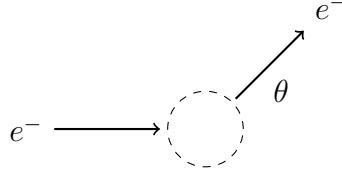
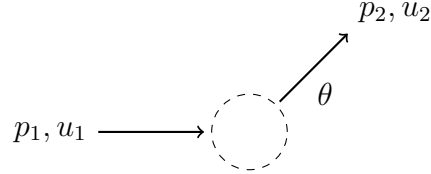


Consider an electron scattered by an atomic nucleus.



Here is the same diagram with momentum and spinor labels.



The path of the incident electron can be modeled as the  $z$  axis, resulting in the following momentum vectors.

$$p_1 = \begin{pmatrix} E \\ 0 \\ 0 \\ p \end{pmatrix} \quad p_2 = \begin{pmatrix} E \\ p \sin \theta \cos \phi \\ p \sin \theta \sin \phi \\ p \cos \theta \end{pmatrix}$$

inbound electron                  outbound electron

Symbol  $p$  is incident momentum,  $E$  is total energy  $E = \sqrt{p^2 + m^2}$ , and  $m$  is electron mass. Polar angle  $\theta$  is the observed scattering angle. Azimuth angle  $\phi$  cancels out in scattering calculations.

The spinors are

$$u_{11} = \begin{pmatrix} E + m \\ 0 \\ p \\ 0 \end{pmatrix} \quad u_{12} = \begin{pmatrix} 0 \\ E + m \\ 0 \\ -p \end{pmatrix} \quad u_{21} = \begin{pmatrix} E + m \\ 0 \\ p_{2z} \\ p_{2x} + ip_{2y} \end{pmatrix} \quad u_{22} = \begin{pmatrix} 0 \\ E + m \\ p_{2x} - ip_{2y} \\ -p_{2z} \end{pmatrix}$$

inbound electron, spin up    inbound electron, spin down    outbound electron, spin up    outbound electron, spin down

The spinors shown above are not individually normalized. Instead, a combined spinor normalization constant  $N = (E + m)^2$  will be used.

The following formula computes a probability density  $|\mathcal{M}_{ab}|^2$  for Rutherford scattering where  $a$  is the spin state of the inbound electron and  $b$  is the spin state of the outbound electron.

$$|\mathcal{M}_{ab}|^2 = \frac{Z^2 e^4}{q^4} \frac{1}{N} |\bar{u}_{2b} \gamma^0 u_{1a}|^2$$

Symbol  $Z$  is the atomic number of the nucleus,  $e$  is electron charge, and  $q = p_1 - p_2$  is momentum transfer.

The expected probability density  $\langle |\mathcal{M}|^2 \rangle$  is computed by summing  $|\mathcal{M}_{ab}|^2$  over all four spin states

and then dividing by the number of inbound states. There are two inbound states.

$$\begin{aligned}
\langle |\mathcal{M}|^2 \rangle &= \frac{1}{2} \sum_{a=1}^2 \sum_{b=1}^2 |\mathcal{M}_{ab}|^2 \\
&= \frac{Z^2 e^4}{2q^4} \frac{1}{N} \sum_{a=1}^2 \sum_{b=1}^2 |\bar{u}_{2b} \gamma^0 u_{1a}|^2 \\
&= \frac{Z^2 e^4}{2q^4} \text{Tr} \left( (\not{p}_1 + m) \gamma^0 (\not{p}_2 + m) \gamma^0 \right) \\
&= \frac{2Z^2 e^4}{q^4} (E^2 + m^2 + p^2 \cos \theta)
\end{aligned}$$

Run “rutherford-scattering-1.txt” to verify the following formulas.

$$\begin{aligned}
\frac{1}{N} \sum_{a=1}^2 \sum_{b=1}^2 |\bar{u}_{2b} \gamma^0 u_{1a}|^2 &= \text{Tr} \left( (\not{p}_1 + m) \gamma^0 (\not{p}_2 + m) \gamma^0 \right) = 4(E^2 + m^2 + p^2 \cos \theta) \\
q^4 &= (p_1 - p_2)^4 = 16p^4 \sin^4(\theta/2) = 4p^4(\cos \theta - 1)^2
\end{aligned}$$

## Low energy approximation

For low energy electrons such that  $p \ll m$  we can use the following approximation.

$$E^2 + m^2 + p^2 \cos \theta \approx 2m^2$$

Hence

$$\langle |\mathcal{M}|^2 \rangle = \frac{4m^2 Z^2 e^4}{q^4}$$

Substituting  $e^4 = 16\pi^2 \alpha^2$  and  $q^4 = 4p^4(\cos \theta - 1)^2$  we have

$$\langle |\mathcal{M}|^2 \rangle = \frac{16\pi^2 m^2 Z^2 \alpha^2}{p^4(\cos \theta - 1)^2}$$

The differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\langle |\mathcal{M}|^2 \rangle}{16\pi^2} = \frac{m^2 Z^2 \alpha^2}{p^4(\cos \theta - 1)^2}$$

We can integrate  $d\sigma$  to obtain a cumulative distribution function. Recall that

$$d\Omega = \sin \theta d\theta d\phi$$

Hence

$$d\sigma = \frac{m^2 Z^2 \alpha^2}{p^4(\cos \theta - 1)^2} \sin \theta d\theta d\phi$$

Let  $I(\theta)$  be the following integral of  $d\sigma$ .

$$\begin{aligned}
I(\theta) &= \left( \frac{p^4}{m^2 Z^2 \alpha^2} \right) \frac{1}{2\pi} \int_0^{2\pi} \int d\sigma \\
&= \int \frac{1}{(\cos \theta - 1)^2} \sin \theta d\theta \\
&= \frac{1}{\cos \theta - 1}, \quad a \leq \theta \leq \pi
\end{aligned}$$

Angular support is limited to an arbitrary  $a > 0$  because  $I(0)$  is undefined.

Let  $C$  be the normalization constant

$$C = I(\pi) - I(a)$$

Then the cumulative distribution function  $F(\theta)$  is

$$F(\theta) = \frac{I(\theta) - I(a)}{C}, \quad a \leq \theta \leq \pi$$

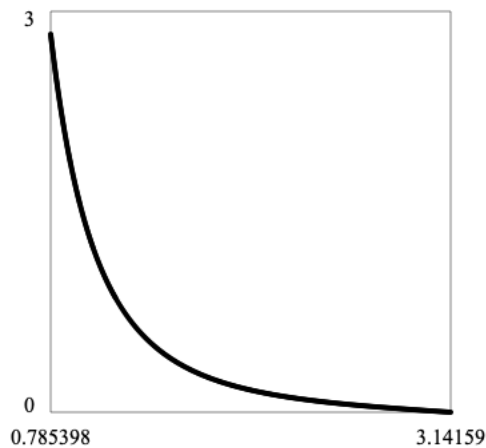
The probability of observing scattering events in the interval  $\theta_1$  to  $\theta_2$  can now be computed.

$$P(\theta_1 \leq \theta \leq \theta_2) = F(\theta_2) - F(\theta_1)$$

Probability density function  $f(\theta)$  is the derivative of  $F(\theta)$ .

$$f(\theta) = \frac{dF(\theta)}{d\theta} = \frac{\sin \theta}{C(\cos \theta - 1)^2}$$

Run “rutherford-scattering-3.txt” to draw a graph of  $f(\theta)$  for  $a = \pi/4 = 45^\circ$ .



Probability distribution for  $45^\circ$  bins ( $a = 45^\circ$ ).

| $\theta_1$  | $\theta_2$  | $P(\theta_1 \leq \theta \leq \theta_2)$ |
|-------------|-------------|---|
| $0^\circ$   | $45^\circ$  | —                                       |
| $45^\circ$  | $90^\circ$  | 0.83                                    |
| $90^\circ$  | $135^\circ$ | 0.14                                    |
| $135^\circ$ | $180^\circ$ | 0.03                                    |

Note: The original Rutherford scattering experiment in 1911 used alpha particles, not electrons. However, scattering of any charged particle by Coulomb interaction is now known as Rutherford scattering. The first Rutherford scattering experiment using electrons appears to have been done by F. L. Arnot, then a student of Rutherford, in 1929.