

Lab N-12: Detection of γ -rays via scintillation of NaI

Flip Tanedo*

*Institute for High-Energy Phenomenology (CIHEP)
Newman Laboratory for Elementary Particle Physics
Cornell University, Ithaca, NY 14853, USA*

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We measure the gamma ray detection efficiency of the scintillating material NaI(Tl). The spectrum of scintillation radiation from 0.51 MeV photons incident on NaI(Tl) is constructed using the coincidence method Hofstadter and McIntyre [1]. This allows one to discriminate between Compton and photoelectric interactions of the photon with the NaI(Tl) crystal and hence check the relative cross sections of the two processes. We find an efficiency of $\varepsilon = 0.315 \pm 0.004$ and a ratio of Compton to photoelectric scattering of $N_{\text{Comp}}/N_{\text{Photo}} = 2.426 \pm 0.018$.

Keywords: 510 Lab, NaI(Tl), scintillation

I. INTRODUCTION

Scintillators are high index of refraction materials that radiate photons when charged particles pass through them. Such materials can be used for gamma ray spectroscopy since typical interactions of high-energy photons with matter produce electrons and positrons. Scintillator-based spectroscopy plays a major role in detecting electromagnetic particles in modern experiments such as the Large Hadron Collider [2, 3] and the Fermi Gamma-ray Space Telescope [4].

Thallium-doped Sodium Iodide, NaI(Tl), is one of the first materials found to be transparent to its own characteristic scintillating radiation [5], allowing one to detect light emitted in the entire crystal volume rather than just the surface as in previous scintillators¹. Further, it is convenient in contemporary experiments for its low-cost and sharp spectral resolution [4]. An understanding of the efficiency of NaI(Tl) for detecting gamma rays through scintillation is thus important for current experiments.

In order to directly measure such efficiencies, however, one requires a controlled gamma ray source. A natural choice is a radioactive sample such as ²²Na which undergoes nuclear β -decay to produce a positron that comes to rest before annihilating with an electron into two photons traveling in opposite directions with energies equal to the electron mass, $m_e = 0.51$ MeV. Unfortunately, this decay also produces 1.30 MeV gamma radiation as ²²Na goes to the ground state of ²²Ne. In 1950 Hofstadter and McIntyre showed that one may use the coincident nature of the two 0.51 MeV photons to dramatically reduce this 1.30 MeV background by only considering NaI(Tl) scintillation signals with a coincident 0.51 MeV event measured in the antipodal direction [1]. We shall adopt this

method to determine the efficiency of NaI(Tl) crystal for measuring 0.51 MeV radiation.

High-energy photons (gamma rays) may interact with matter via three primary processes: electron-positron pair production, the photoelectric effect, and Compton scattering. Since we consider only 0.51 MeV photons, pair production is kinematically forbidden and the only interaction processes are the photoelectric effect and Compton scattering. The former will produce electrons of energy $m_e c^2 - \phi$ where ϕ is the NaI(Tl) work function. The latter produces electrons with a range of energies depending on the scattering angle. Since the frequency of scintillation radiation produced by these electrons is proportional to the electrons' energy, we expect the scintillation spectrum to have a sharp peak at the photoelectric frequency and a broad feature representing the Compton events.

II. EXPERIMENTAL PROCEDURE

A schematic of the experimental set up is shown in Figure 1. NaI(Tl) crystals are attached to the photocathodes of two photomultiplier tubes (PMT) A and B. The larger crystal, A, has a diameter of 4.45 cm and a depth of 3.81 cm and is placed 45 mm from the ²²Na source. The smaller crystal, B, is placed 100 mm from the source and is used to identify coincident 0.51 MeV photon pairs. Since crystal A has a larger area and is closer to the source, we assume that any 0.51 MeV paired photon entering B must necessarily have a partner that enters A.

The signals are put through differential discriminators that output a standard pulse for inputs within a preset frequency window. The A window is left unrestricted while the B window is set narrowly around the frequency of photoelectric effect scintillation for 0.51 MeV pho-

*Electronic address: pt267@cornell.edu; URL: <http://www.lepp.cornell.edu/~pt267/>

¹ The amount of Thallium doping is less than 0.5% by mass. Thus, at the precision of our experiment we are justified in neglecting the NaI(Tl) Thallium content in the following analysis.

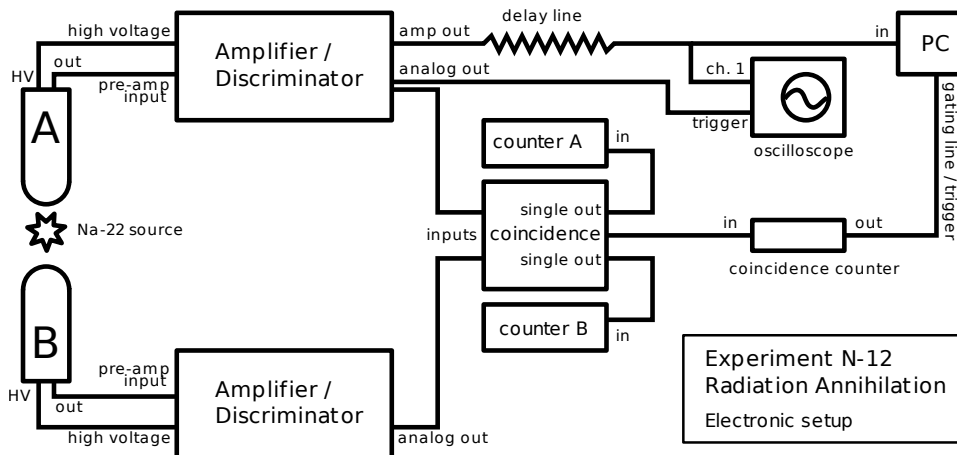


FIG. 1: Experimental set up, adapted from lab manual. PMT A

tons². These are both sent to a coincidence unit which outputs a standard pulse when the input signals are coincident up to a time delay. Counters attached to the coincident unit are used to measure the number of coincidences and the number of input pulses from B over the course of a data-taking run. This latter quantity is the total number of 0.51 MeV photon pairs in our data set that passed through both A and B. The output of the coincidence unit is used as a trigger for the data acquisition system ('PC').

The signal input for the data acquisition system is the amplified output of PMT A. This is passed through a delay line to account for the time delay of the coincidence unit and ensure that the trigger and signal arrive at the same time. Since the set up only triggers on 0.51 MeV photons, this signal represents the spectrum of scintillation radiation of 0.51 MeV photons in NaI(Tl).

The photomultipliers and scintillators are covered in a thin layer of tin to prevent signals from ambient light. The set up is surrounded by lead to reduce radiation exposure and cosmic ray backgrounds. A 20 minute data run with no source confirmed that the cosmic ray background is negligible.

The dominant source of background comes from 'accidental' 1.30 MeV photons detected by PMT A coincident with a 0.51 MeV photon triggered in B. This background is measured by taking data with PMT B set at a 40° angle relative to its original position, removing the collinear 0.51 MeV photon pair signal but preserving the isotropic 1.30 MeV photon background. A much smaller source of background comes from two accidental 1.30 MeV photons with one of them faking a 0.51 MeV photon in the trigger by undergoing Compton scattering to produce a \sim 0.51 MeV photon that then undergoes the photoelectric effect. For this analysis we ignore this contribution since

TABLE I: Data showing the total number of 0.51 MeV photons, the total number of coincident photons, the number of Compton scatters, and the number of Photoelectric scatters.

Run	Total	Coinc. ^a	Compton	Photo
Main	274,431	92,516	61,879	25,496
BG	284,726	5,966	4,673	817

^aThe total number of coincidences are measured by counting the coincident unit output signals, while the number of Compton and Photoelectric scatters are measured by the data acquisition system. The sum of the scattering counts do not match the total number of coincidences due to slightly different thresholds for the data system.

it is suppressed relative the the dominant background by a factor of α_{EM} .

III. RESULTS AND DISCUSSION

The results of data taking a 20 minute run and a 20 minute 'background' run are presented in Table I. The measured spectra are shown in Figure 2. For N measured coincidences in the main configuration, N_{bg} coincidences in the background configuration, and T total 0.51 MeV photon pairs, the efficiency for gamma ray detection is given by

$$\varepsilon = \frac{N + N_{bg}}{T}, \quad (1)$$

with an uncertainty of

$$\delta\varepsilon = \varepsilon \sqrt{\left(\frac{\sqrt{N} + \sqrt{N_{bg}}}{N + N_{bg}}\right)^2 + \left(\frac{\sqrt{T}}{T}\right)^2}. \quad (2)$$

The data from Table I then gives a total gamma ray efficiency for NaI(Tl)

$$\varepsilon = 0.315 \pm 0.004. \quad (3)$$

² This 'photo peak' is dominant and easily identifiable, see [1].

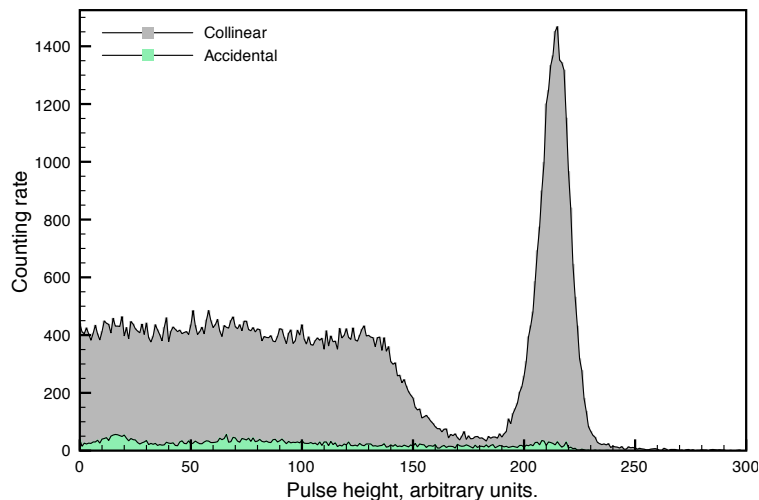


FIG. 2: Measured pulse distribution for NaI(Tl). The horizontal axis corresponds to frequency bins and the vertical axis is in counts per bin. Background counts are shown in green (light gray).

This measured efficiency is approximately a factor of two smaller than the expected value for NaI(Tl) [6]. We suspect this is due to an improperly timed offset in the coincidence unit such that the trigger and signal pulses only appreciably overlapped half of the time since the adjustment of this timing in the current set up was non-trivial due to some missing equipment. We discuss future prospects in Section IV.

We can further check the ratio of Compton scattering to photoelectric scattering, which we find to be

$$\frac{N_{\text{Comp}}}{N_{\text{Photo}}} = 2.426 \pm 0.018. \quad (4)$$

We would like to compare this to the theoretical cross sections found in standard references³. We normalize these by ϕ_0 , the cross section for Thompson scattering,

$$\phi_0 = \frac{8\pi}{3} \left(\frac{e^2}{mc^2} \right)^2 = 6.651 \times 10^{-25} \text{ cm}^2. \quad (5)$$

The photoelectric effect cross section is given by⁴

$$\begin{aligned} \frac{\sigma_P}{\phi_0} &= 5\sqrt{2} \frac{Z^5}{137^4} \left(\frac{1}{\gamma} \right)^{\frac{7}{2}} \\ &= 8.394, \end{aligned} \quad (6)$$

where $Z = 53$ is the atomic number of iodine, which is the dominant source of photoelectric scattering in NaI,

and

$$\gamma = \frac{h\nu}{mc^2} = 1$$

is the ratio of the ratio of the incident photon energy to the electron mass.

The Compton cross section is given by

$$\begin{aligned} \frac{\sigma_C}{\phi_0} &= \frac{3n_e}{8\gamma} \left\{ \left[1 - \frac{(\Gamma + 1)}{\gamma^2} \right] \log \Gamma + \frac{1}{2} + \frac{4}{\gamma} - \frac{1}{2\Gamma^2} \right\} \\ &= 27.568, \end{aligned} \quad (7)$$

where $n_e = 64$ is the total number of electrons in NaI and Γ is a simple function of γ ,

$$\Gamma = 2\gamma + 1 = 3.$$

The probability for an interaction of cross section σ_i in a material with molecular number density n and depth ℓ is given by

$$P_i = 1 - e^{-\sigma_i n \ell}, \quad (8)$$

from which we expect ratio of Compton to photoelectric scattering to be

$$\left(\frac{N_{\text{Comp}}}{N_{\text{Photo}}} \right)_{\text{theory}} = 2.419. \quad (9)$$

This theoretical result agrees very well with the measured value in equation (4).

IV. CONCLUSION

Though the measured efficiency of the NaI(Tl) is smaller than the expected value, the measured ratio of

³ See, in particular, equations (91) and (108) in Segrè [7].

⁴ To compare with standard references, this is $5/4\sigma_K$ where σ_K is the cross section for photoelectric scattering off of K -shell electrons.

Compton to photoelectric scattering matches the predicted result. This reinforces our hypothesis that the low efficiency may be due to misaligned pulses in the coincident unit timing.

Further work is necessary to measure the efficiency with carefully calibrated coincident unit timing. In the Physics 510 lab, this experiment can be facilitated with another ‘mini-banana’-to-BNC cable so that one may simultaneously view the pulses generated by the coincident unit and align their delays and widths. Only one such cable was available during this experiment, making such an alignment difficult.

Acknowledgments

P.T. would like to thank Anders Ryd for useful discussions and the Cornell Physics Department for its ‘kind hospitality.’ While this document was being prepared, the author was made aware of similar work in [8]. Though the approach is similar, that paper has a slightly different focus. We prepared this document using the REVTeX 4 template.

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