Massachusetts Institute of Technology

Inelastic Scattering of Photons by Electrons to Verify Particle Nature of Light

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Junior Lab 8.13 Presentation

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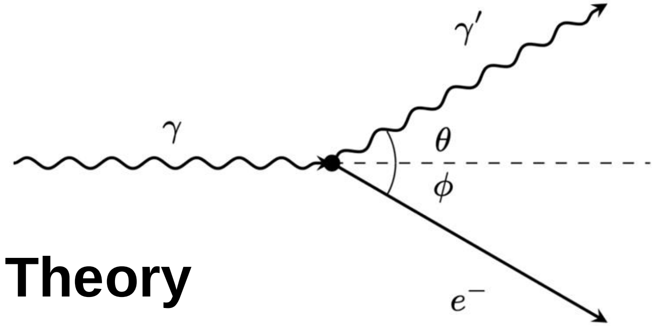
Light: Wave or Particle?



Wave Theory	Particle Theory

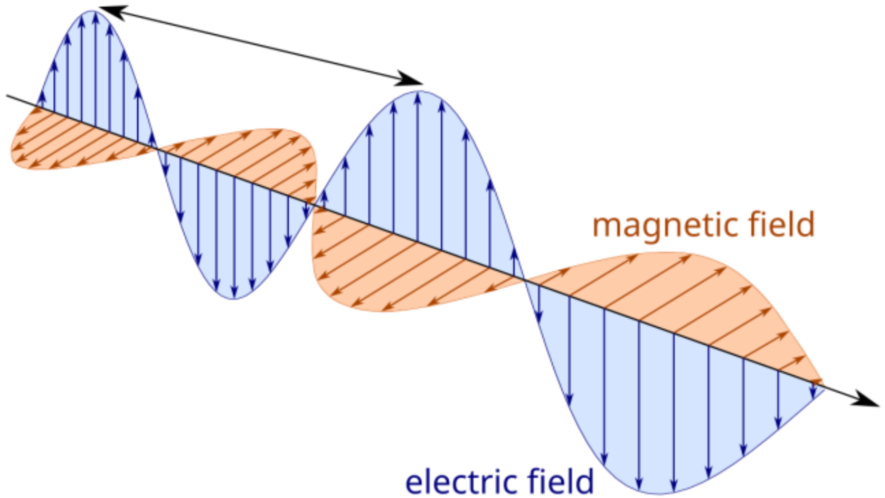


Image credit: Piotr Fita

Classical electromagnetism

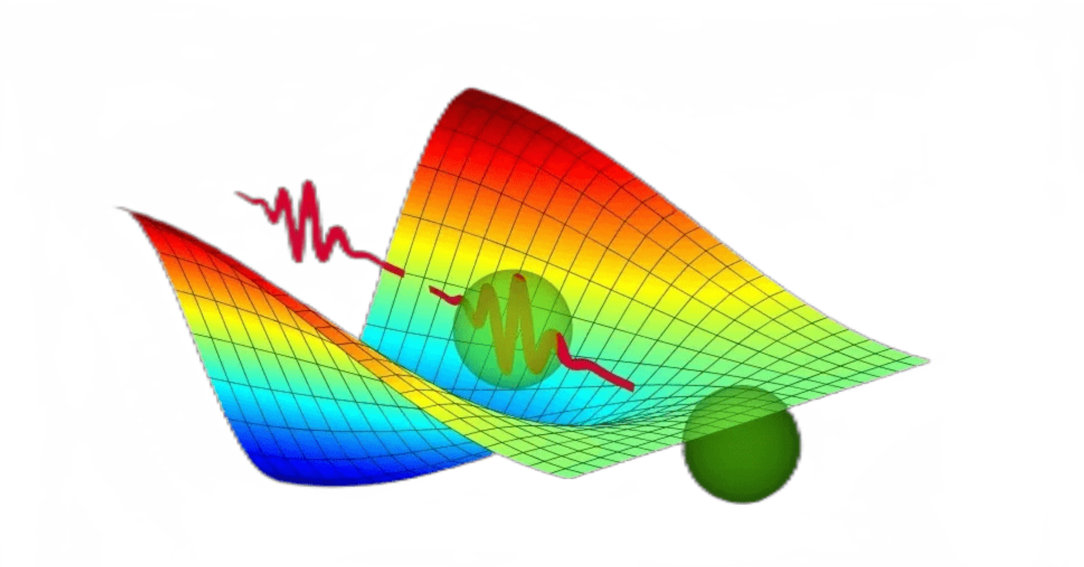
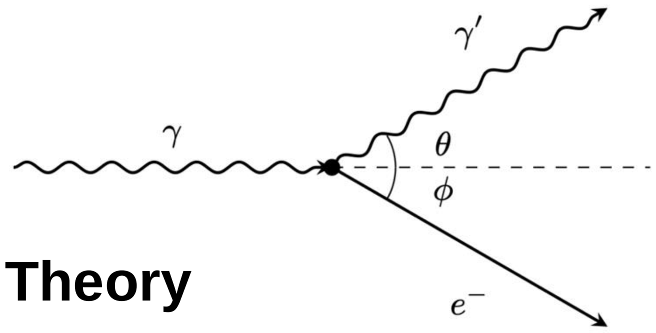


Image credit: S. Tanzilli, CNRS

Relativistic Mechanics

Scattering Rate and Cross Section Differs between Wave and Particle Prediction



Wave Theory

$$\nabla^2 \vec{E} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

Thomson Scattering

$$\frac{d\sigma}{d\Omega} = r_0^2 \left(\frac{1+\cos^2\theta}{2} \right)$$

$$r_0 = \frac{e^2}{4\pi\epsilon_0 m_e c^2}$$

Thomson Scattering Total Cross Section

$$\sigma = \frac{8\pi}{3} r_0^2 \approx 66.5 \text{ fm}^2$$

J. D. Jackson. Classical electrodynamics; 2nd ed. Wiley, New York, NY, 1975.

Particle Theory

$$\gamma^\mu \partial_\mu \psi + im\psi = 0$$

Klein-Nishina Scattering

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left(\frac{E_f}{E_i} \right)^2 \left(\frac{E_f}{E_i} + \frac{E_i}{E_f} - \sin^2\theta \right)$$

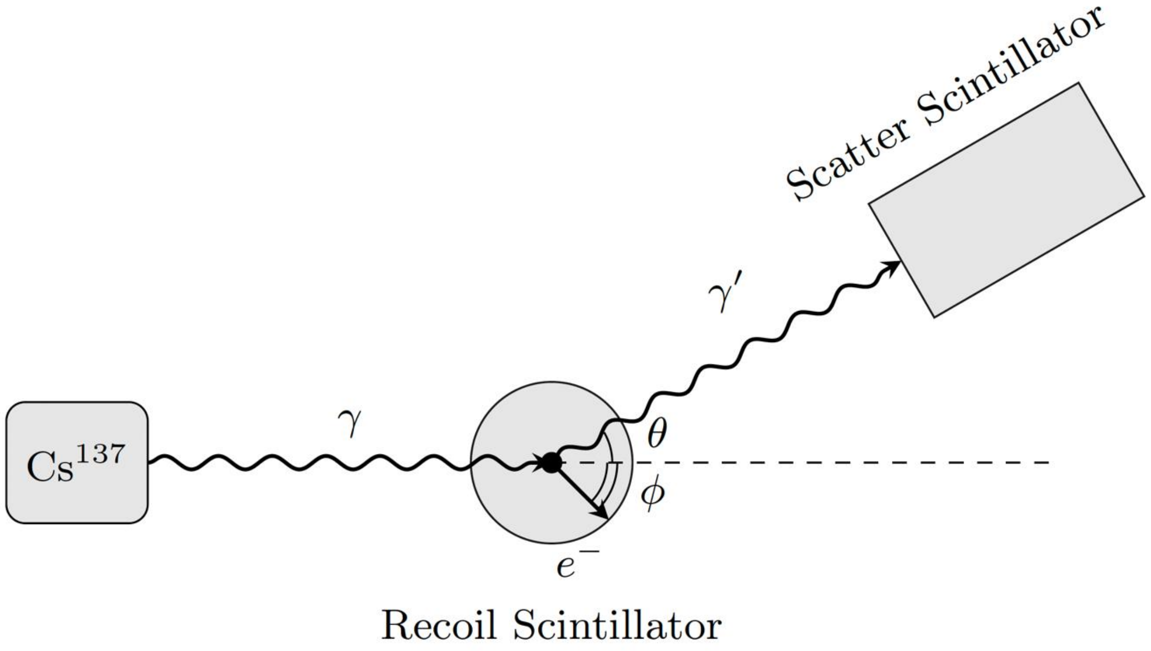
Klein-Nishina Total Cross Section

$$\sigma = 2\pi r_e^2 \left[\frac{1+x}{x^3} \left(\frac{2x(1+x)}{1+2x} - \ln(1+2x) \right) + \frac{\ln(1+2x)}{2x} - \frac{1+3x}{(1+2x)^2} \right]$$

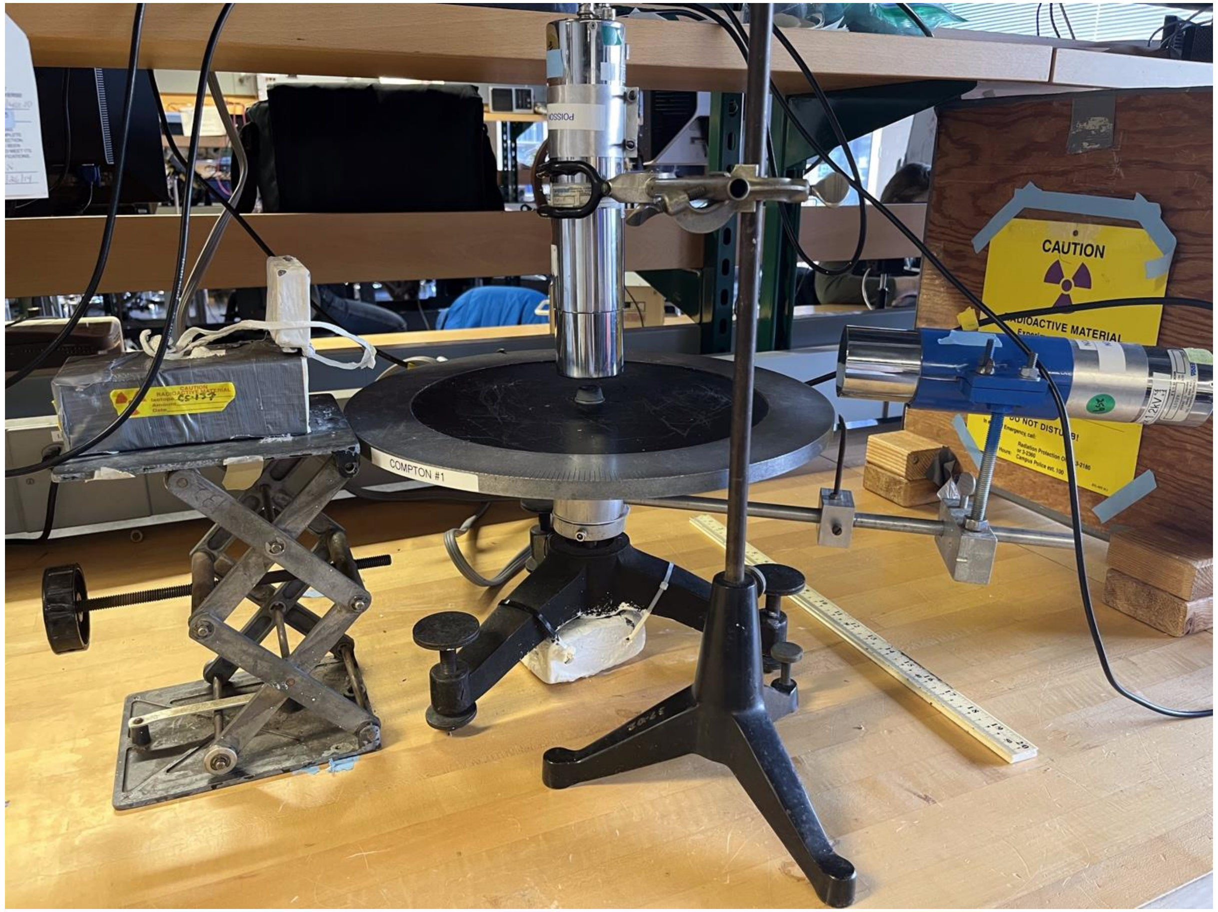
$$x = \frac{E_i}{m_e c^2}$$

S. Weinberg. The Quantum theory of fields. Vol. 1: Foundations. Cambridge University Press, 6 2005.

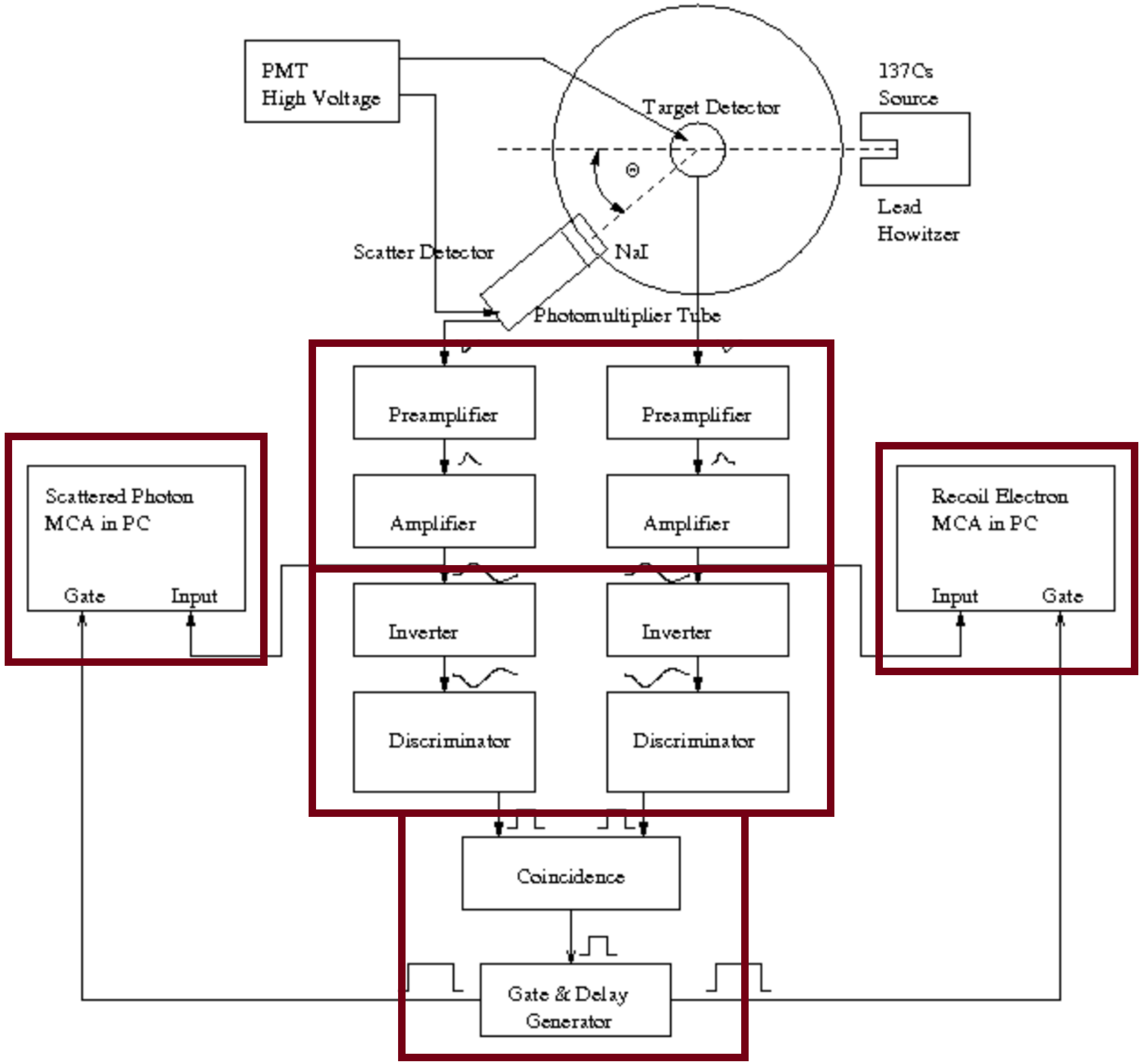
Experimental Setup for Angular-dependent Measurements



$\theta \in [0^\circ, 135^\circ]$ (at 15° intervals)



Coincidence Circuit to Ensure that Only the Scattering Events are Picked up



MIT Department of Physics. Compton scattering. https://mitx.mit.edu, August 2023. MIT Junior Lab Experiment Documentation.

Data Analysis: Peak fitting

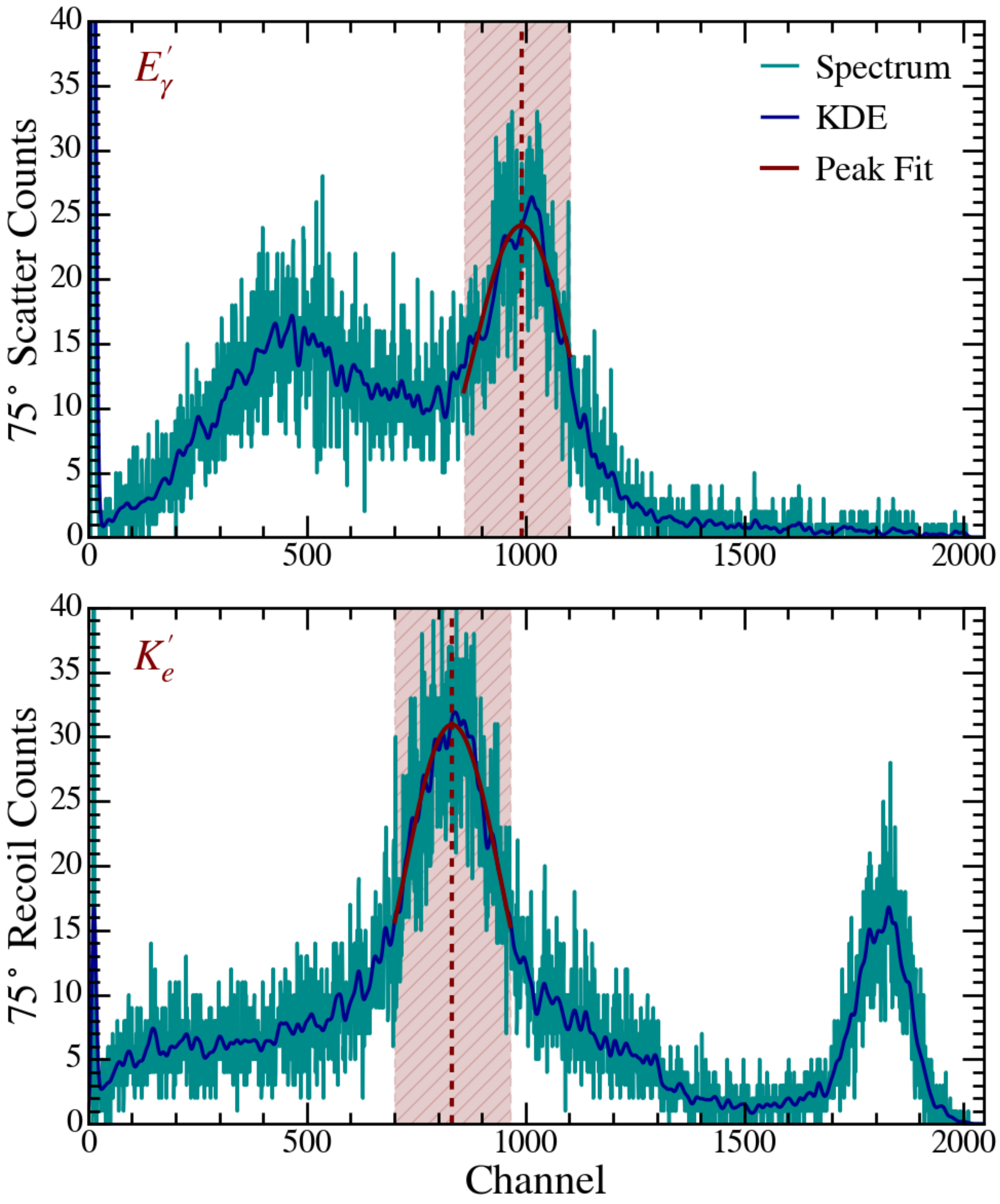
KDE to smooth data

Peak-finding algorithm

Fit Gaussian function with original data

Use height of boundary to sample new boundary height

Find error of median and FWHM



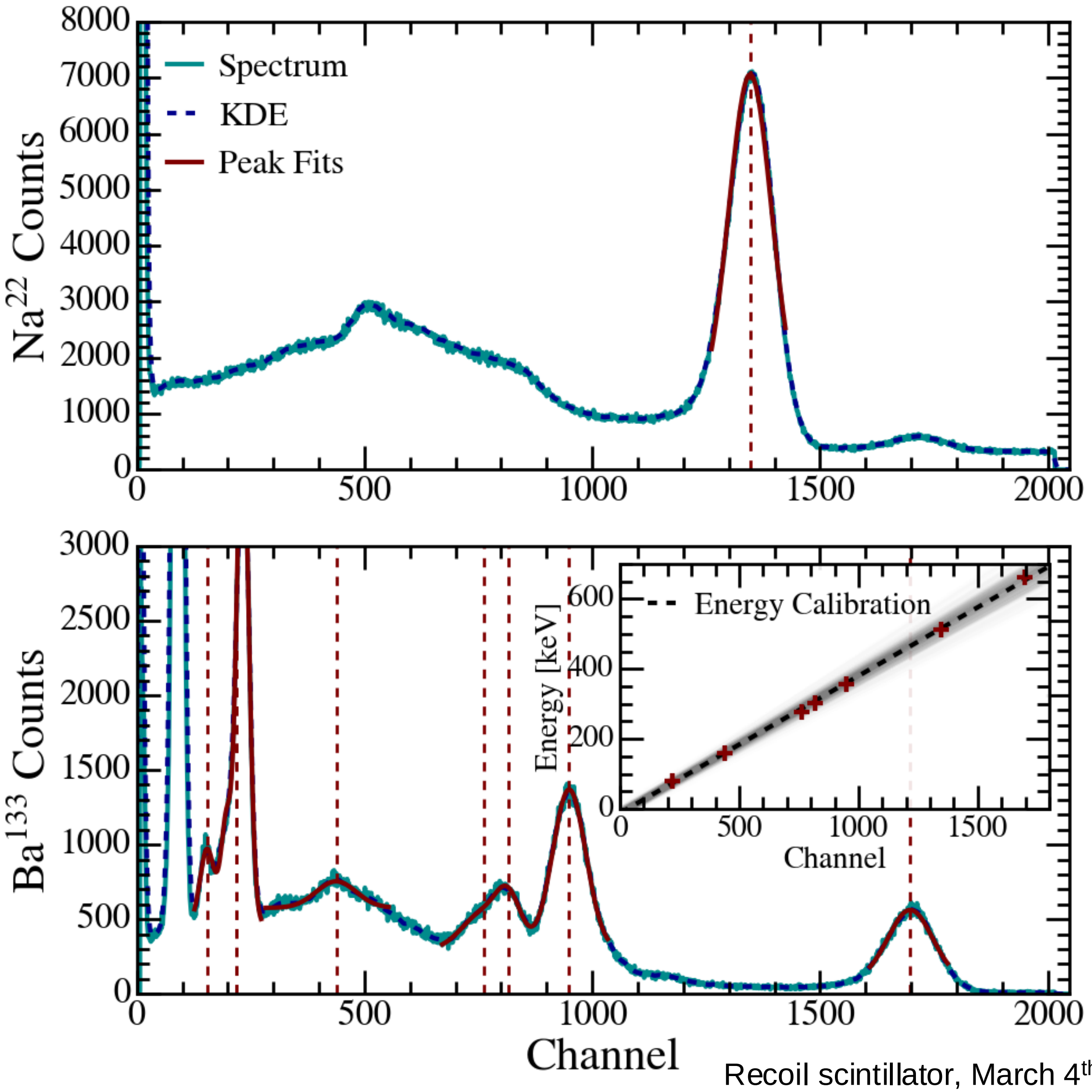
Calibration of MCA using Known Energy Source Converts Channel number to Energy

Channel-energy conversion relation

$$E_i = aC_i + b$$

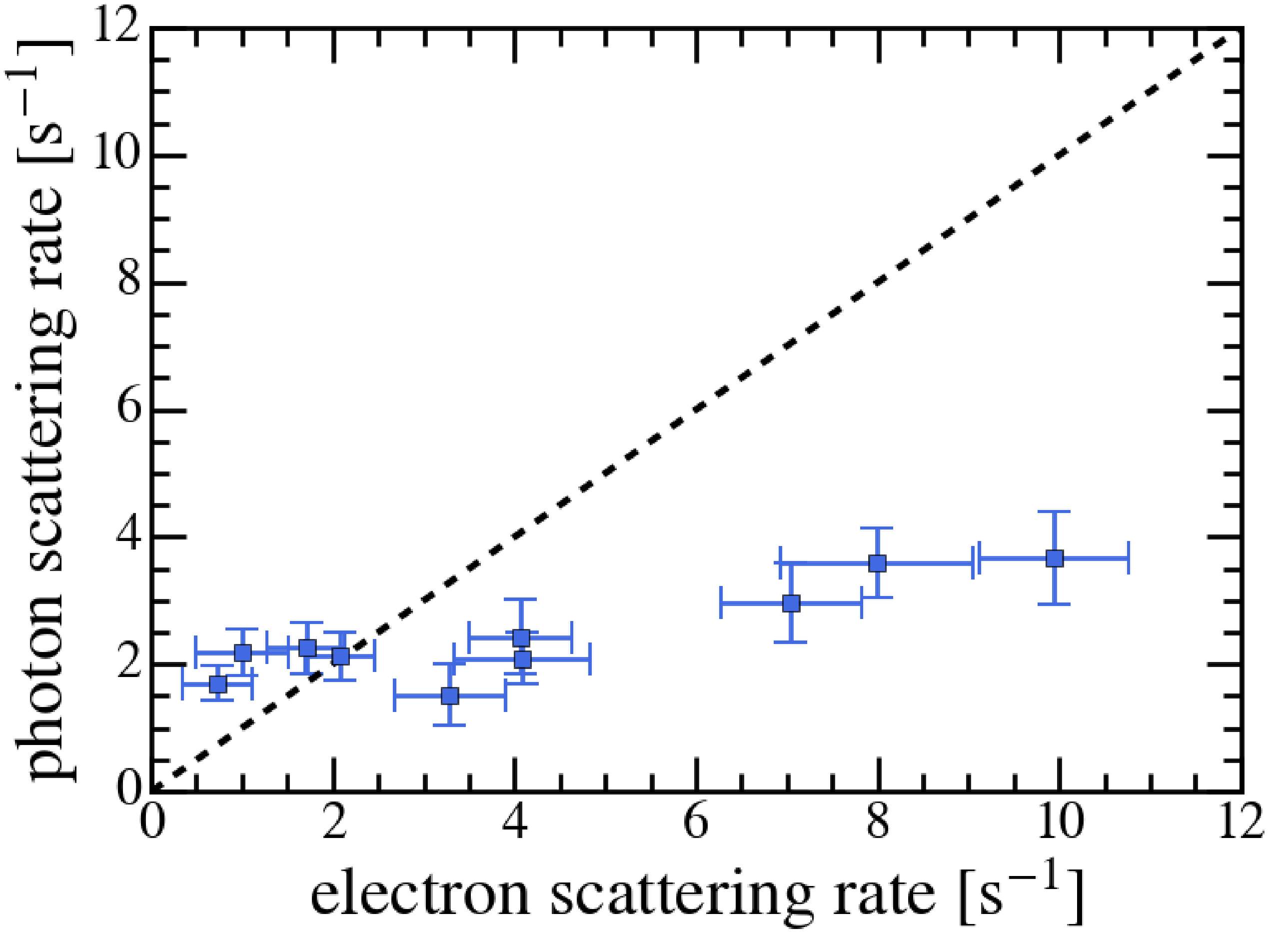
$$a = (0.390 \pm 0.014)\ \mathrm{keV}$$

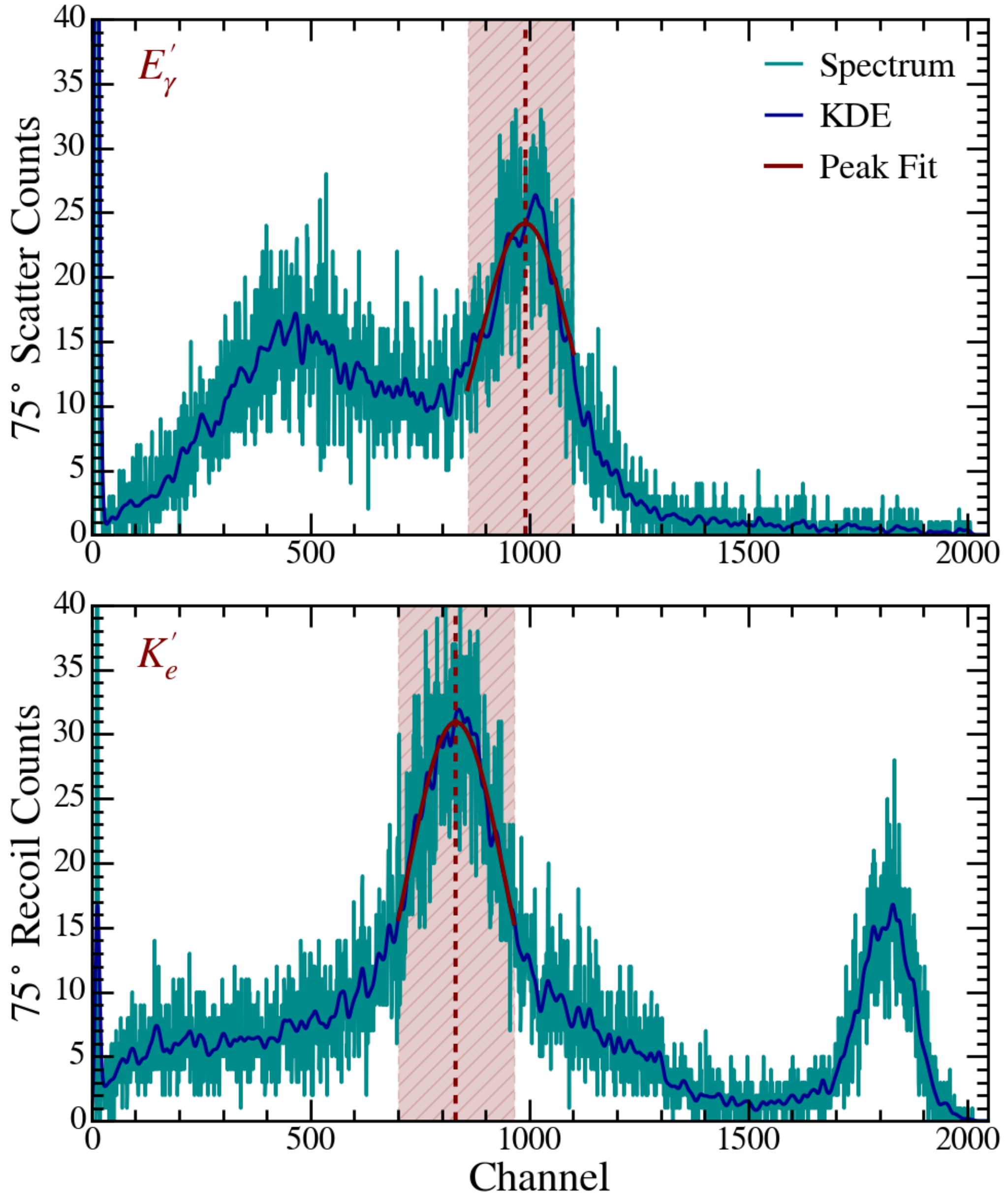
$$b = (-10.5 \pm 6.2)\ \mathrm{keV}$$



Recoil scintillator, March 4th 2025

Recoil Detector is used for Measuring Rate instead of Scatter Detector





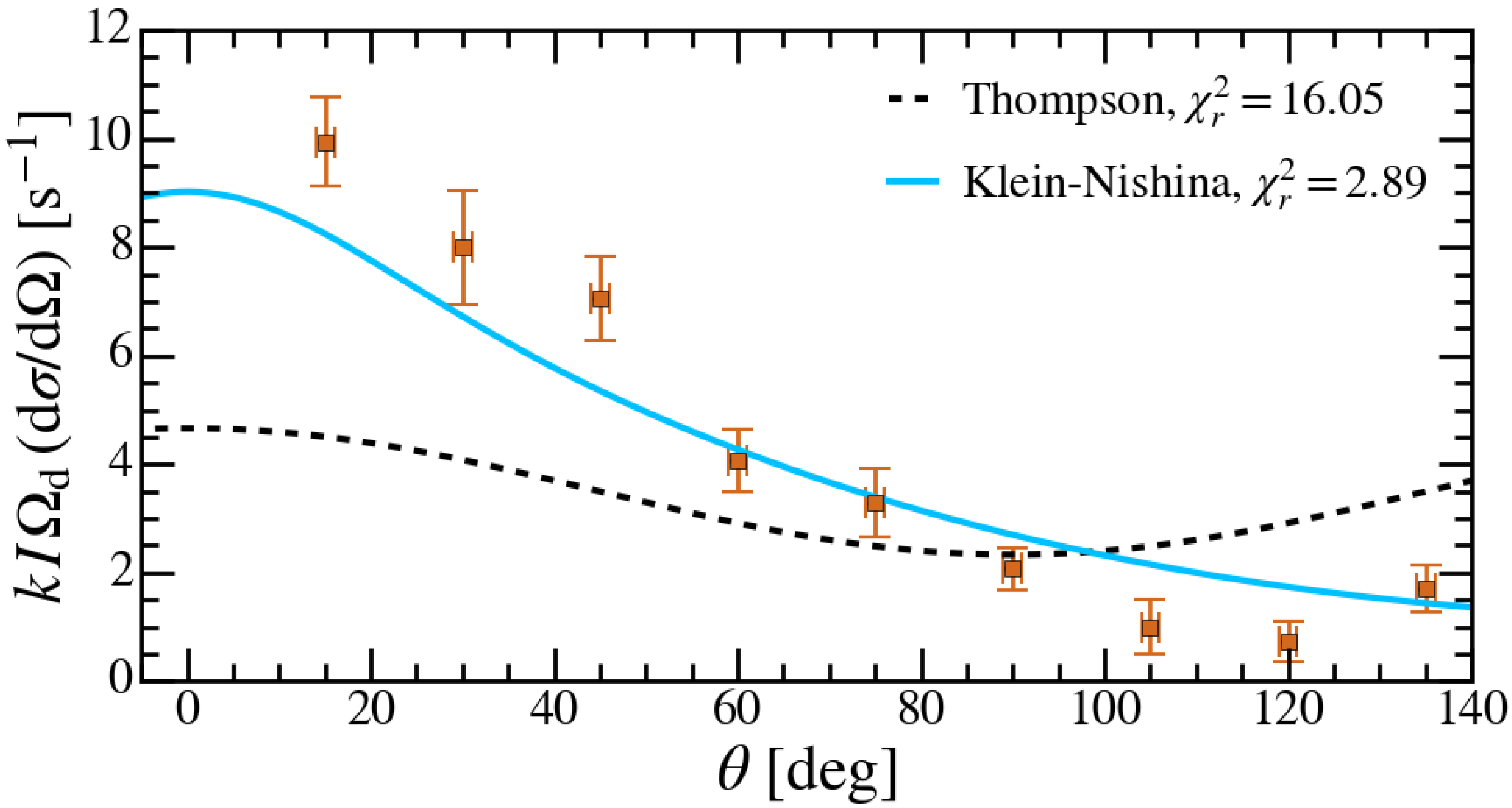
Angular Dependence of Scattering Rate Follows Klein-Nishina Prediction

Thomson Scattering

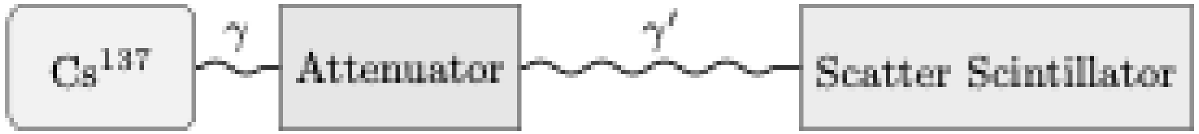
$$\frac{d\sigma}{d\Omega} = r_0^2 \left(\frac{1 + \cos^2\theta}{2} \right)$$

Klein-Nishina Scattering

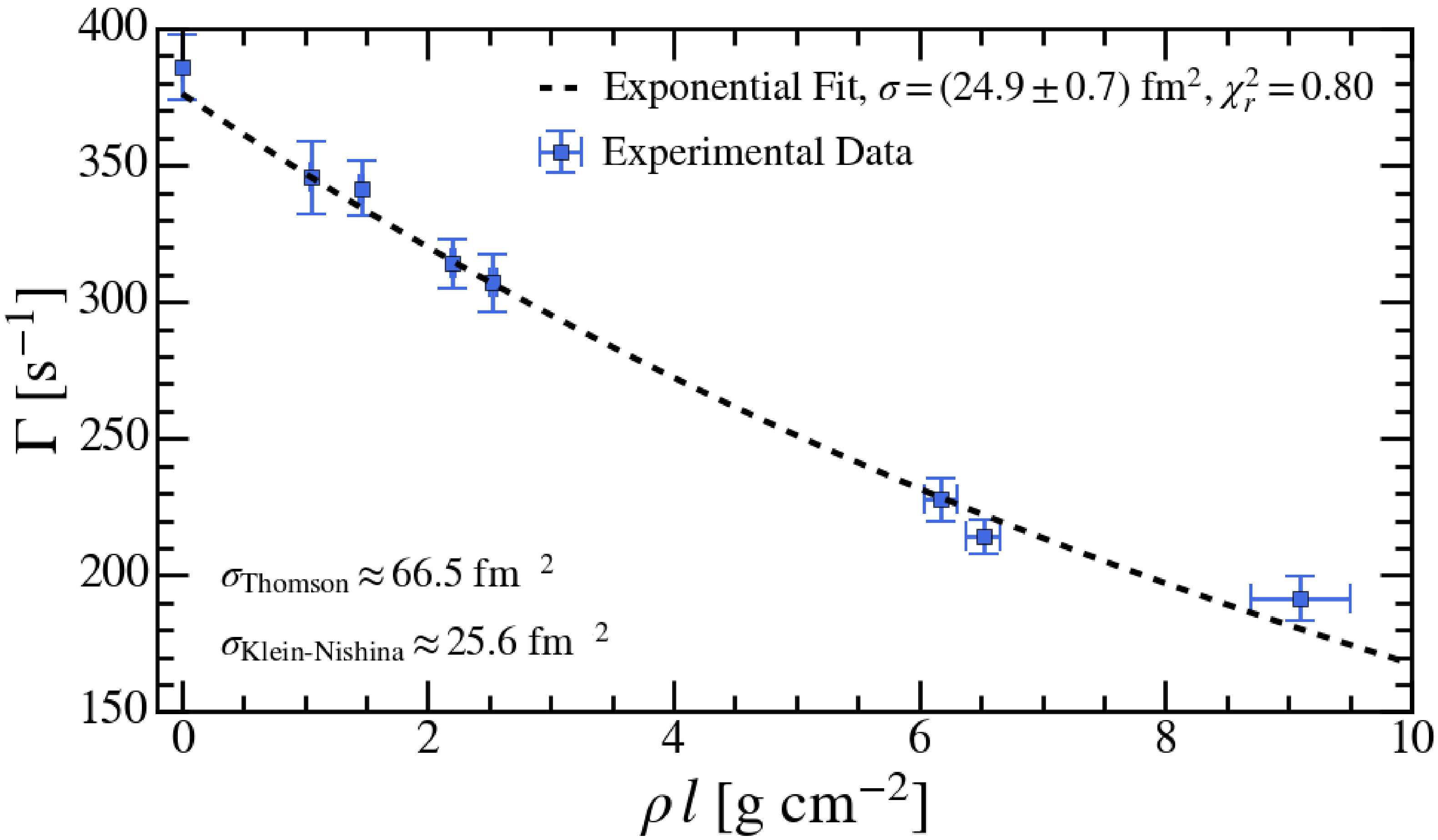
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left(\frac{E_f}{E_i} \right)^2 \left(\frac{E_f}{E_i} + \frac{E_i}{E_f} - \sin^2\theta \right)$$



Total Cross Section from Attenuation Follows Klein-Nishina Prediction



Attenuation dependence $A = A_0 e^{-\mu x} = A_0 e^{-\sigma N \rho l}$



Uncertainties in the Experiment

Statistical Uncertainty

- Inherent statistical nature of scattering: the statistical error of peak position and width of peak

Systematic Uncertainty

- Angle offset of the setup: fitted offset $\theta_0 = 2.56 \pm 0.71°$
- Time resolution of MCA: Resolution of angle, time, length, mass measurement: $\sigma_\theta^{\text{sys}} \sim 0.5°, \sigma_t^{\text{sys}} \sim 0.01\ \text{s},\ \sigma_l^{\text{sys}} \sim 0.05\ \text{cm}, \sigma_m^{\text{sys}} \sim 0.05\ \text{g}$
- Coincidence circuit unable to filter all background: $n_{\text{F}} = 2\tau n_r n_s$
- Fitting of scatter spectrum with gaussian function

Conclusion: Light is made of particles!

Successfully demonstrated particle nature of light

Verified Klein-Nishina Scattering