Measuring the Electron Mass through Compton Scattering

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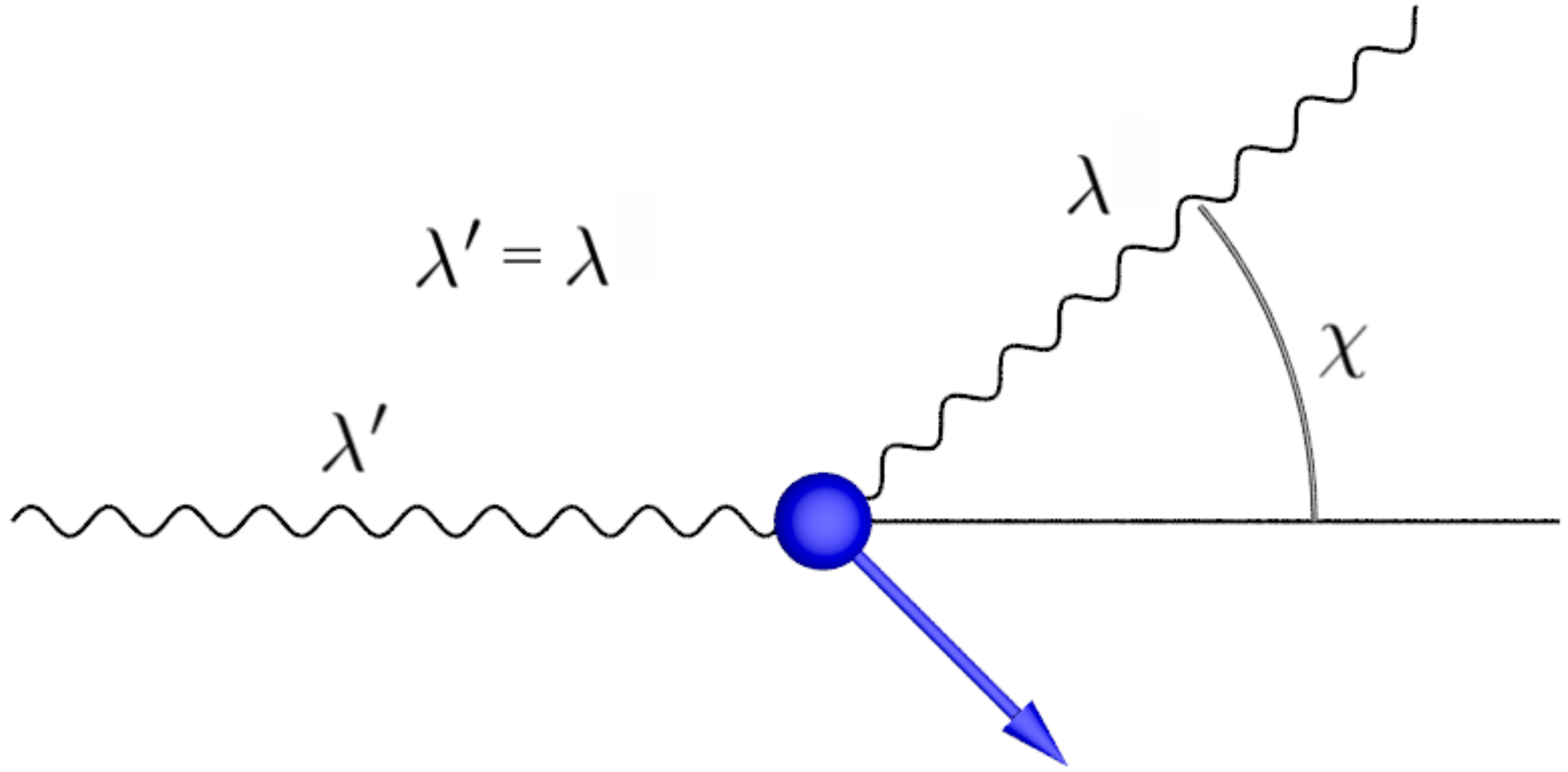
Classical Radiation-Electron Scattering (i.e. Thomson Scattering)

- Radiation incident on an electron causes electron to oscillate
- Causes electron to radiate away energy in all directions, due to acceleration of electron
- Classical electromagnetism predicts that wavelength of emitted radiation is equal to wavelength of incident radiation
- Compton's experiments showed that emitted radiation has longer wavelengths, violating the classical theory



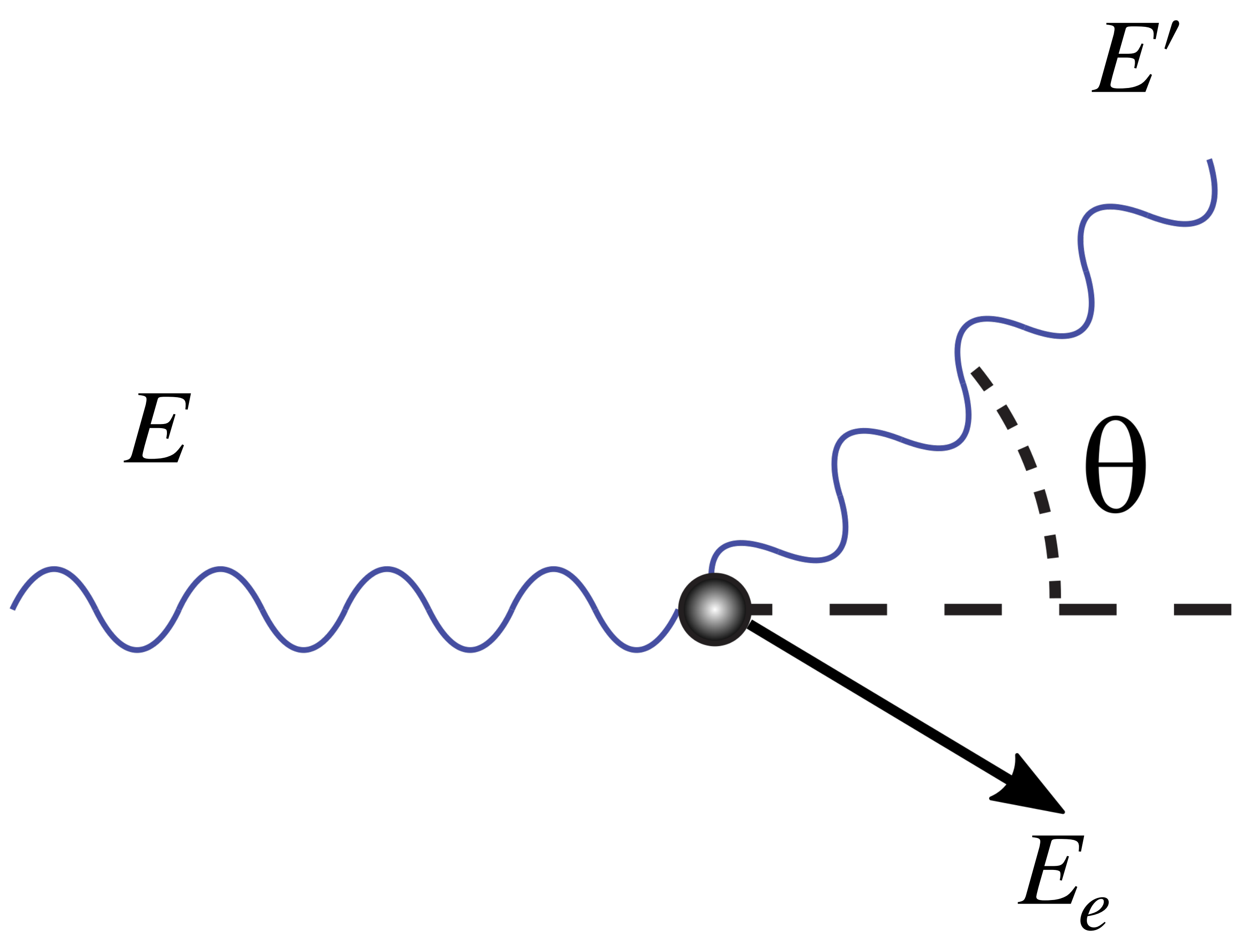
Schematic depiction of Thomson Scattering

(https://commons.wikimedia.org/wiki/File:Thomson-scattering.png)

Compton Scattering

- Uses the quantized photon model of light
- Models the scattering process as a relativistic collision between a photon and an electron
- Using relativistic dynamics, we can derive

$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_e c^2}(1 - \cos\theta)$$

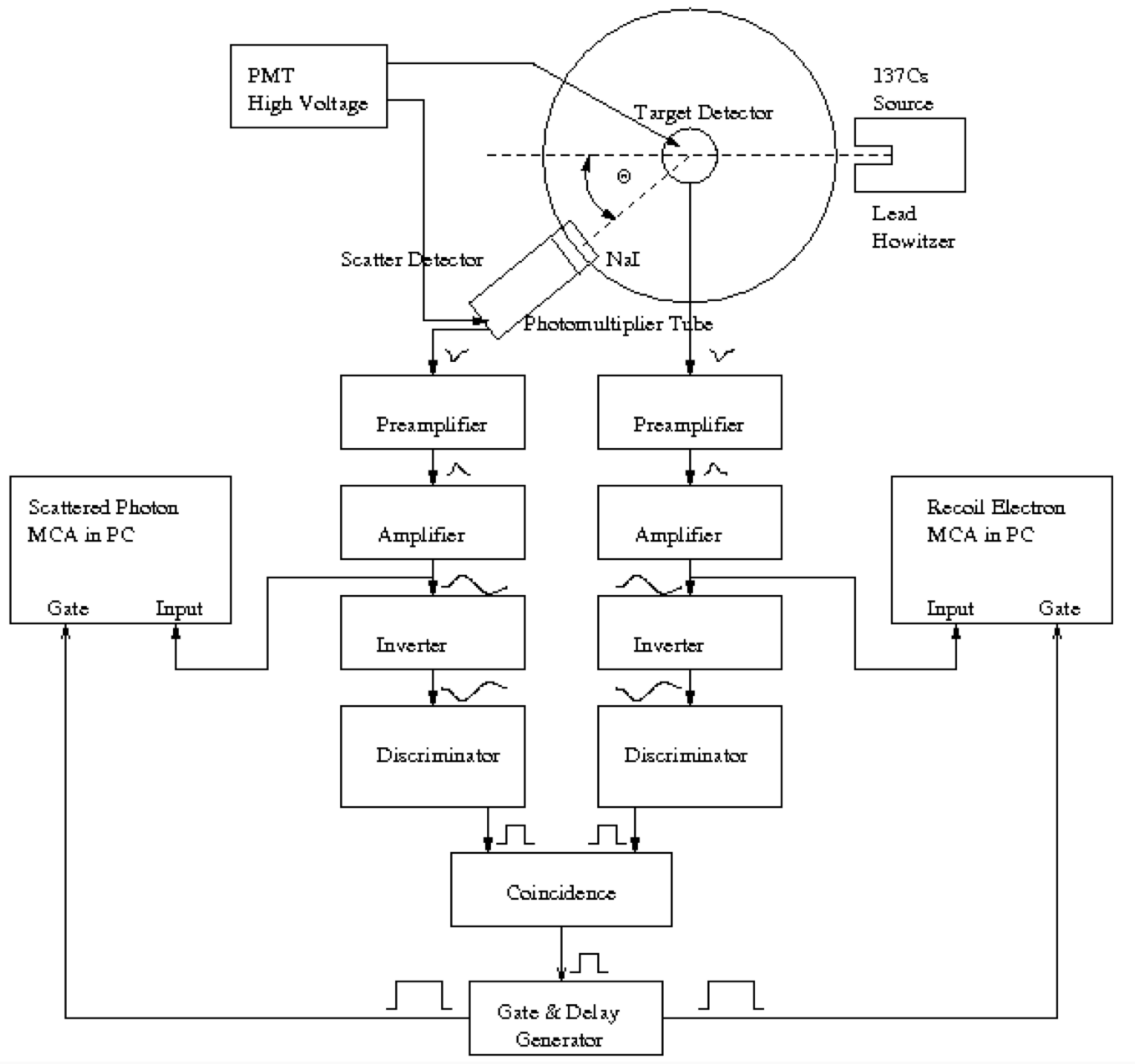


Schematic depiction of Compton Scattering

(https://commons.wikimedia.org/wiki/File:Compton-scattering.svg)

Experimental Setup

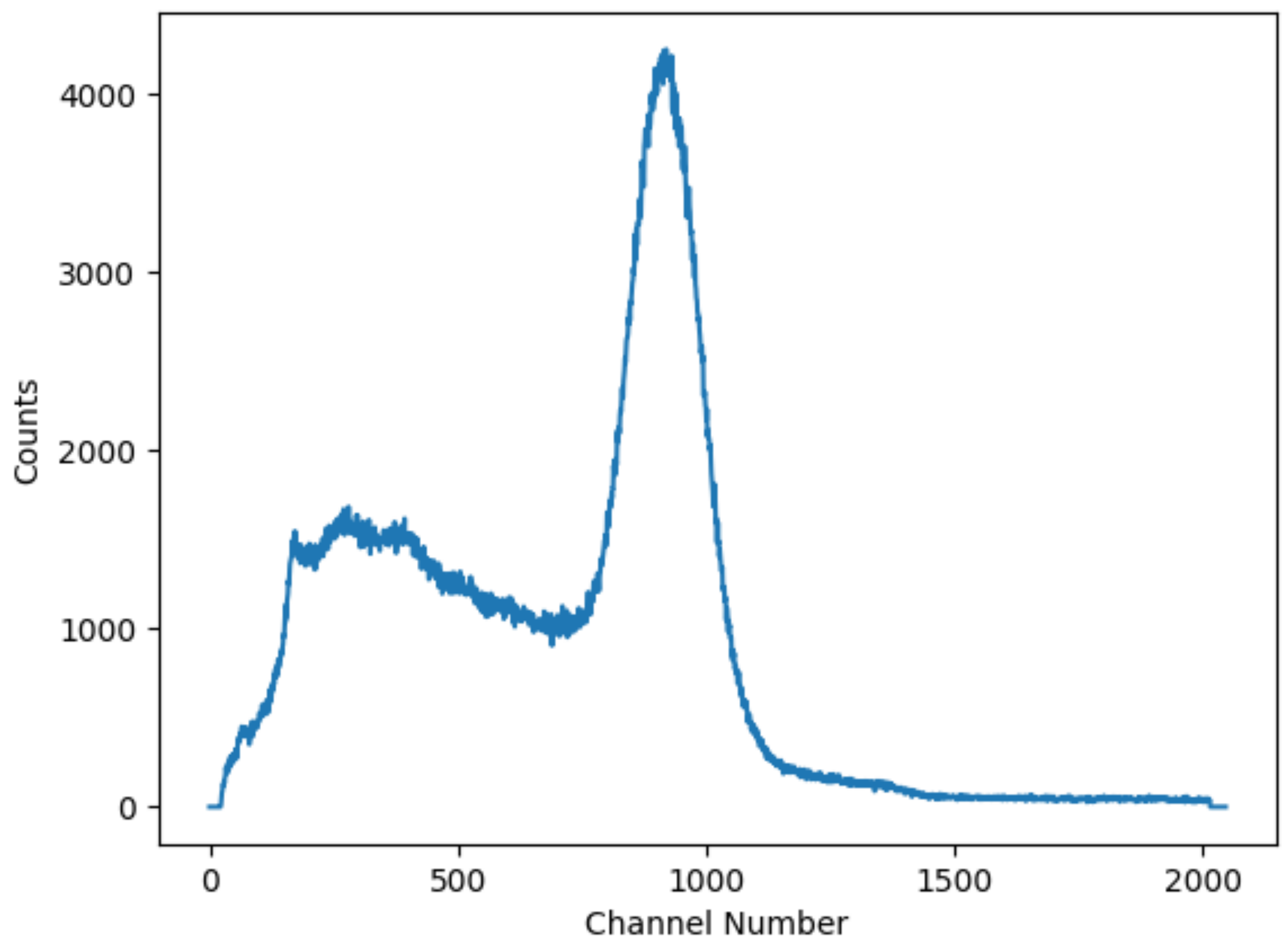
- Gamma rays generated through ^{137}Cs, which has strong photopeak at 661.6 keV
- Gamma rays Compton scatter off free electrons in target detector
- Electron energy dumped in target, scattered photon energy dumped in scatter detector
- Use coincidence detection to restrict to Compton events



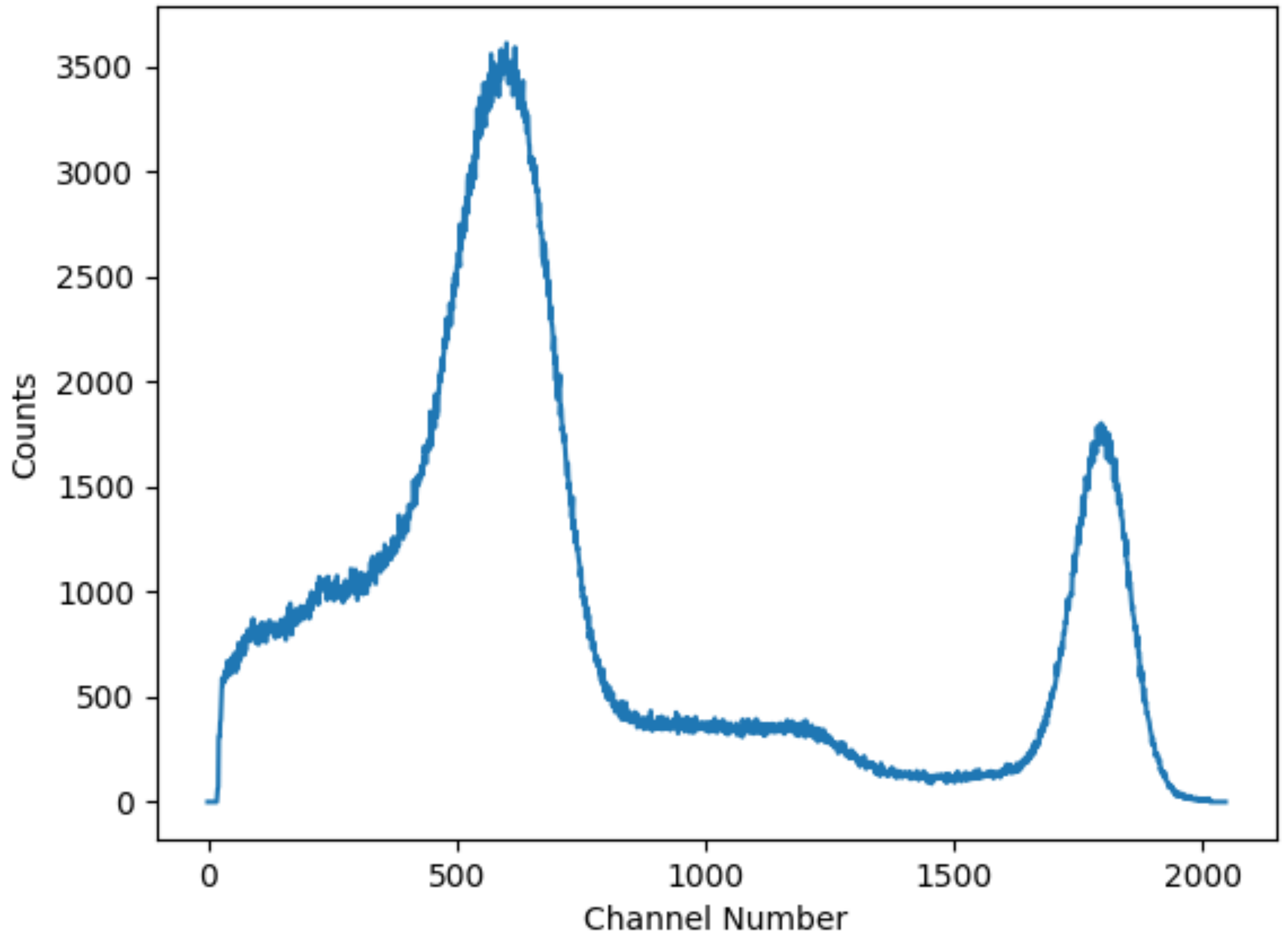
Schematic for Compton Scattering Experiment
(https://web.mit.edu/8.13/www/JLExperiments/JLExp01.pdf)

Experimental Functionality

- Can vary the angle of the scatter detector
- Software outputs (uncalibrated) histogram of energy values registered by detectors
- Coincidence can be turned on or off using software



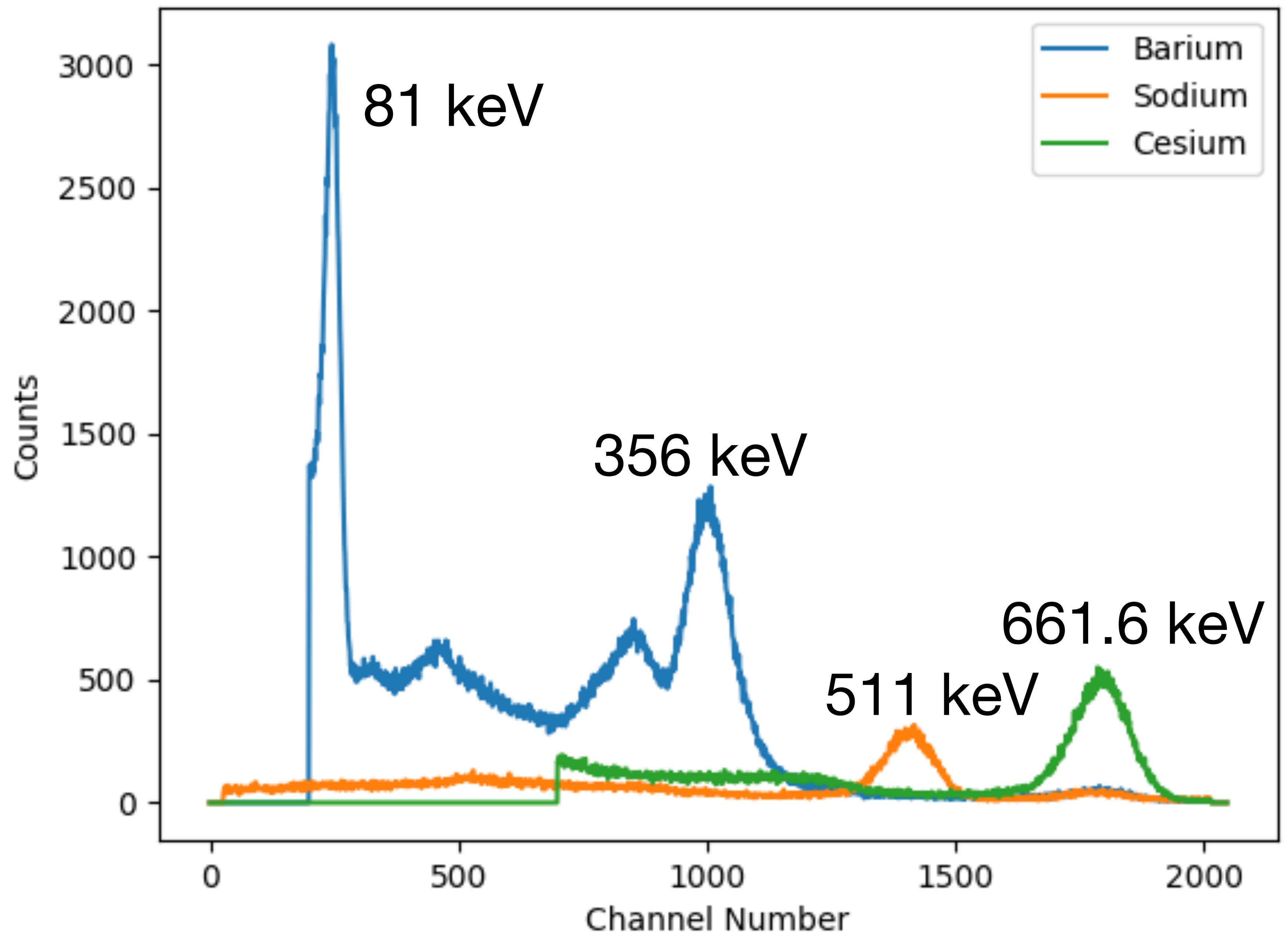
Scatter output for Compton with $\theta = 60°$



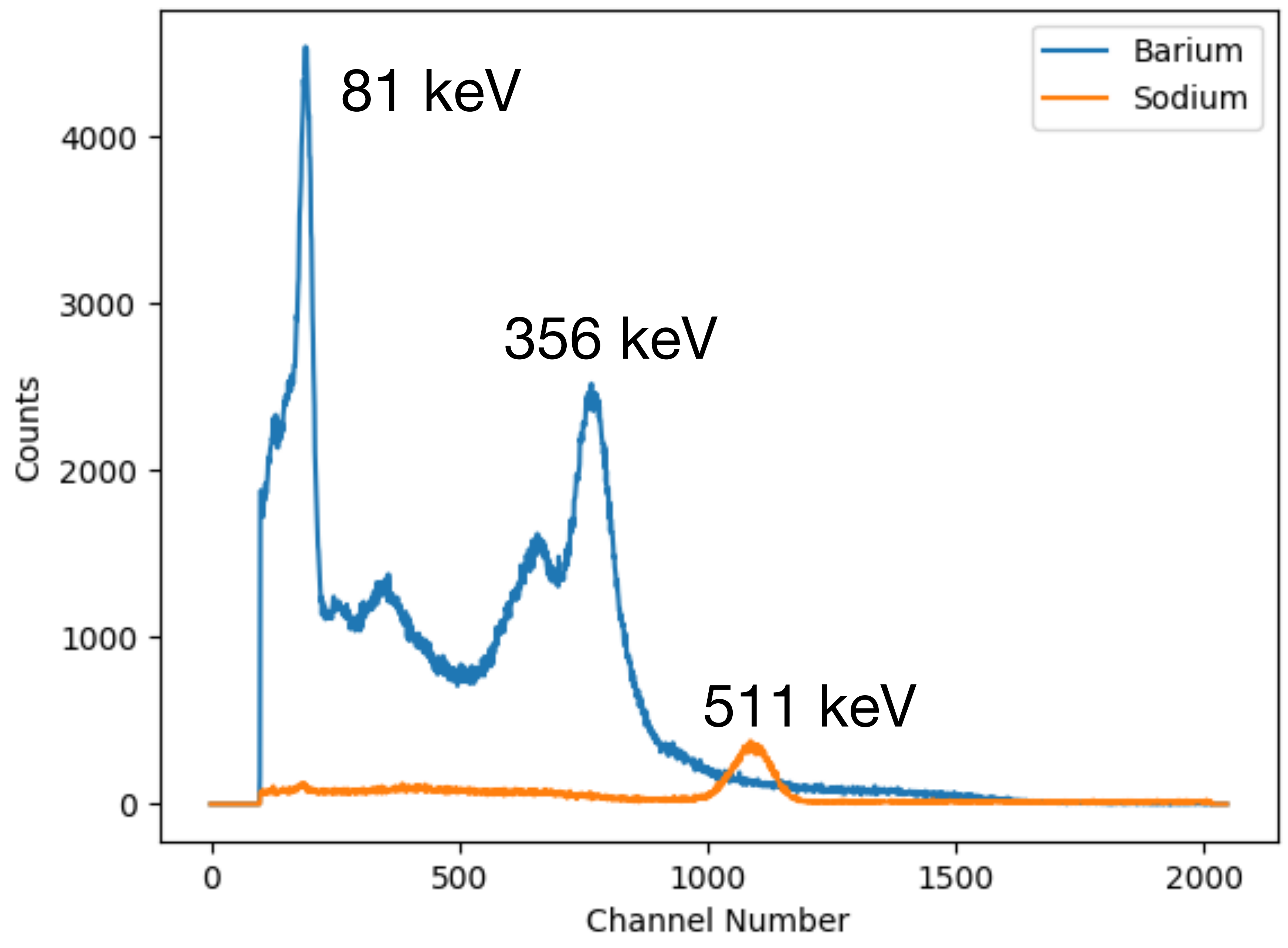
Target output for Compton with $\theta = 60°$

Energy Calibration

- Use ^{137}Cs, ^{22}Na, and ^{133}Ba gamma peaks to calibrate the detectors



Spectra of calibration sources with labeled true peaks (target detector)



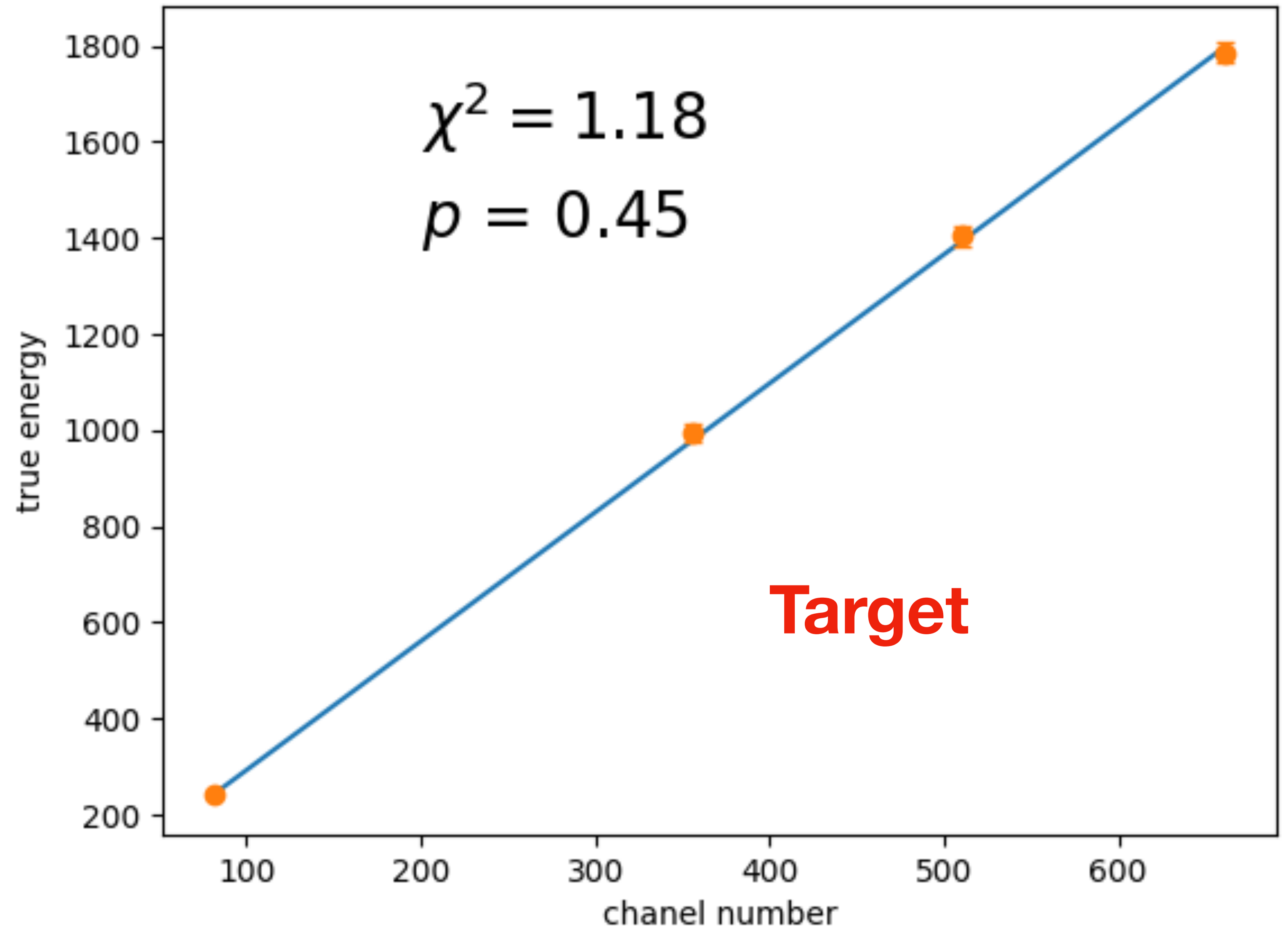
Spectra of calibration sources with labeled true peaks (scatter detector)

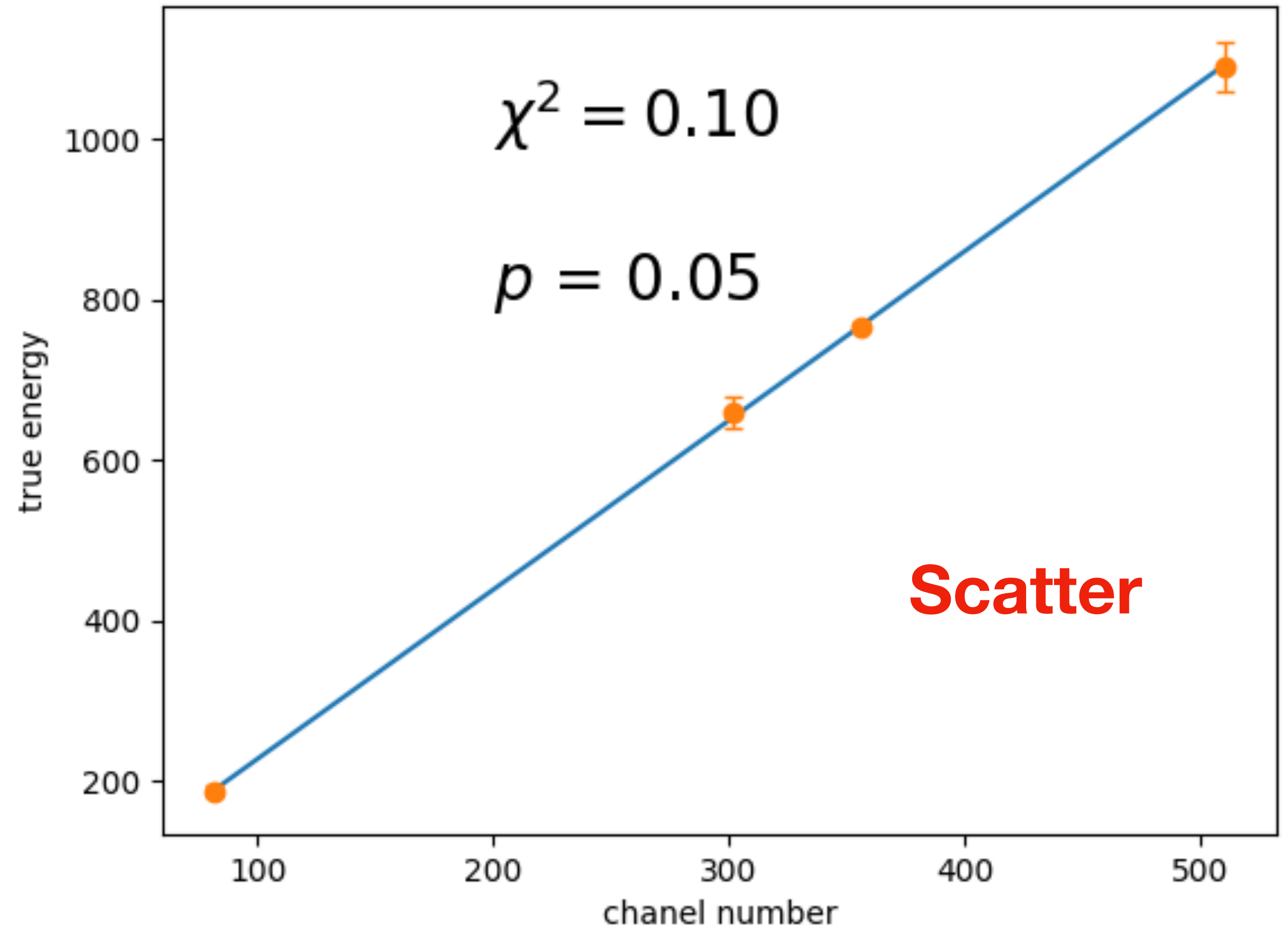
Energy Calibration

- Use a linear fit between channel number N and true energy E
  $N = \alpha E + \beta$

- Target: $\alpha = [2.68 \pm 0.03]\frac{\text{counts}}{\text{keV}}$,
  $\beta = 24 \pm 6\,\text{counts}$

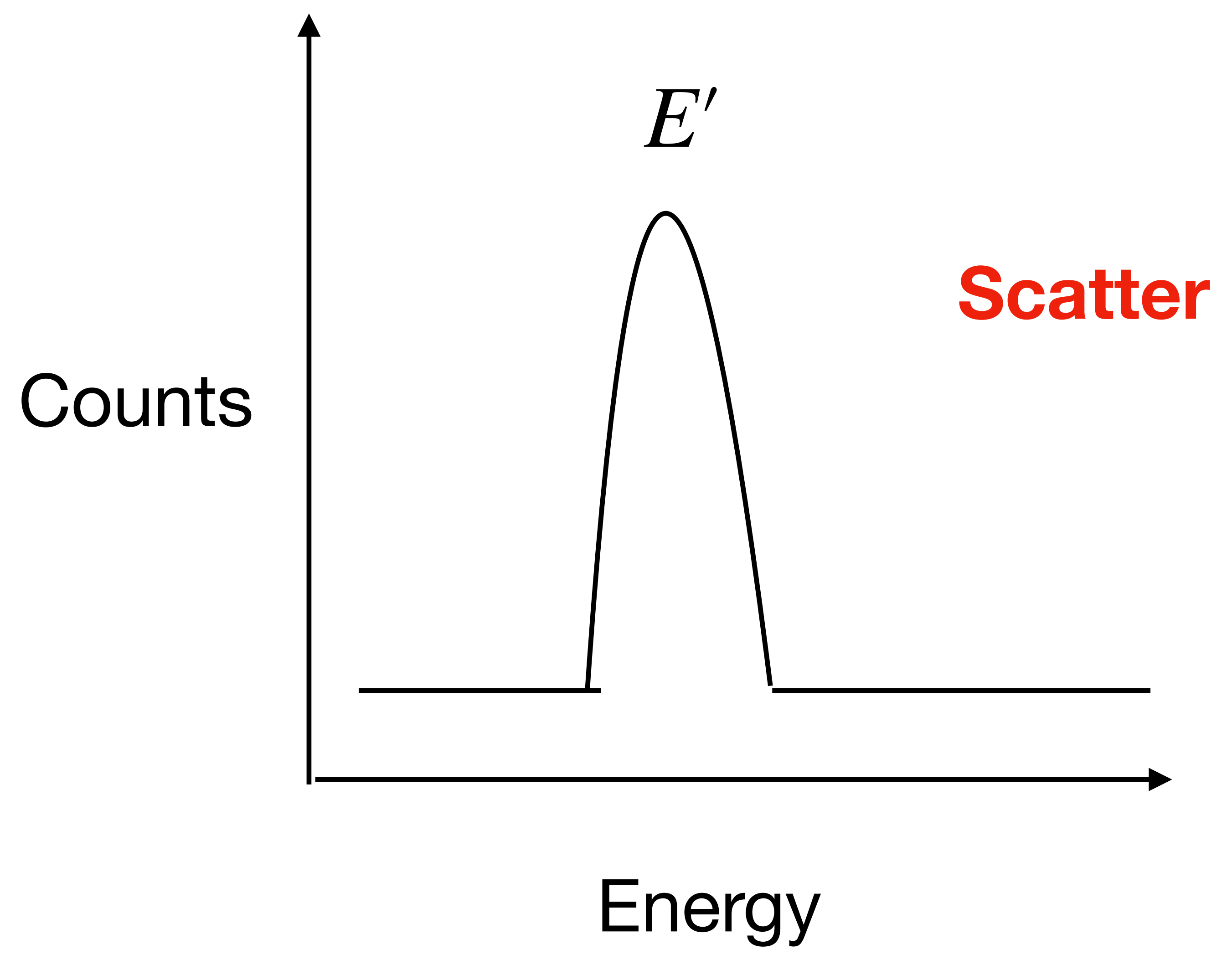
- Scatter: $\alpha = [2.11 \pm 0.03]\frac{\text{counts}}{\text{keV}}$,
  $\beta = 16 \pm 10\,\text{counts}$

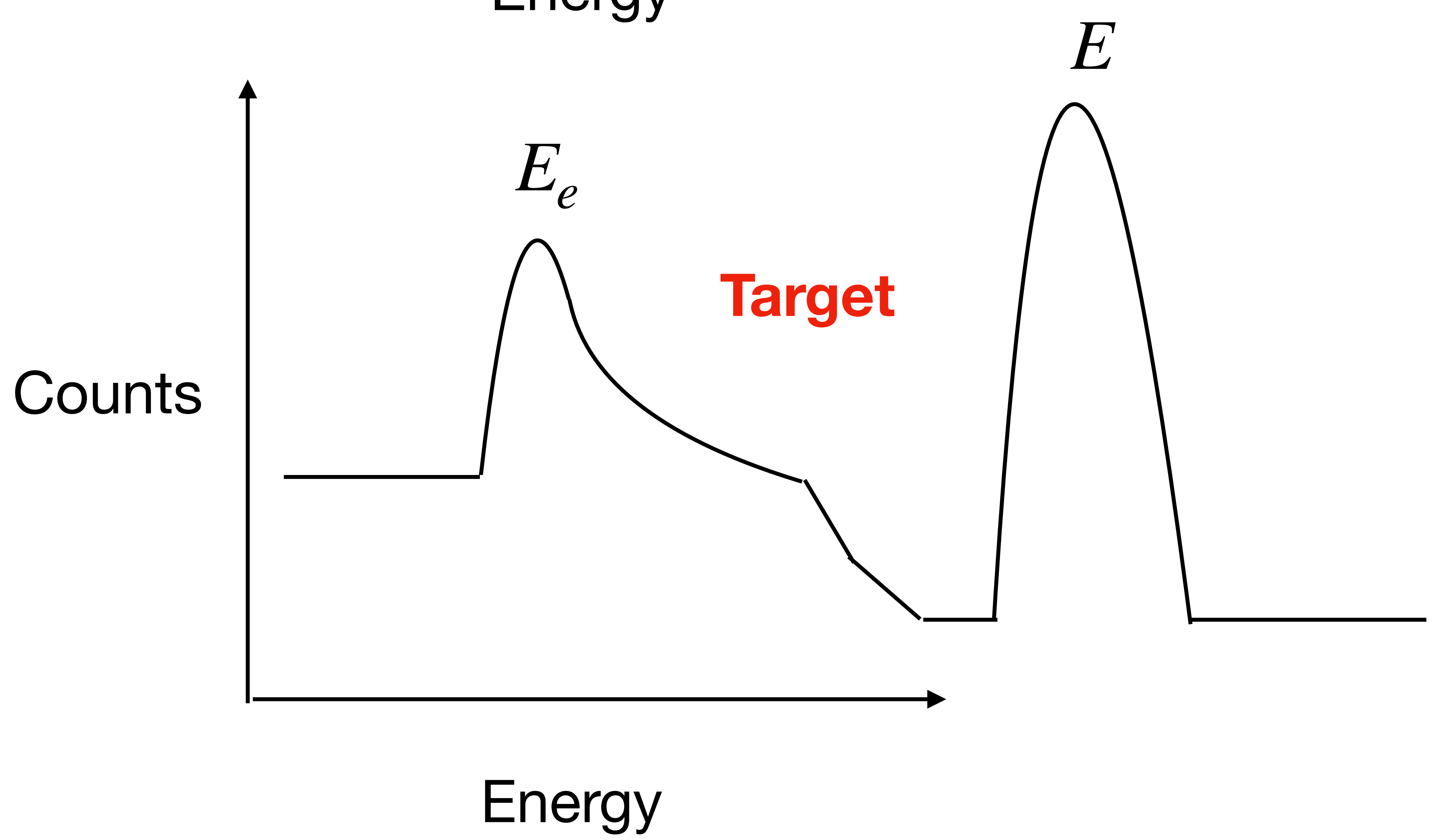




Expected Compton Spectra

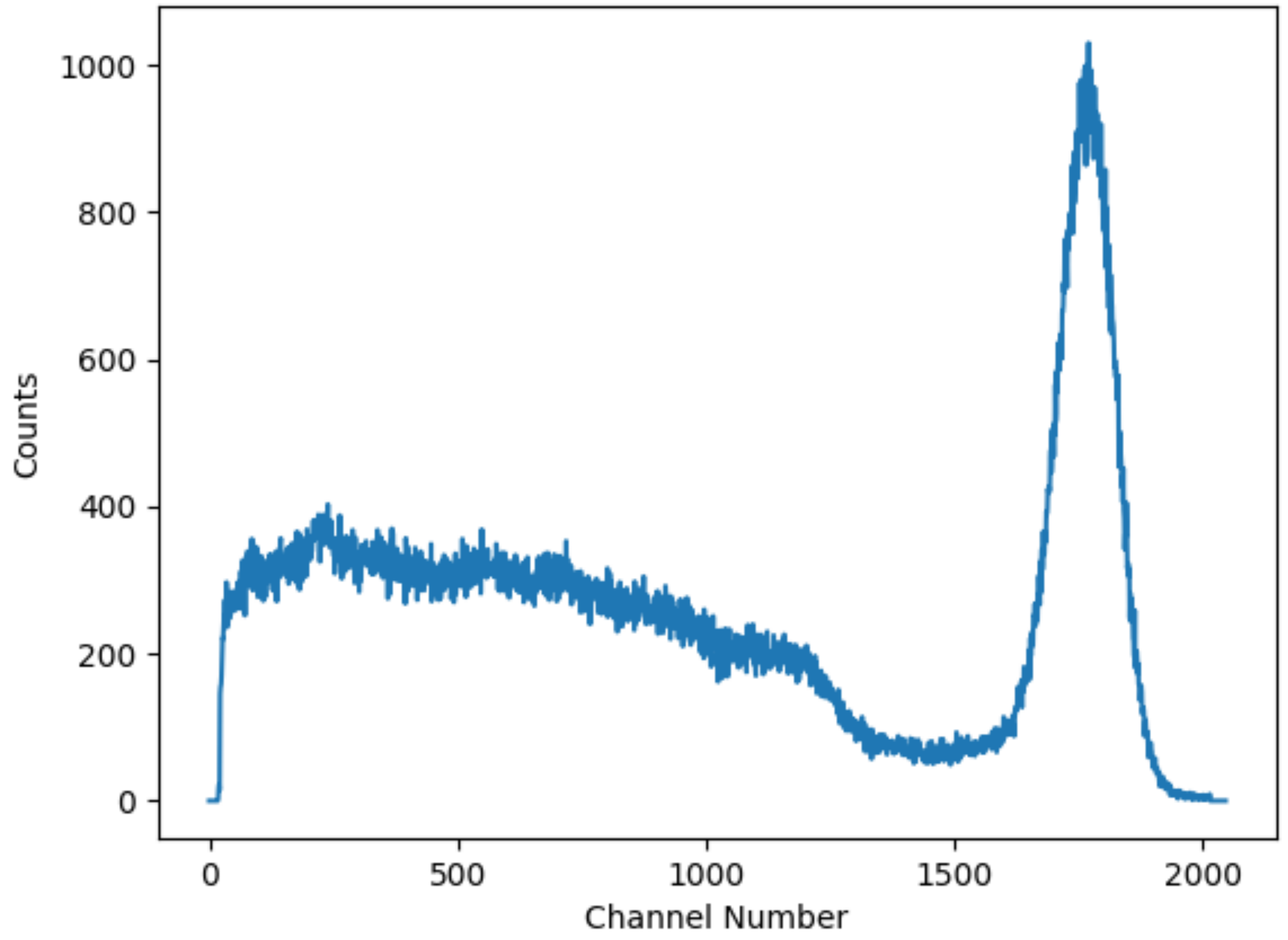
- Assumes nontrivial fraction of coincidence events are true Compton events
- Scatter should be a large peak at scattered photon energy in the angular direction
- Target picks up electron energies for Compton at all angles, weighted higher for ones of the right angle
- Peak at E_e, and fall off at Compton edge
- Large peak at E due to high density of non-Compton events





Measured Spectra

- Measured multi-day exposures at $\theta = 30, 60, 90, 135, 150$
- The electron energy peak is washed out for $\theta = 90$, and is very weak for $\theta = 135, 150$



Target detector output for $\theta = 90$

Extracted Peaks

- Energy given in keV, with statistical, then systematic uncertainty
- Systematic uncertainty arises from uncertainty in calibration parameters
- For $\theta = 30, 60, 135$, we find that $E_e + E' \approx E$, with a relative error of between 5% and 10%.

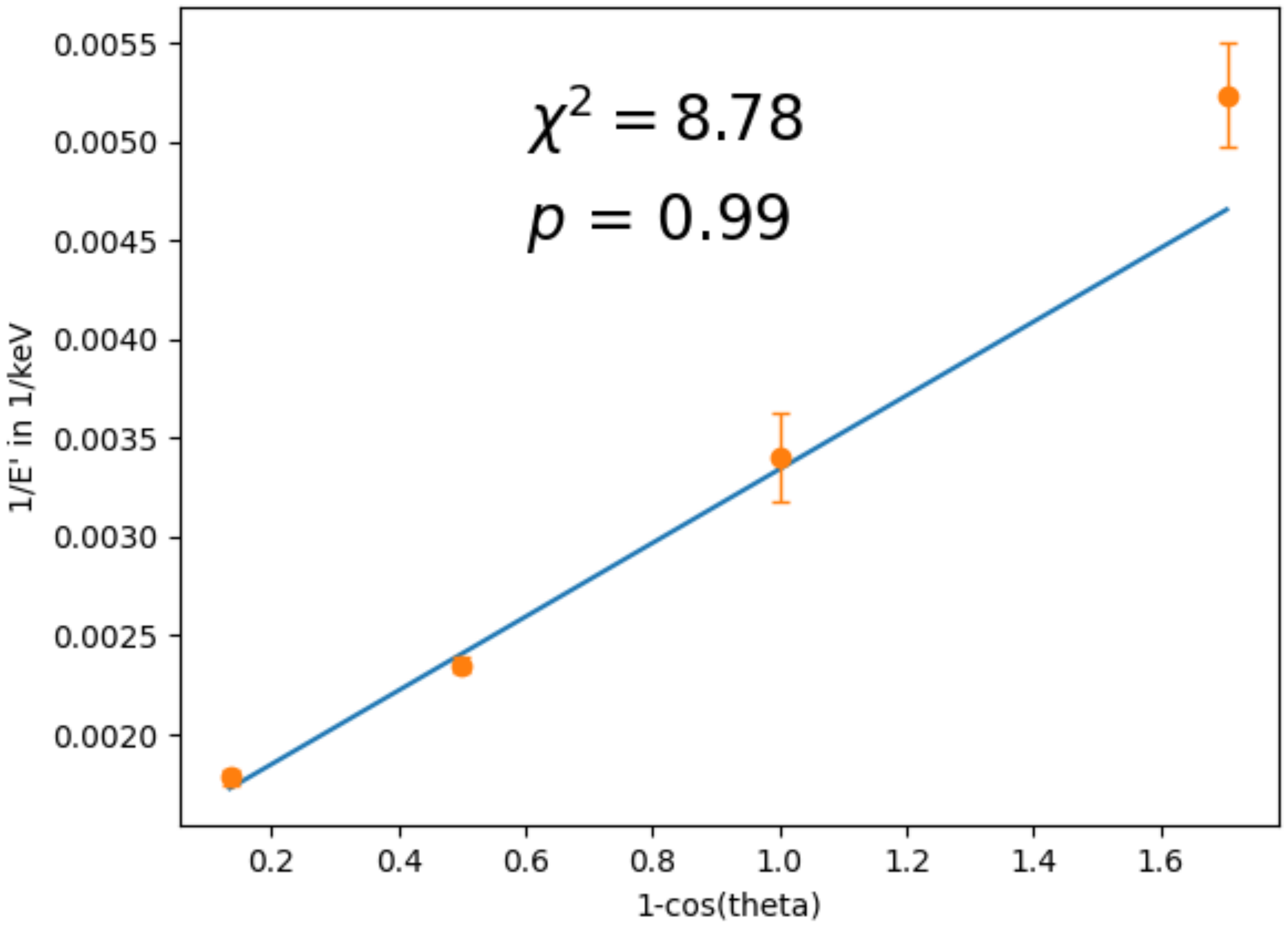
θ	N_e	N'	E_e	E'
30	189±25	1200±20	61±9±5	561±9±8
60	599±25	914±10	214±9±5	425±5±6
90	N/A	637±40	N/A	294±19±4
135	1129±40	420±20	412±15±5	191±9±3
150	1154±40	N/A	421±15±5	N/A

Checking Compton Prediction

- Recall the prediction
$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_e c^2}(1 - \cos\theta)$$

- We do a linear fit of $1/E'$ against $1 - \cos\theta$

- Curve fit tells us
$$\frac{1}{m_e c^2} = [1.86 \pm 0.1] \cdot 10^{-3}\,\mathrm{keV}^{-1}$$
$$\frac{1}{E} = [1.48 \pm 0.05] \cdot 10^{-3}\,\mathrm{keV}^{-1}$$



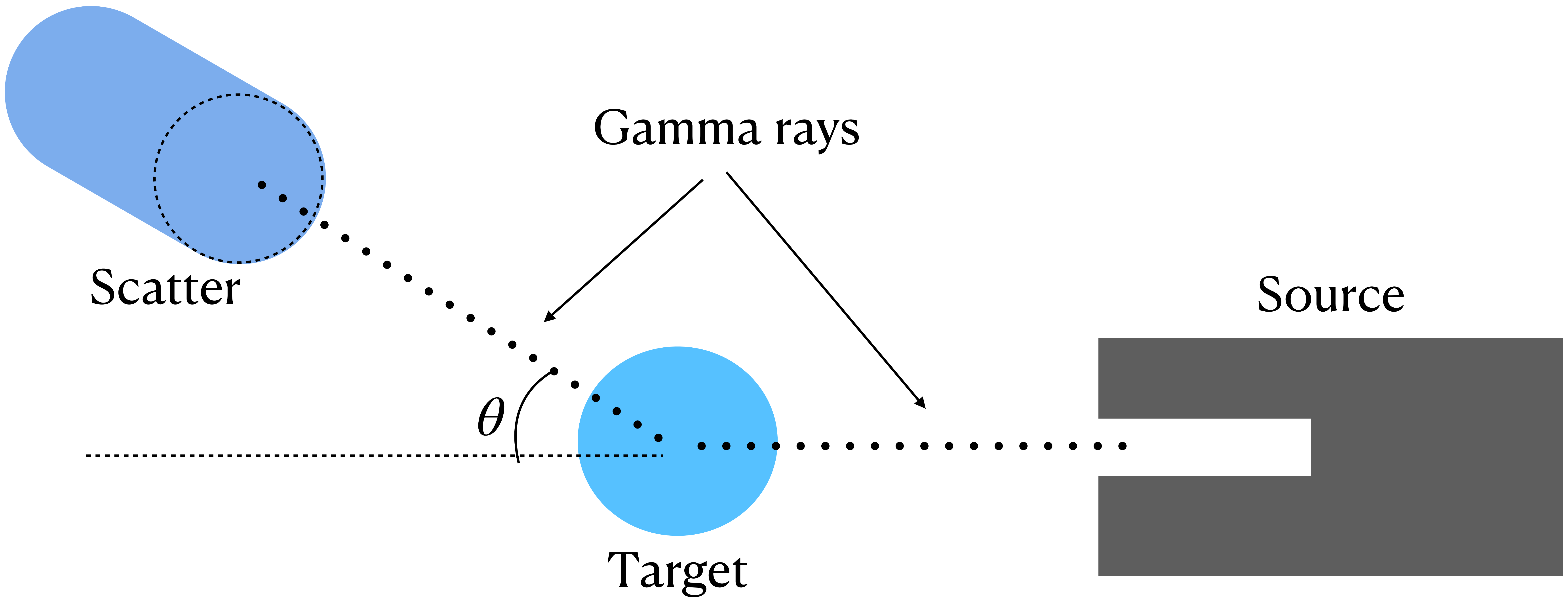
Linear fit of $1/E'$ against $1 - \cos\theta$

Conclusions

- Converting our previous results, we find the mass of electron to be $537 \pm 25\,\mathrm{keV}$, which matches known value of $511\,\mathrm{keV}$ and we find $E = 675 \pm 25\,\mathrm{keV}$, which also matches known value of $661.6\,\mathrm{keV}$

- This gives strong evidence for Compton's theory over Thomson's theory, which gives further evidence for the quantum nature of light

- Electrical components broke several times, and this leads to an unknown systematic error in results, due to uncertainty in state of system over the multi-day runs



Gamma rays
Scatter
Source
θ
Target