{coincidence}) = \frac{N(\text{NaI1} \cdot \text{NaI2})/\text{live fraction}}{N(^{68}\text{Ge decays}) \cdot \text{branching ratio}}$$



Photograph of Experiment 2. The ^{68}Ge source was sandwiched between two copper disks. The source was coaxial with and equidistant from the two NaI detectors.



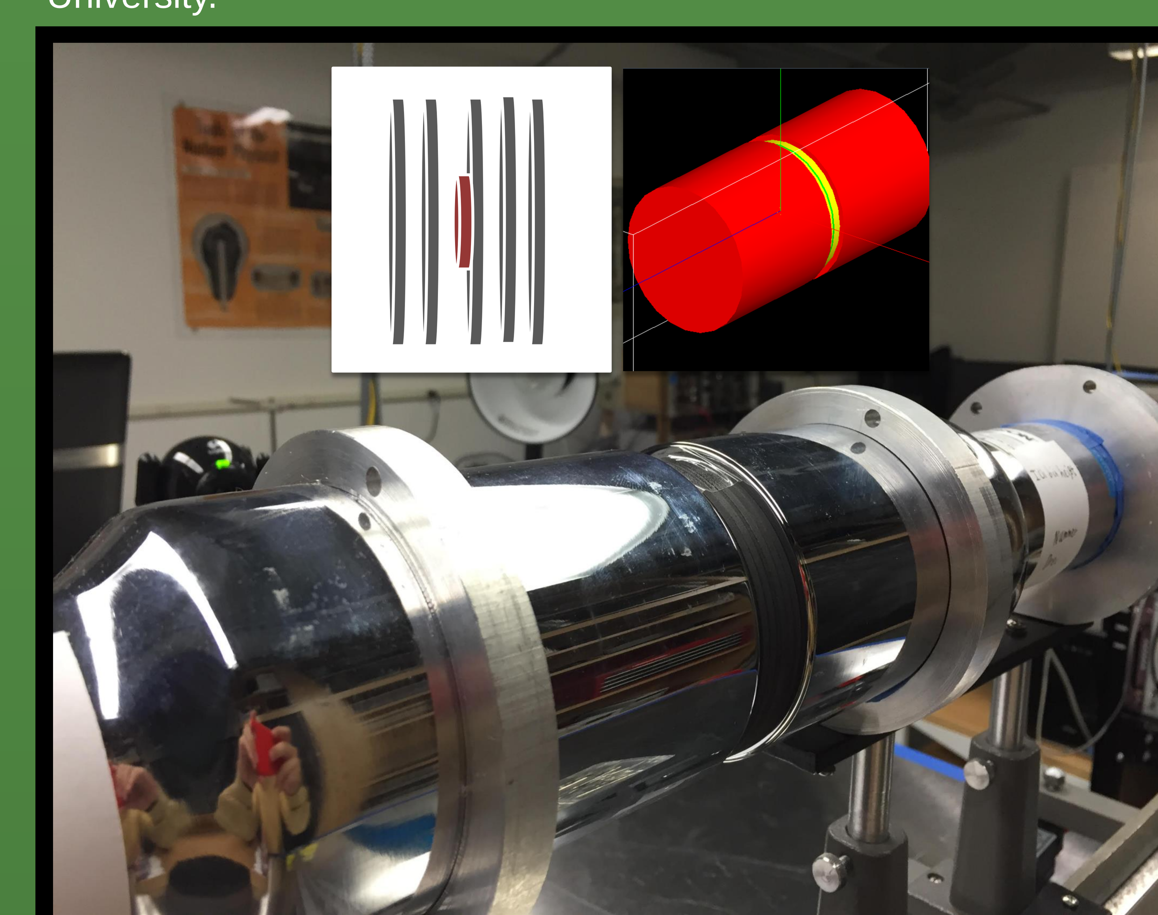
Full-peak coincidence efficiency as a function of the distance between the calibrated ^{22}Na source and NaI detectors. GEANT calculations (blue curve) agreed with measurements (red squares) to within about 7% at close distances.



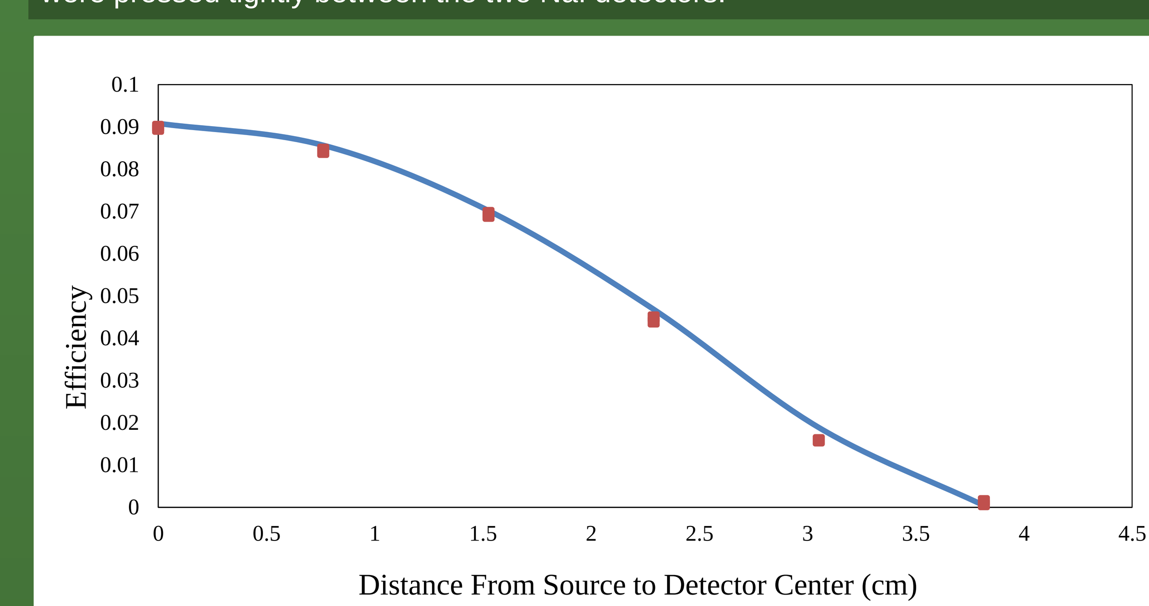
Full-peak coincidence efficiency as a function of the distance between the calibrated ^{68}Ge source and NaI detectors. GEANT calculations (blue curve) agreed with measurements (red squares) to within about 3% at close distances.

VI Experiment Three

In order to replicate the Ohio University measurement as closely as possible, the ^{68}Ge source was sandwiched between graphite disks to achieve the same thickness graphite as was used. This simulates a similar degree of Compton scattering as in the experiment at Ohio University.



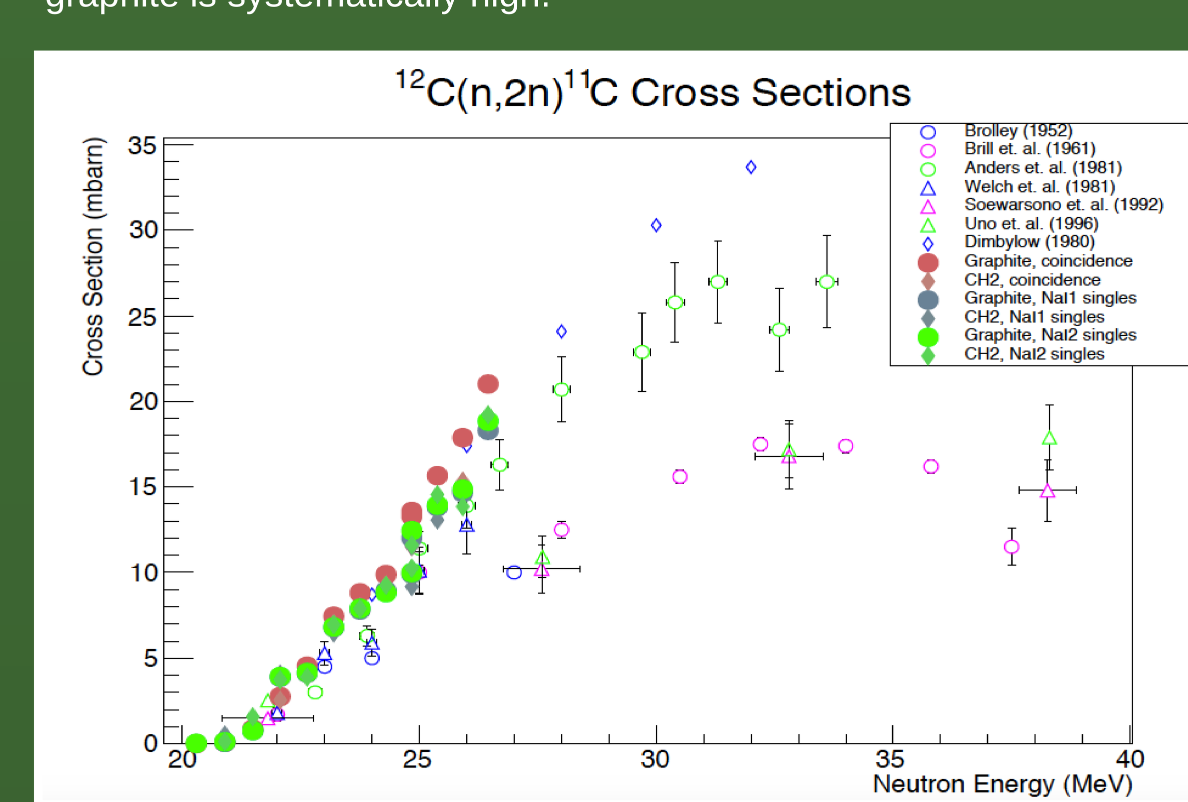
Photograph of Experiment 3. The ^{68}Ge source was sandwiched between graphite disks similar to those used in the Ohio University Experiment. The disks and source were pressed tightly between the two NaI detectors.



Full-peak coincidence efficiency as a function of the distance between the calibrated ^{68}Ge source and the center axis of the detectors. In this experiment, the distance for the source to each detector is held fixed at 7.62 mm and the source is moved radially across the face of the detectors. GEANT calculations (blue curve) agreed with measurements (red squares) to about 1% at close distances.

VII Results

The GEANT calculation, having been validated by the three different experiments, was used in the calculation of $^{12}C(n, 2n)^{11}C$ cross sections. Both the graphite and polyethylene targets were counted using each NaI detector in singles mode and together in coincidence, allowing six quasi-independent measurements of the cross section. The rms percent difference between the measured cross section using each of the six target and detector combinations and the average for all the methods, is about 7%. However, the coincidence efficiency in graphite is systematically high.



Preliminary cross sections for the $^{12}C(n,2n)^{11}C$ reaction (solid symbols) determined using the coincidence (green) and singles from detector 1 (red) and detector 2 (blue) with the graphite (circles) and polyethylene (diamonds) targets Previous measurements (open symbols) are from Brolley et al. (blue circles), Brill et al. (pink circles), Anders et al. (green circles), Welch et al. (blue triangles), Soewarsono et al. (pink triangles), Uno et al. (green triangles), and Dimbylow (blue diamonds).