Detection of coincident gamma rays produced by Na_{22} decay using scintillators and photomultiplier tubes

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To measure the correlation function of gamma rays produced from the decay process of Na_{22}, we use scintillator detectors, photomultiplier tubes, and a coincidence detector to count the number of coincident gamma rays detected for various angles of scintillator detector separation.

I. INTRODUCTION

Currently, Na_{22} is being researched as a source of cold positrons, or antimatter, for the production of muons for catalyzing the fusion of deuterium. In positron annihilation spectroscopy, Na_{22} is also frequently used as a positron source. [1]

We investigate the correlation function of the two gamma rays emitted via the beta decay of Na_22 by detecting the coincident gammas with a coincidence detector circuit and two scintillator detectors coupled with photomultiplier tubes.

II. THEORETICAL BACKGROUND

Beta decay was discovered by Ernest Rutherford in 1899 following Henri Becquerel's discovery of radioactivity in 1896 and Marie and Pierre Curie's subsequent observation. [2] Generally, β-decay is a radioactive decay involving a beta particle, a fast energetic electron or positron, which is emitted from the nucleus of an atom. [2]

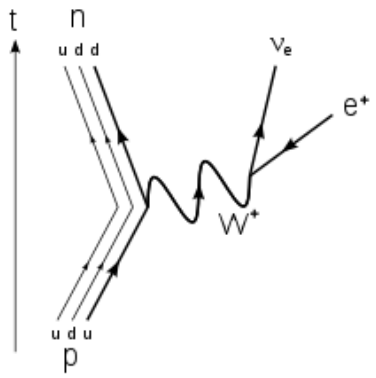

FIG. 1. Leading order Feynman diagram for β^+ decay of a proton into an electron neutrino, neutron, and positron with intermediate W^+ boson [2] [3]

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1. Sodium-22 Decay

With a half-life of 950.5±0.4 days, sodium-22 decays into stable neon-22, emitting a positron. [4] This positron interacts with electrons in the surrounding matter, causing both to annihilate at an annihilation radiation of 511 keV. Due to conservation of momentum, the annihilation produces two γ quanta which are emitted in opposite directions. [4] These gamma rays are related by a correlation function [5]

$$C(\theta) = \delta(\pi - \theta). \tag{1}$$

When Na_{22} decays, 0.06% becomes the ground state of neon, while the remaining portion results in an excited state of neon ($Ne_2$2), mainly via positron emission and partially (9.5%) by electron capture from the inner atomic shell. [4] In electron capture, a proton in the nucleus captures an electron within the atom, resulting in a neutron and releasing an electron neutrino. [2] The excited neon state, with a lifetime of 3.7 picoseconds, achieves the ground state, emitting a 1275 keV γ quantum is emitted. [4]

$Na_2$2 decays via β^+ decay, or positron emission. In this process, the weak interaction changes an atomic nucleus to a nucleus with an atomic number decreased by one and emitting a positron (e^+) and electron neutrino (v_e). [2]

A. Experimental Components

1. Scintillator Detector

A scintillator is a material that scintillates, emits absorbed energy as light, when incident radiation strikes its surface. [2]

2. Photomultiplier Tube (PMT

A photomultiplier tube (PMT) is a vacuum tube that uses incident photons to produce an electrical signal. In our experiment, the PMT is coupled with a scintillator detector. Thus, the PMT absorbs the emitted light from

the scintillator detector and re-emits the energy as a photon via the photoelectric effect. [6] [7] [8] [9] [10]

III. EXPERIMENTAL PROCEDURE

In order to detect coincident gamma rays produced from the collision and annihilation of the electron and positron emitted from the decay of Na_22, we used two equidistant scintillator detectors and two photomultiplier tubes (PMTs) aligned with our Na_22 source. After connecting each of these PMTs to preamplifiers, linear amplifiers, single channel analyzers, a time delay, coincidence detector, DAQ, and computer, we used a LabView program to count the number of detected coincident gamma rays within a specified time period.

We began by placing our 2019 Na_22 source in a holder located equidistant between a scintillator detector on a platform, and a second scintillator detector atop a platform that we were able to change the angle of relative to the source.

Within the center of each of these cylindrical scintillator detectors, we placed a PMT which were each connected to separate power sources via BNC cables. We set these power sources to 0.69 Volts.

Since our signal thus far would be too small to measure, we connected each PMT's cathode using BNC cables to a pre-amplifier set to a gain of 100 Volts.

We then connected the outputs of each of these to separate linear amplifiers using BNC cables. Next, we placed BNC tees on the unipolar outputs of these linear amplifiers, and connected one of the outputs of these to separate Single Channel Analyzers (SCAs).

For each linear amplifier, we placed a BNC tee on its unipolar output, and connected one of the tee's outputs to a single channel analyzer (SCA).

Single channel analyzers determine if a signal is within a specific energy range by emitting a square pulse if the signal is within that range, and emitting nothing if not. In order to set the SCAs to the correct energy ranges, we connected the other half of the BNC tee on the output of the linear amplifier to channel one of an oscilloscope, and the output of the corresponding SCA to the external trigger input of the oscilloscope.

We then viewed the signal from channel one while triggering from the external trigger. Essentially, when the SCA was detecting a signal within its specified energy range and outputting a square pulse, the trigger would produce that signal on the oscilloscope. We adjusted the range on the SCA so that it was only detecting the 0.511 MeV electron mass resonance pulse which we desired. We repeated this for the signal for the second PMT and corresponding SCA.

Once both SCAs were correctly set, we viewed the outputs of both on the oscilloscope to determine which signal we needed to delay. The delay was necessary since each signal did not have identical circuitry. These deviations were a result of various BNC cable lengths, PMT detection capability, and different manufacturers of the pre-amplifiers, linear amplifiers, and SCAs.

Once we determined which signal needed a delay, we connected this signal to a time delay, and connected the delay's output to the oscilloscope using a BNC cable. We then adjusted the delay until each of the signals coincided.

We then disconnected the signals from the oscilloscope and connected each to an input on a coincidence detector using the same BNC cables. Next we connected the output of this coincidence detector to an input on our DAQ using a BNC cable, and connected the DAQ to a computer via USB cable.

We then used our LabView program, which was set to record the number of counts from the coincidence detector for our specified time period of 10 seconds, to take recordings at angles from 180 degrees to 195 degrees in 1 degree increments. We changed this angle by manually displacing the variable PMT.

IV. DATA

Our collected data for coincident gammas as a function of scintillator detector separation angle is shown in figure 3. The area of our scintillator detector had a height of 4.2 ± 0.1 millimeters and a width of 1 ± 0.1 millimeter.

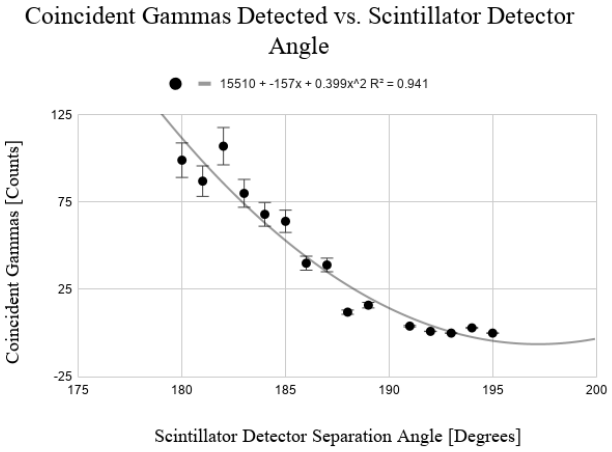

FIG. 2. Coincident gamma rays emitted from the positron and electron annihilation as a result of Na_22 decay as a function of scintillator and PMT detector separation angle

V. CONCLUSION

Our correlation function was found to be $C(\theta) = 15510 + -157\theta + 0.399\theta^2$ with an R^2 value of 0.941. We were able to confirm the principle of conservation of momentum within our bounds of uncertainty.

A considerate source of error in this experiment is a result of the detection area of the scintillator detector,

which we minimized by using a detector cover with a slit of known dimensions. The angle of our detector separation also limited the precision of our measurements since it was only marked to the nearest degree.

The most significant source of systematic error in our experiment was due to the interference on our radiation measurements from cosmic rays. [11]

We also would have systematic error from interference from dust particles or other unknown sources. [11] [12]

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