# Title

* Here, we present our result in verifying the Klein-Nishina prediction using the Compton scattering of 661.7 keV photons with electrons in sodium iodine (NaI) scintillators

# Theoretical

Slide 2:

* Compton scattering, descibe the inelastic scattering of high-energy photons, typically in the X-ray regime, with charge particles, typically electrons.
* The phenomenon is special in that it proves the wave-particle duality of light particle, opening a pathway for the development of quantum mechanics.

Slide 3:

* Compton scattering can be characterize by the following formula. (show formular)
* E\_gammas are the energy of the incident and scattered photons. m\_e is the mass of the electron. Which,
* we approximate to be intially at rest, which is quite reasonable in our energy regime.
* Here is a little schema for the phenomenon.

Slide 4:

* The differential cross section, describing the rate of scattering per unit of solid angle, follow from the Klein-Nishina quantum relativistic treatment.
* Lambdas here are the wavelength of the incident and scattered photons. r\_e is the classical radius of the electron.

Slide 5:

* In the classical regime, where the wavelength does not change, the cross section follow the Thompson formula

# Apparatus

Slide 6:

* For our experiment arrangement, we have a Cs137 source generating 661.7 keV incident photons.
* These photons then scatter with electrons in a sodium iodine scintillator, denoted as the recoil scintillator, where the energies of the recoil electrons are also measured.
* These electrons are bound; however, they can be considered to be free, as the photon energies are much larger than the bonding energies.
* The scattered photons then reach a second scintillator, denoted as the scatter scintillator, where their energy is recorded.

Slide 7:

* We measure scattering events at 10 different angles, at intervals of 15 degrees.

Slide 8:

* Here is a picture of our setup in the lab.

# Circuits and coincidence mode

Slide 9:

* Each scintillator is connected to a photomultiplier tube, where the light signals are converted to electric signals and amplified.
* Such signals are then further amplified before being feed into a multichannel analyzer (MCA), where the energy spectrum is measured in 2048 channels.
* However, if we only measure in this mode, without any restriction, the spectrum will be dominated by background events and unrelated signal, especially in the recoil scintillator.

Slide 10:

* For such reason, we employ coincidence mode on the two MCAs, where only event occuring within 2 microseconds are registered, which mean, ideally, the MCA only measure signal when there are recoil electrons and scattered photons detected.
* This is achieved by using the gate function, which only turn the MCAs on when events are coincident.

Slide 11:

* False events can still be detected, at this rate (show the fomular), with n\_r as the background rate in the recoil scintillator and n\_s as the background rate in the scatter scintillator.

Slide 12:

* We reduce such rates by using a discriminator circuits, which only allow signal abover certain threshold to pass.
* Setting the threshold to be 60 mV, reduce the noise rate to less than 1 Hz, while the signal rate, that is the rate of Compton scattering events, remain at around 20 Hz.

# Cs137 spectrum

Slide 13:

* After all these details about the setup and theory, you may ask, why Cs137.
* The answer can be seen in its energy spectrum, which exhibit a very distinct and isolated peak at 661.7 keV.
* This is ideal for our experiment, and simplify the system into a single incident photon energy.

# Calibration

Slide 14:

* Another question arise from the fact that the MCAs measure the energy spectrum in terms of channels number rather energy.
* And we will need a way to convert between the two.
* We approximate the channel-energy dependency as linear and follow this equation (show equation).
* alpha here is the energy scaling factor, and b is an offset.

Slide 15:

* We obtain these values by using calibration measurements with Na22 and Ba133.
* Na22 has a clear 511 keV electron annihilation peak in our energy regime, while Ba133 exhibits a more populated energy spectrum.
* In total, there are around 9 peaks that can be used in obtaining the conversion relation, including the Cs137 peak.

# Spectrum analysis

Slide 16:

* Here is an example of the Compton measurement in coincidence mode.
* The top figure is for the scatter scintillator, with the photon peak accompanied by additional Compton spectrum.
* The bottom figure is for the recoil scintillator, where a typically clear peak resulting form the energy of the recoil electron is present. Additionally, there is also a smaller peak from the contamination of the original Cs137 line.
* The energies of the peak centers can typically be extracted with high confidence in both detector. However, the scattering rate can only be reliably obtained from the recoil scintillator, as the result of the Compton spectrum complicating measurements in the scatter scintillator.

Slide 17:

* The spectrum analysis pipline follows.
* First we apply a Gaussian blur to smoothen out the energy spectrum, resulting in a kernel density estimation (KDE) displayed in solid blue.
* The choice of sigma = 5 channels provide the best smoothening effect while keeping features clear.

Slide 18:

* The local minima and maxima are then identified using derivative-based peak finding algorithms.
* Neighboring extrema are also merged in respond to statistic fluctuations.
* These local minima and maxima are used to aid in the peak fitting boundaries and initial conditions.

Slide 19:

* The peak are then fitted with Gaussian functions with optional offset.
* For the calibration measurements, we also employed triple-peak Gaussian fitting for the clustered features.

Slide 20:

* For Compton measurements, we take Poisson-based likelihood approach to fitting peaks. This is in respond to the low count per bin.

# Calibration result

Slide 21:

* Follow the procedule as described before, we obtain the the peaks information for the calibration measurements.
* This is an example from the recoil scintillator measured in our first measuring day.

Slide 22:

* The result comes to alpha equal … and b equal …
* These uncertainties are systematics in nature, but we can propagate them as part of the statistical errors

# Energy-angle dependency

Slide 23:

* Here is our result of the energy-angle dependency.
* Red indicates the scattered photon energies, while orange shows the kinetics energies of the recoil electrons.

Slide 24:

* The reconstructed energies of the incident photons, as show in the upper panel, is consistent with the value of 661.7 keV.
* Especially considering the systematic error of 10 keV from the regressed energy being lower than the peak position for the scattered photons, as a result of the Compton spectrum interference.

Slide 25:

* The photon and electron energies follow the Compton theory well, as displayed.

Slide 26:

* With the system not totally being aligned, we fit the energies and obtain the initial offset of …
* The error here is around the same as the systematic error in scattering angle, being …

# Scattering rate

Slide 27:

* Here is our result for the scattering rate at different angles.
* The scattering angles are adjusted for the initial offset.
* The statistical uncertainties are propagated using Monte Carlo method with the peak fitting uncertainties.
* The systematic errors, approximated from the measurements with the KDE, are shown in shaded bars.

Slide 28:

* The scattering rate follow the Klein-Nishina formula very well, as shown.
* Except for the forward scattering case, where the MCA is not sensitive enough to measure accurately the scattering rate for low-energy electrons.

Slide 29:

* The classical Thompson formula fails to describe the observed data

Slide 30:

* All and all, this confirms the need for quantum relativistic treatment for the current energy regime.