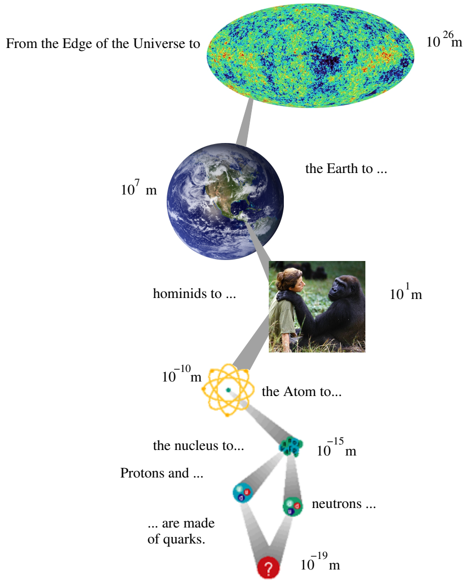
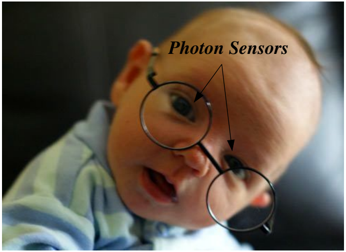

From the Edge of the Universe to
10^{26} m
the Earth to ...
10^{7} m
hominids to ...
10^{1} m
10^{-10} m
the Atom to...
the nucleus to...
10^{-15} m
Protons and ...
neutrons ...
... are made of quarks.
10^{-19} m

Watch

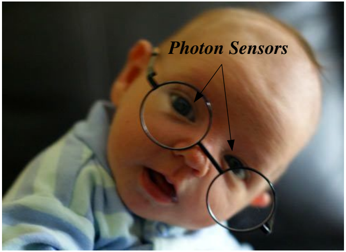
How Do We Know The Really Small Stuff?

SCATTERING!



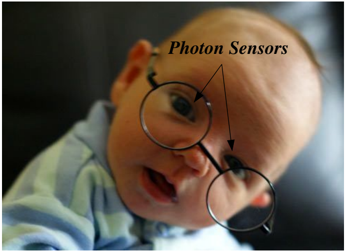
SCATTERING!

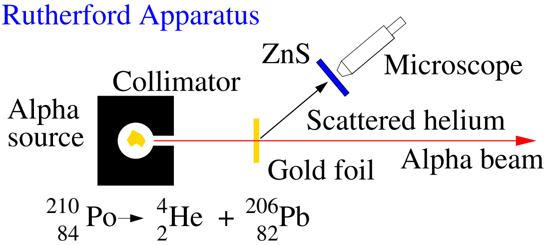
RUTHERFORD SCATTERING!



SCATTERING!

RUTHERFORD SCATTERING!

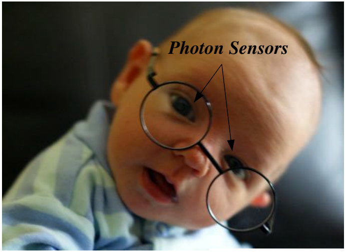




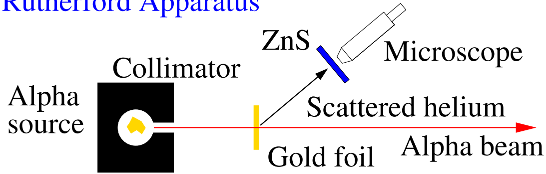
Simulation is here.

SCATTERING!

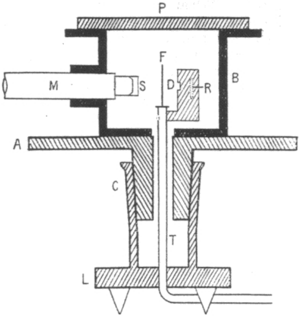
RUTHERFORD SCATTERING!



Rutherford Apparatus



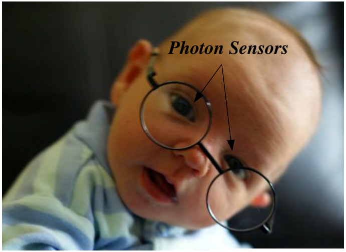
$$^{210}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{206}_{82}\text{Pb}$$

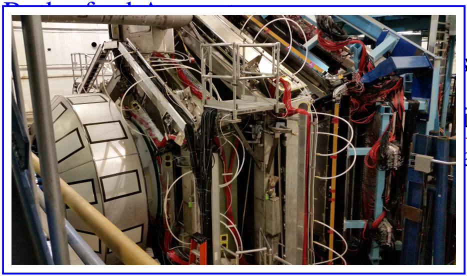


Simulation is here.

SCATTERING!

RUTHERFORD SCATTERING!

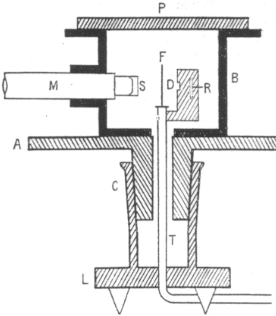




scope

ium

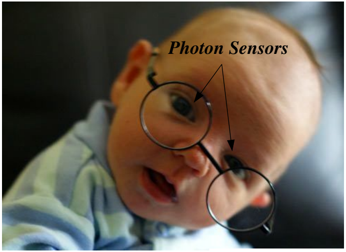
a beam

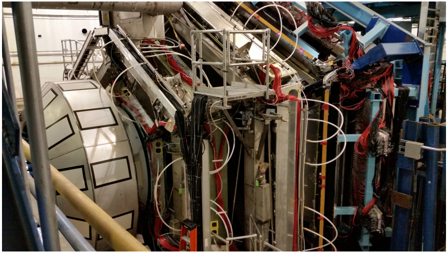


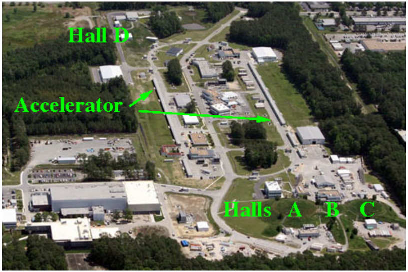
Simulation is here.

SCATTERING!

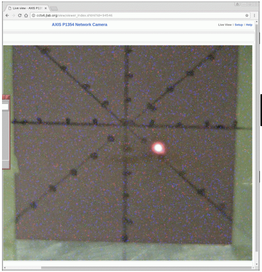
RUTHERFORD SCATTERING!

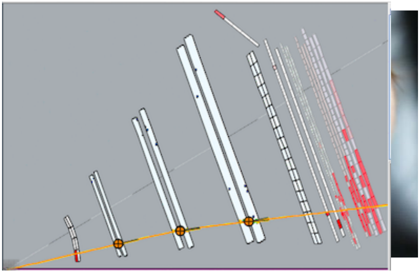


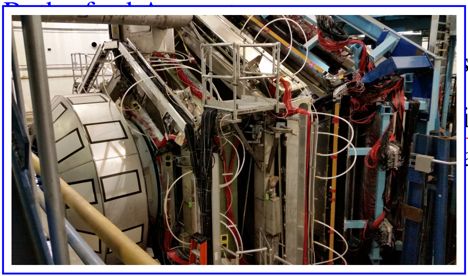


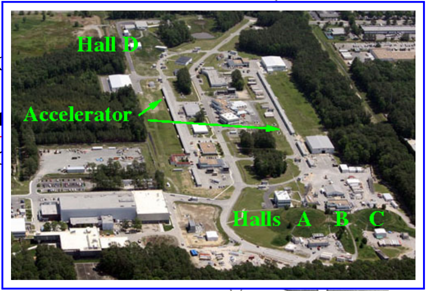


Simulation is here.



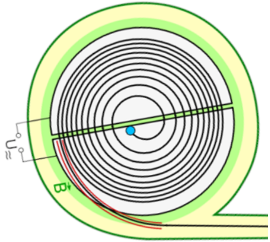




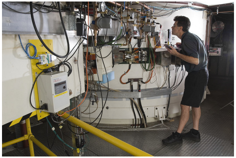


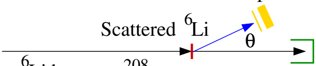
Simulation is here.

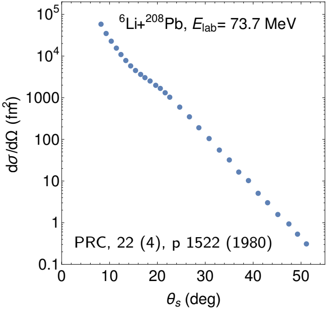
The experimental setup shown below is analogous to Rutherford's used to discover the nucleus. A beam of $^{6}\mathrm{Li}$-nuclei is accelerated to an energy $E_{lab} = 73.7\ \mathrm{MeV}$ in a cyclotron. It strikes a lead ($^{208}\mathrm{Pb}$) target scattering $^{6}\mathrm{Li}$ into a $\Delta\mathrm{E}-\mathrm{E}$ silicon detector. The plot shows the differential cross section measured as a function of θ. (1) How do these results compare to the Rutherford cross section? (2) What is the distance of closest approach (DOCA) of the $^{6}\mathrm{Li}$ to the $^{208}\mathrm{Pb}$ target before the $^{6}\mathrm{Li}$ and $^{208}\mathrm{Pb}$ actually collide?

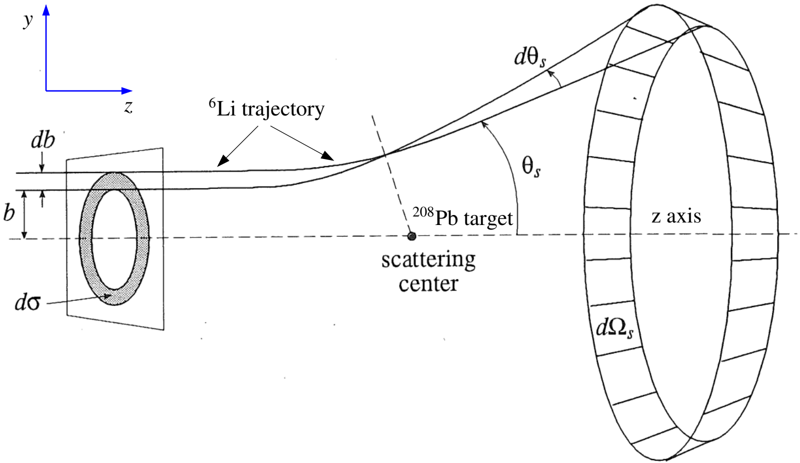


Cyclotron

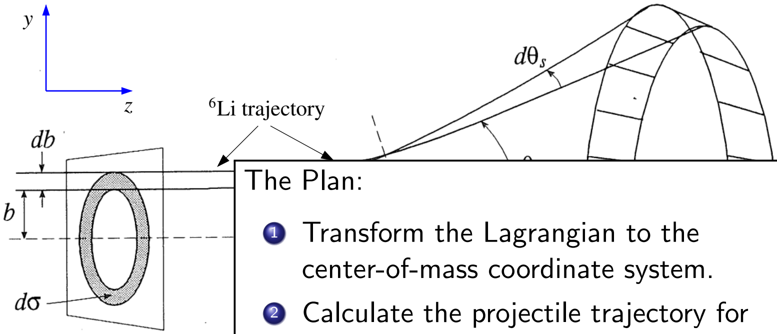








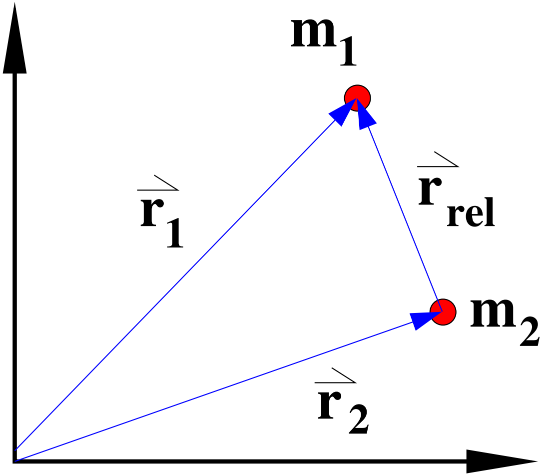
Simulation is here.



The Plan:

1. Transform the Lagrangian to the center-of-mass coordinate system.
2. Calculate the projectile trajectory for Coulomb repulsion.
3. Relate b and θ_s.
4. Construct $d\sigma/d\Omega$.
5. Get $d\sigma/d\Omega$ for random impact parameters.
6. Compare with data.

Simulation is here.


m1
r1
rel
r
m2
r2

For two particles m_1 and m_2 interacting through some force we will use a particular coordinate system called the center-of-mass (CM) system. In the CM frame the total momentum is required to be zero so the CM is

$$\vec{r}_{cm} = \frac{m_1 \vec{r}_1 + m_2 \vec{r}_2}{m_1 + m_2}$$

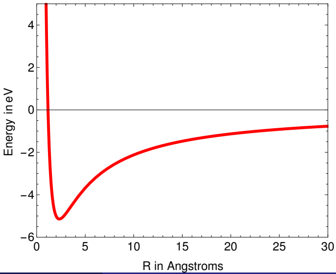
and it acts like this. The two particles in the system now behave as single particle with a different mass called the reduced mass.

$$m_r = \frac{m_1 m_2}{m_1 + m_2}$$

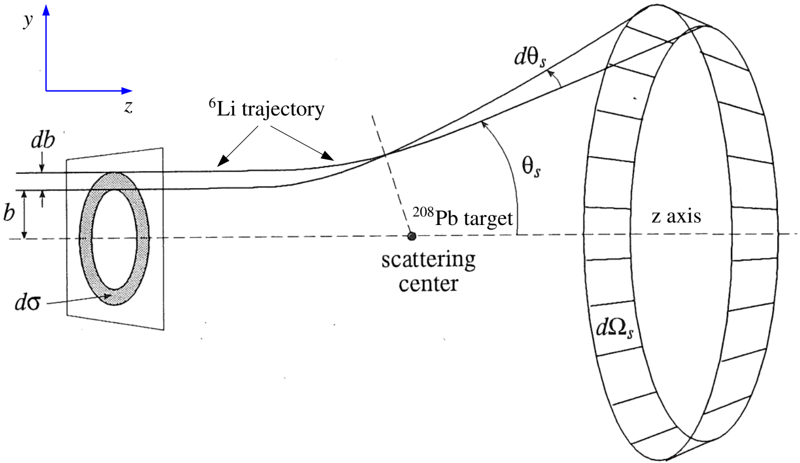
The potential energy between a Na^+ ion and a Cl^- ion is

$$V(r) = -\frac{A}{r} + \frac{B}{r^2}$$

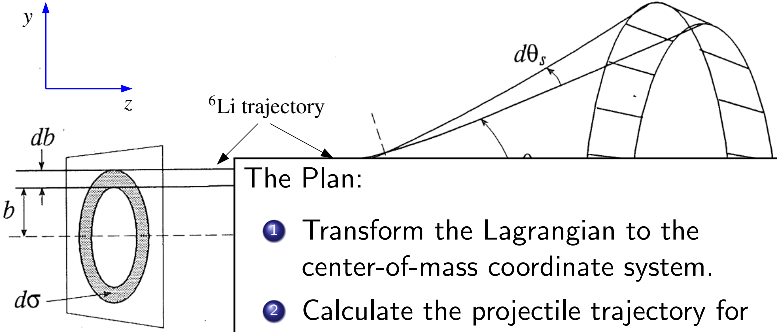
where $\mathrm{A} = 24\ \mathrm{eV} - \mathrm{Å}$ and $\mathrm{B} = 28\ \mathrm{eV} - \mathrm{Å}^2$. Is the attractive part of V consistent with the force between two point charges? Where is the equilibrium point? What equation describes the ions' separation near the equilibrium point? What is the energy of the system? At $t = 0$, the separation of the ions is $2.0\ \mathrm{Å}$ and their relative velocity is zero.



We treated the vibrations of the Na-Cl system as a single harmonic oscillator with an 'average' mass.



Simulation is here.



The Plan:

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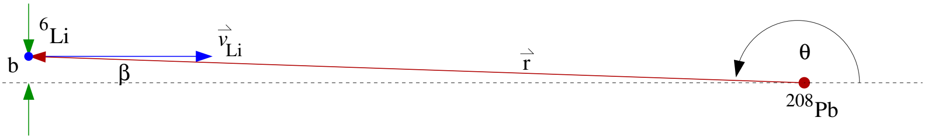
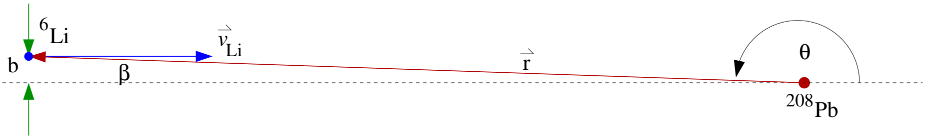
3. Relate b and θ_s.
4. Construct $d\sigma/d\Omega$.
5. Get $d\sigma/d\Omega$ for random impact parameters.
6. Compare with data.

Simulation is here.

Initial Rutherford scattering geometry

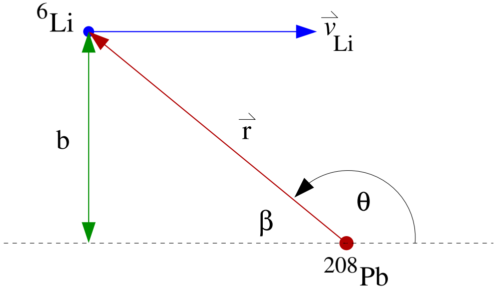


Initial Rutherford scattering geometry



Re-scale it to see the angles better.

$$L = \mu r^2 \dot{\theta} = \mu r (r\dot{\theta})$$



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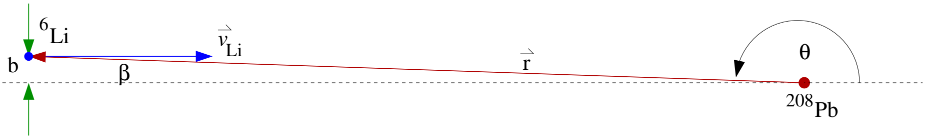

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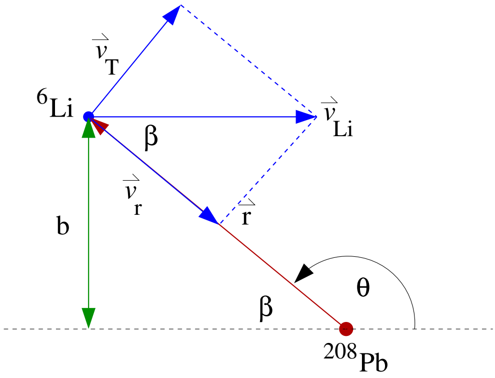
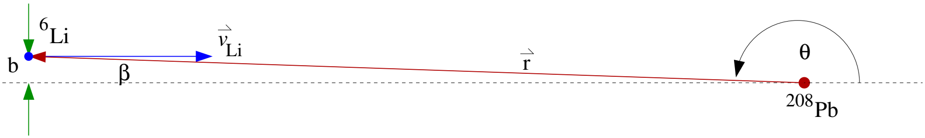
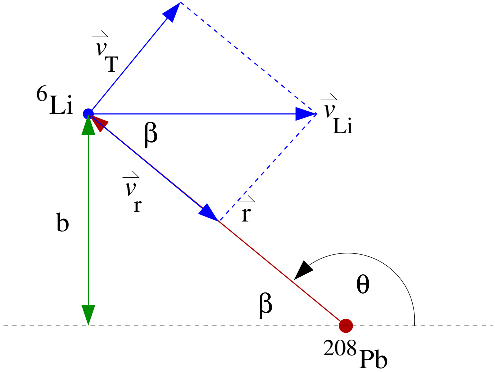


Initial Rutherford scattering geometry

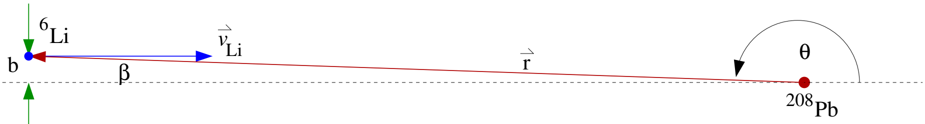


Re-scale it to see the angles better.

$$L = \mu r^2 \dot{\theta} = \mu r (r\dot{\theta}) = \mu r v_T$$

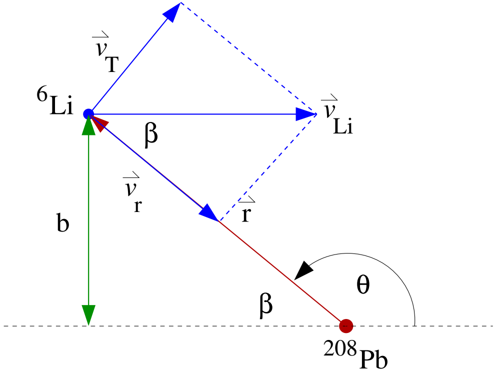


Initial Rutherford scattering geometry

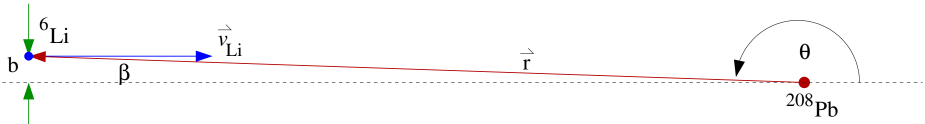


Re-scale it to see the angles better.

$$L = \mu r^2\dot{\theta} = \mu r(r\dot{\theta}) = \mu r v_T$$
$$= \mu r v_{Li} \sin\beta$$



Initial Rutherford scattering geometry



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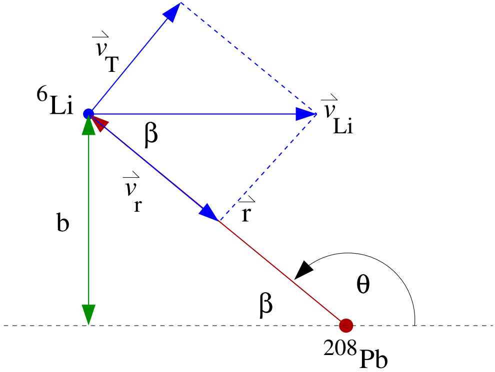
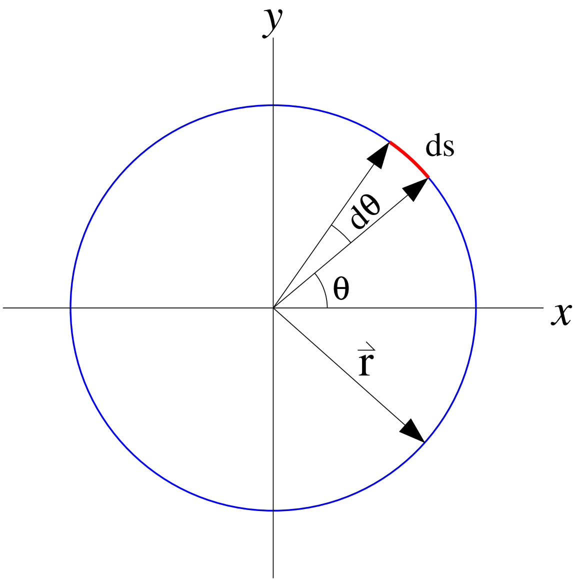
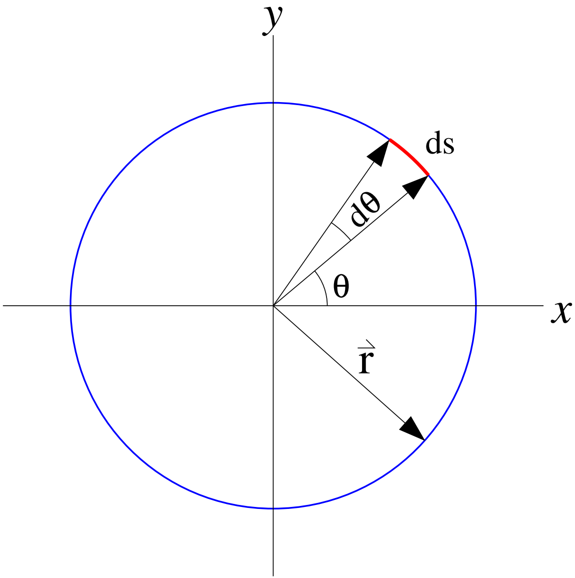


$$L = \mu r^2 \dot{\theta} = \mu r(r\dot{\theta}) = \mu r v_T$$
$$= \mu r v_{Li} \sin\beta = \mu v_{Li} b$$

What is an Angle?

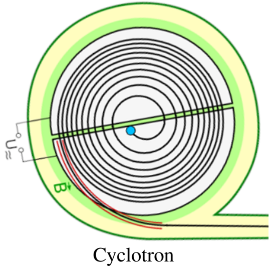


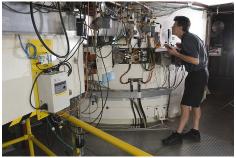
What is an Angle?

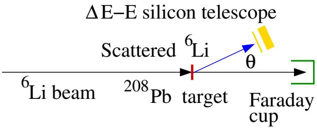


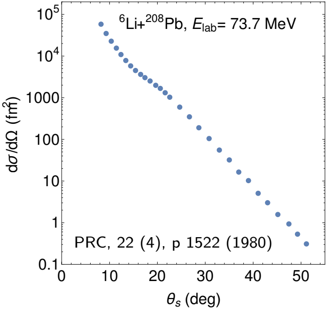
$$d\theta = \frac{ds}{|\vec{r}|}$$

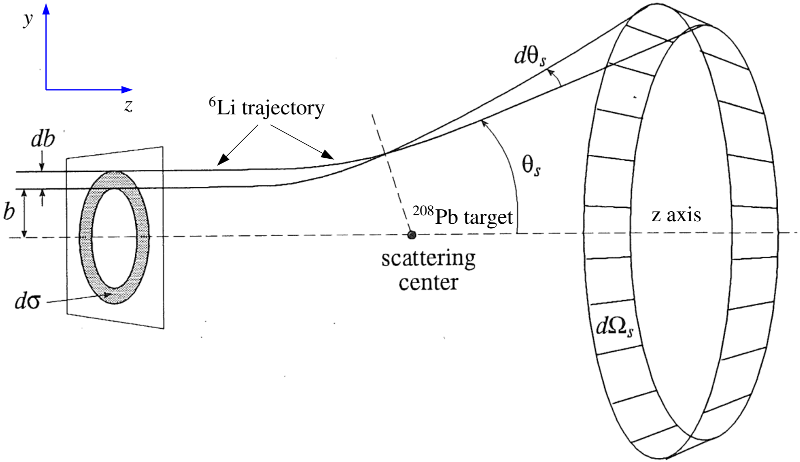
The experimental setup shown below is analogous to Rutherford's used to discover the nucleus. A beam of $^{6}\mathrm{Li}$-nuclei is accelerated to an energy $E_{lab} = 73.7\ \mathrm{MeV}$ in a cyclotron. It strikes a lead ($^{208}\mathrm{Pb}$) target scattering $^{6}\mathrm{Li}$ into a $\Delta\mathrm{E} - \mathrm{E}$ silicon detector. The plot shows the differential cross section measured as a function of θ. (1) How do these results compare to the Rutherford cross section? (2) What is the distance of closest approach (DOCA) of the $^{6}\mathrm{Li}$ to the $^{208}\mathrm{Pb}$ target before the $^{6}\mathrm{Li}$ and $^{208}\mathrm{Pb}$ actually collide?

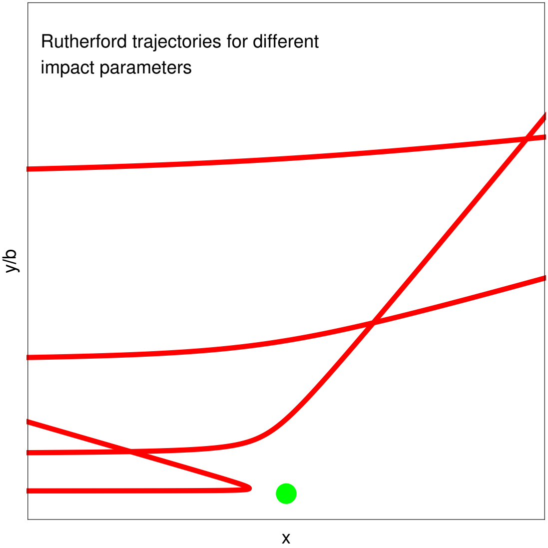






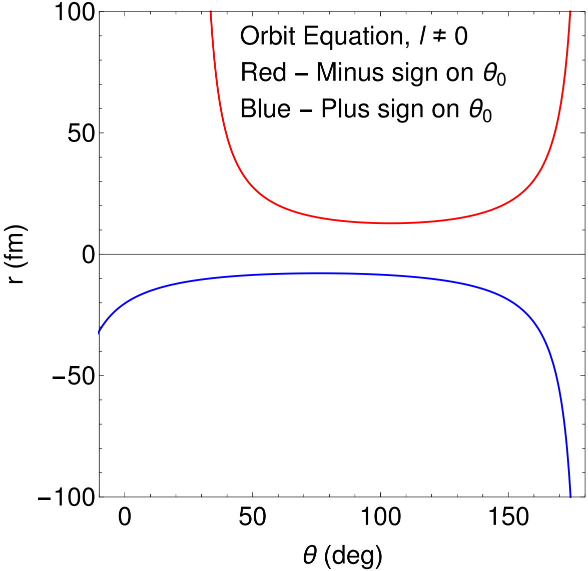



y
z
db
b
dσ
6Li trajectory
208Pb target
scattering center
dθs
θs
z axis
dΩs


Rutherford trajectories for different
impact parameters
y/b
x

Phase Relations for Trignometric Functions

$$
\begin{aligned}
\sin(\pi-\theta) &= +\sin\theta & \sin\left(\theta+\tfrac{\pi}{2}\right) &= +\cos\theta \\
\cos(\pi-\theta) &= -\cos\theta & \cos\left(\theta+\tfrac{\pi}{2}\right) &= -\sin\theta \\
\tan(\pi-\theta) &= -\tan\theta & \tan\left(\theta+\tfrac{\pi}{2}\right) &= -\cot\theta \\
\csc(\pi-\theta) &= +\csc\theta & \csc\left(\theta+\tfrac{\pi}{2}\right) &= +\sec\theta \\
\sec(\pi-\theta) &= -\sec\theta & \sec\left(\theta+\tfrac{\pi}{2}\right) &= -\csc\theta \\
\cot(\pi-\theta) &= -\cot\theta & \cot\left(\theta+\tfrac{\pi}{2}\right) &= -\tan\theta
\end{aligned}
$$



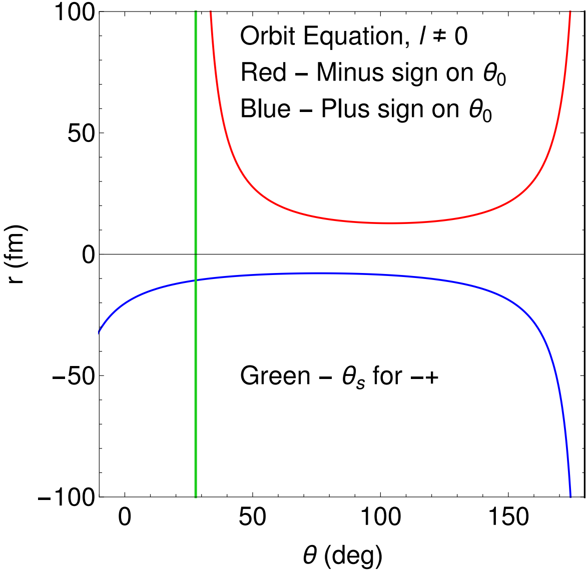
Orbit Equation, $l \neq 0$
Red – Minus sign on θ_0
Blue – Plus sign on θ_0
r (fm)
100
50
0
−50
−100
0
50
100
150
θ (deg)

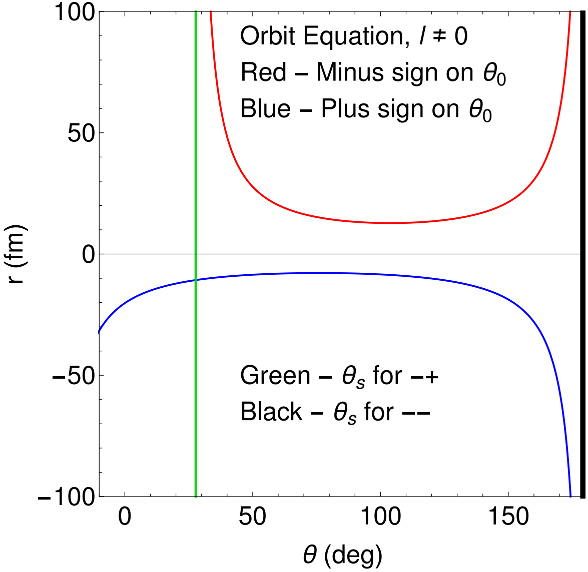
Negative Argument Formulas for Trignometric Functions

$$\sin(-\theta) = -\sin\theta$$
$$\cos(-\theta) = +\cos\theta$$
$$\tan(-\theta) = -\tan\theta$$
$$\csc(-\theta) = -\csc\theta$$
$$\sec(-\theta) = +\sec\theta$$
$$\cot(-\theta) = -\cot\theta$$

Negative Argument Formulas for Inverse Trignometric Functions

$$\arcsin(-x) = -\arcsin(x)$$
$$\arccos(-x) = \pi - \arccos(x)$$
$$\arctan(-x) = -\arctan(x)$$
$$\text{arccot}(-x) = \pi - \text{arccot}(x)$$
$$\text{arcsec}(-x) = \pi - \text{arcsec}(x)$$
$$\text{arccsc}(-x) = -\text{arccsc}(x)$$


Orbit Equation, $l \neq 0$
Red – Minus sign on θ_0
Blue – Plus sign on θ_0
Green – θ_s for −+
r (fm)
100
50
0
−50
−100
0
50
100
150
θ (deg)


Orbit Equation, $l \neq 0$
Red – Minus sign on θ_0
Blue – Plus sign on θ_0
Green – θ_s for –+
Black – θ_s for ––
r (fm)
θ (deg)
100
50
0
−50
−100
0
50
100
150

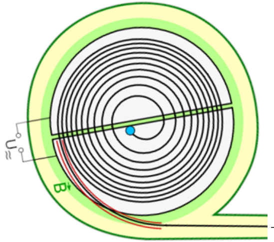
Negative Argument Formulas for Trignometric Functions

$$\sin(-\theta) = -\sin\theta$$
$$\cos(-\theta) = +\cos\theta$$
$$\tan(-\theta) = -\tan\theta$$
$$\csc(-\theta) = -\csc\theta$$
$$\sec(-\theta) = +\sec\theta$$
$$\cot(-\theta) = -\cot\theta$$

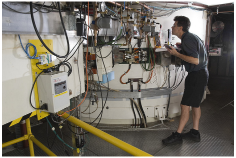
Phase Relationships for Trignometric Functions

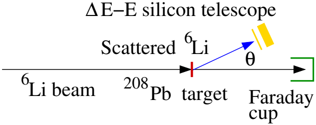
$$\sin(\tfrac{\pi}{2} - \theta) = +\cos\theta \qquad \sin(\theta + \pi) = -\sin\theta$$
$$\cos(\tfrac{\pi}{2} - \theta) = +\sin\theta \qquad \cos(\theta + \pi) = -\cos\theta$$
$$\tan(\tfrac{\pi}{2} - \theta) = +\cot\theta \qquad \tan(\theta + \pi) = +\tan\theta$$
$$\csc(\tfrac{\pi}{2} - \theta) = +\sec\theta \qquad \csc(\theta + \pi) = -\csc\theta$$
$$\sec(\tfrac{\pi}{2} - \theta) = +\csc\theta \qquad \sec(\theta + \pi) = -\sec\theta$$
$$\cot(\tfrac{\pi}{2} - \theta) = +\tan\theta \qquad \cot(\theta + \pi) = +\cot\theta$$

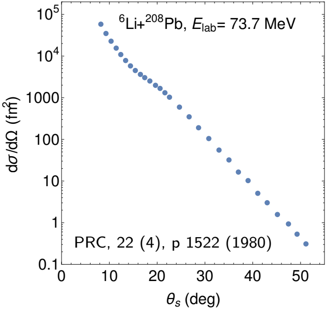
The experimental setup shown below is analogous to Rutherford's used to discover the nucleus. A beam of $^{6}\mathrm{Li}$-nuclei is accelerated to an energy $E_{lab} = 73.7\ \mathrm{MeV}$ in a cyclotron. It strikes a lead ($^{208}\mathrm{Pb}$) target scattering $^{6}\mathrm{Li}$ into a $\Delta\mathrm{E} - \mathrm{E}$ silicon detector. The plot shows the differential cross section measured as a function of θ. (1) How do these results compare to the Rutherford cross section? (2) What is the distance of closest approach (DOCA) of the $^{6}\mathrm{Li}$ to the $^{208}\mathrm{Pb}$ target before the $^{6}\mathrm{Li}$ and $^{208}\mathrm{Pb}$ actually collide?

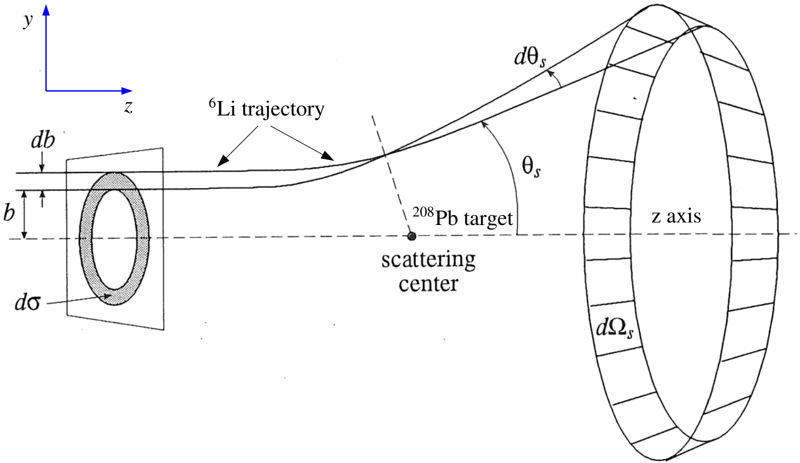


Cyclotron

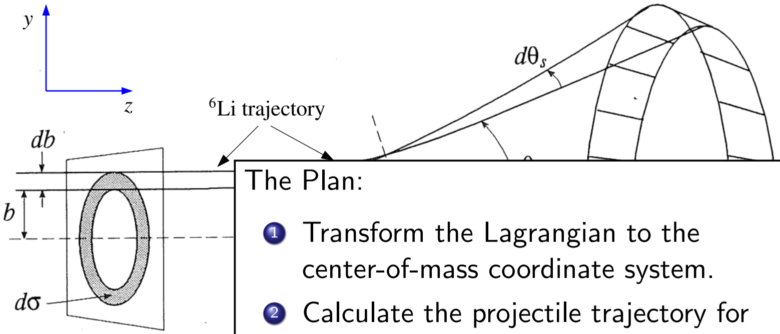








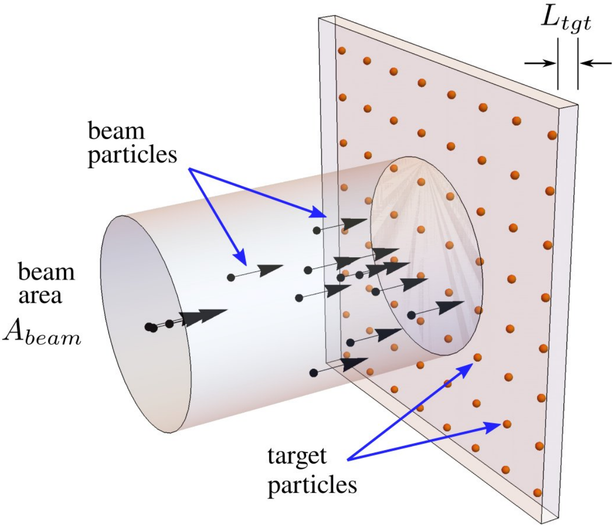
Simulation is here.



The Plan:

1. Transform the Lagrangian to the center-of-mass coordinate system.
2. Calculate the projectile trajectory for Coulomb repulsion.
3. Relate θ_s to input parameters.
4. Construct the cross section.
5. Get $d\sigma/d\Omega$.
6. Compare with data.

Simulation is here.



molar mass A_{tgt}

density ρ_{tgt}

Avogadro's N_A

beam current I_{beam}

beam charge q_{beam}

target thickness L_{tgt}

beamtime on target Δt

beam area A_{beam}

particle rate scattered into dA of detector	$= \frac{dN_s}{dt}$	$\propto$	incident beam rate	$\times$	areal target density	$\times$	angular detector size		

$$\frac{dN_s}{dt} \propto \frac{dN_{inc}}{dt} \times n_{tgt} \times d\Omega$$

$$\frac{dN_s}{dt} = \frac{d\sigma}{d\Omega} \times \frac{dN_{inc}}{dt} \times n_{tgt} \times d\Omega$$

$$\frac{dN_{inc}}{dt} = \frac{\Delta N_{inc}}{\Delta t} = \frac{I_{beam}}{Ze}$$

I_{beam} - beam current
Z - beam charge

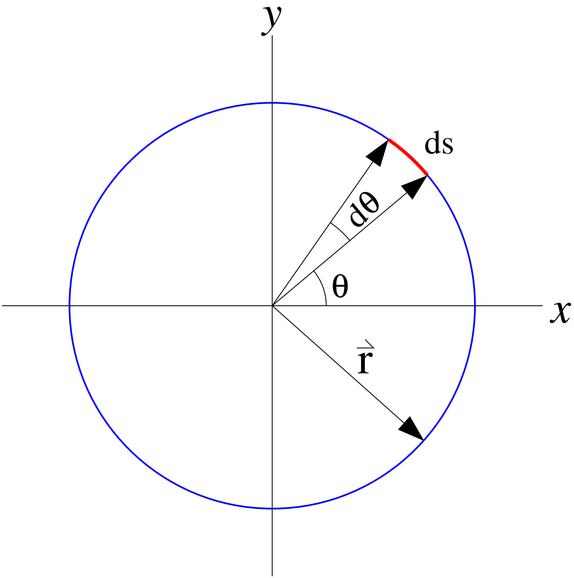
$$n_{tgt} = \frac{N_{tgt}}{A_{beam}} = \frac{\frac{\rho_{tgt}}{A_{tgt}} N_A A_{beam} L_{tgt}}{A_{beam}} = \frac{\rho_{tgt}}{A_{tgt}} N_A L_{tgt}$$

ρ_{tgt} - target density
A_{tgt} - molar mass
A_{beam} - beam area
L_{tgt} - target thickness

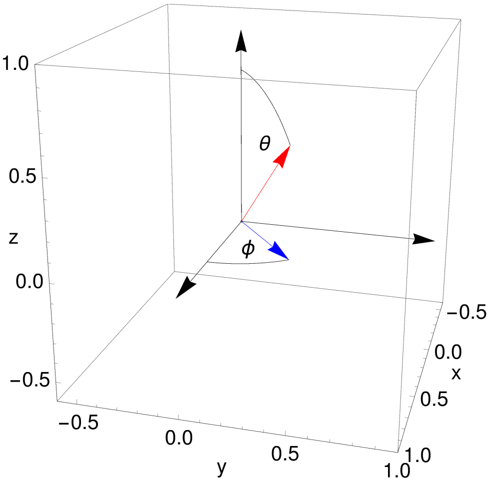
$$d\Omega = \frac{dA_{det}}{r_{det}^2} = \frac{\Delta A_{det}}{r_{det}^2} = \sin\theta d\theta d\phi$$

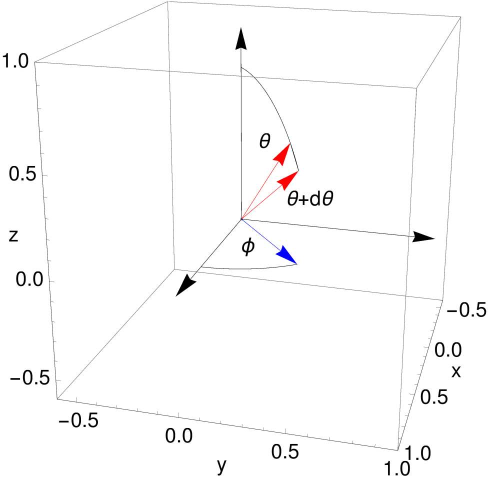
dA_{det} - detector area
r_{det} - target-detector distance

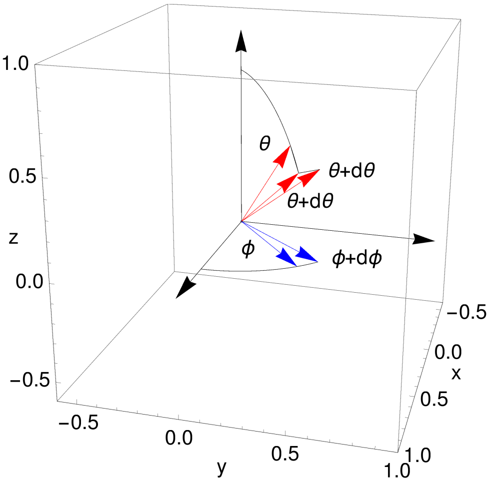
What is an Angle?

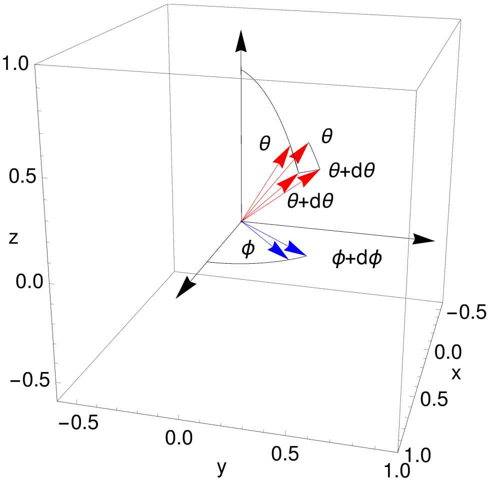


$$d\theta = \frac{ds}{|\vec{r}|}$$

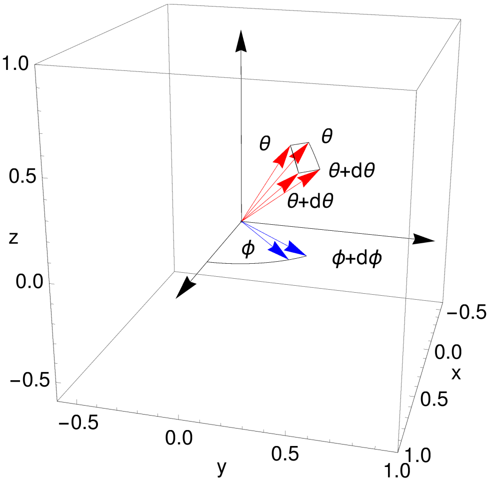

1.0
0.5
z
0.0
−0.5
θ
ϕ
−0.5
0.0
y
0.5
1.0
−0.5
0.0
x
0.5
1.0


1.0
0.5
z
0.0
−0.5
−0.5
0.0
y
0.5
1.0
−0.5
0.0
x
0.5
1.0
θ
θ+dθ
ϕ

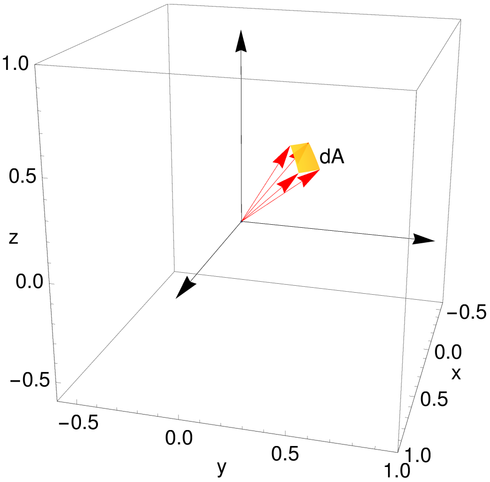

1.0
0.5
z
0.0
−0.5
−0.5
0.0
y
0.5
1.0
−0.5
0.0
x
0.5
1.0
θ
θ+dθ
θ+dθ
ϕ
ϕ+dϕ

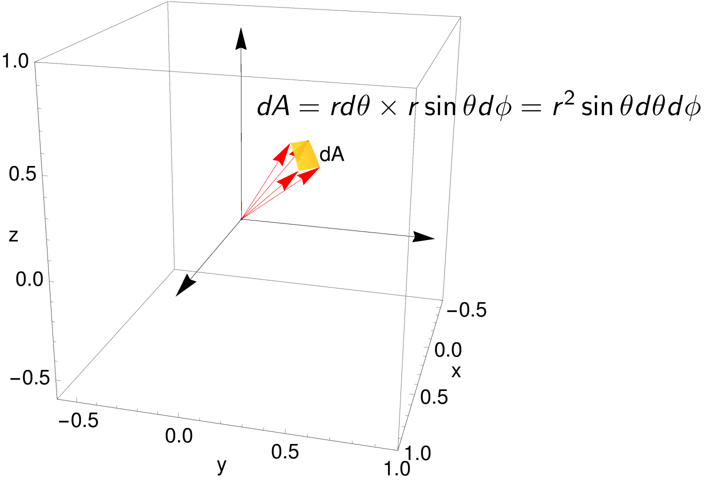

1.0
0.5
z
0.0
−0.5
−0.5
0.0
y
0.5
1.0
−0.5
0.0
x
0.5
1.0
θ
θ
θ+dθ
θ+dθ
ϕ
ϕ+dϕ

Solid Angle

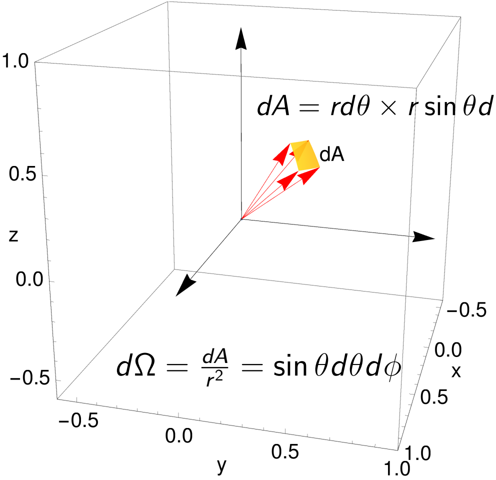


Solid Angle





$dA = rd\theta \times r\sin\theta d\phi = r^2 \sin\theta d\theta d\phi$
dA
1.0
0.5
z
0.0
−0.5
−0.5
0.0
y
0.5
1.0
−0.5
0.0
x
0.5
1.0



$$dA = rd\theta \times r\sin\theta d\phi = r^2 \sin\theta d\theta d\phi$$

$$d\Omega = \frac{dA}{r^2} = \sin\theta d\theta d\phi$$

particle rate scattered into dA of detector	$= \frac{dN_s}{dt}$	$\propto$	incident beam rate	$\times$	areal target density	$\times$	angular detector size
	$\frac{dN_s}{dt}$	$\propto$	$\frac{dN_{inc}}{dt}$	$\times$	n_{tgt}	$\times$	$d\Omega$

$$\frac{dN_s}{dt} = \frac{d\sigma}{d\Omega} \times \frac{dN_{inc}}{dt} \times n_{tgt} \times d\Omega$$

$$\frac{dN_{inc}}{dt} = \frac{\Delta N_{inc}}{\Delta t} = \frac{I_{beam}}{Ze}$$

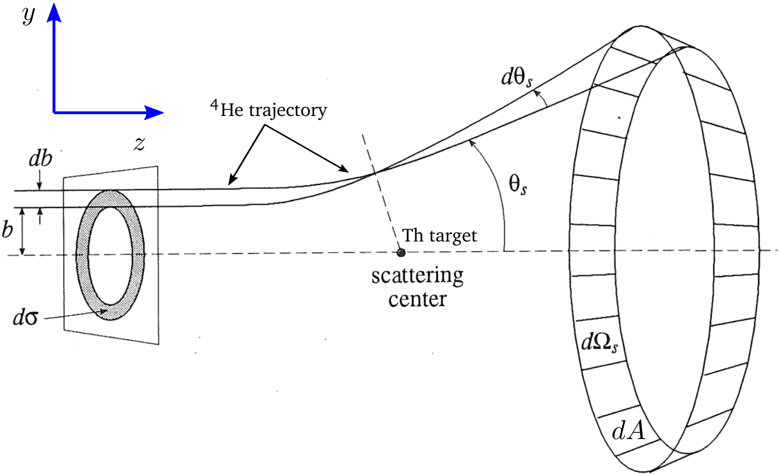
I_{beam} - beam current
Z - beam charge

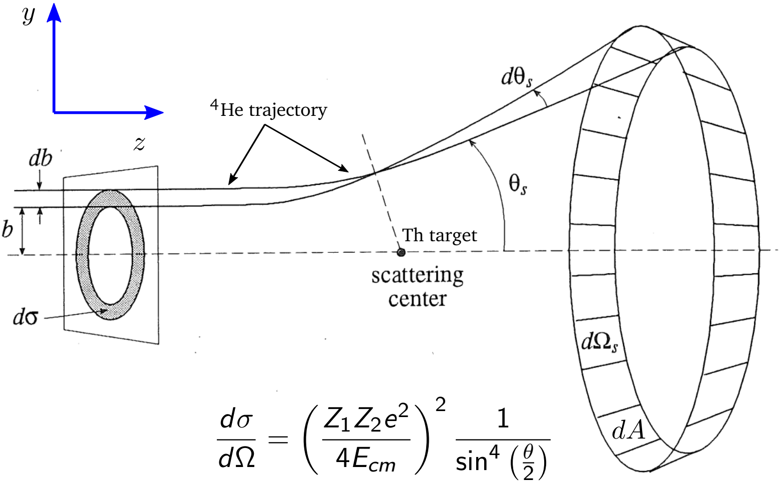
$$n_{tgt} = \frac{N_{tgt}}{A_{beam}} = \frac{\frac{\rho_{tgt}}{A_{tgt}} N_A A_{beam} L_{tgt}}{A_{beam}} = \frac{\rho_{tgt}}{A_{tgt}} N_A L_{tgt}$$

ρ_{tgt} - target density
A_{tgt} - molar mass
A_{beam} - beam area
L_{tgt} - target thickness

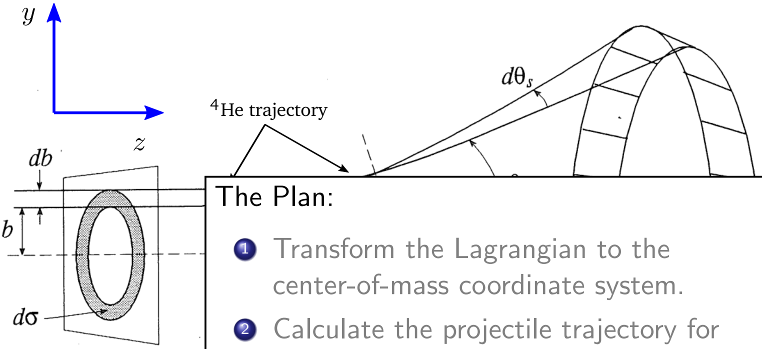
$$d\Omega = \frac{dA_{det}}{r_{det}^2} = \frac{\Delta A_{det}}{r_{det}^2} = \sin\theta d\theta d\phi$$

dA_{det} - detector area
r_{det} - target-detector distance


y
z
^{4}He trajectory
$d\theta_s$
db
b
θ_s
Th target
scattering
center
$d\sigma$
$d\Omega_s$
dA



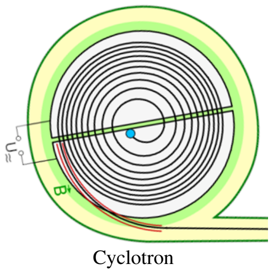
$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4E_{cm}}\right)^2 \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$$

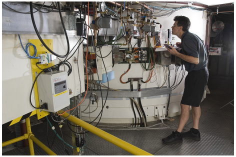


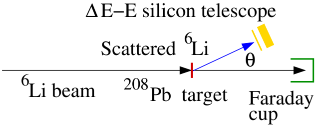
The Plan:

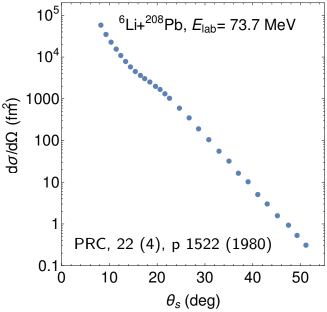
1. Transform the Lagrangian to the center-of-mass coordinate system.
2. Calculate the projectile trajectory for Coulomb repulsion.
3. Relate θ_s to input parameters.
4. Construct the cross section.
5. Get $d\sigma/d\Omega$.
6. Compare with data.

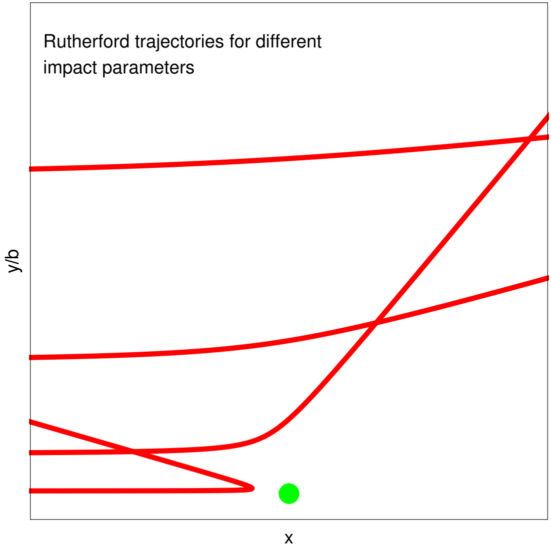
The experimental setup shown below is analogous to Rutherford's used to discover the nucleus. A beam of $^6\mathrm{Li}$-nuclei is accelerated to an energy $E_{lab} = 73.7\ \mathrm{MeV}$ in a cyclotron. It strikes a lead ($^{208}\mathrm{Pb}$) target scattering $^6\mathrm{Li}$ into a $\Delta\mathrm{E} - \mathrm{E}$ silicon detector. The plot shows the differential cross section measured as a function of θ. (1) How do these results compare to the Rutherford cross section calculated with only the Coulomb force active? (2) What is the distance of closest approach (DOCA) of the $^6\mathrm{Li}$ to the $^{208}\mathrm{Pb}$ target before the $^6\mathrm{Li}$ and $^{208}\mathrm{Pb}$ actually collide?

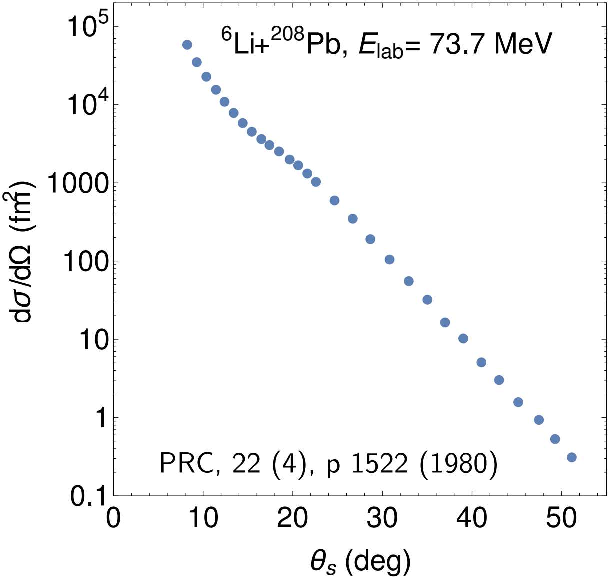


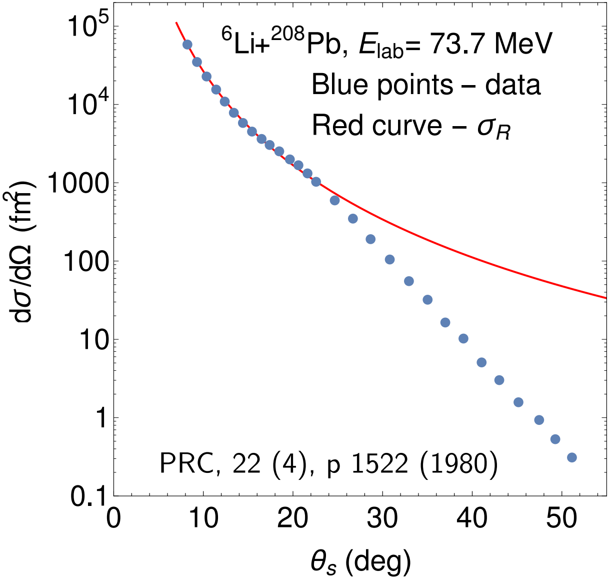




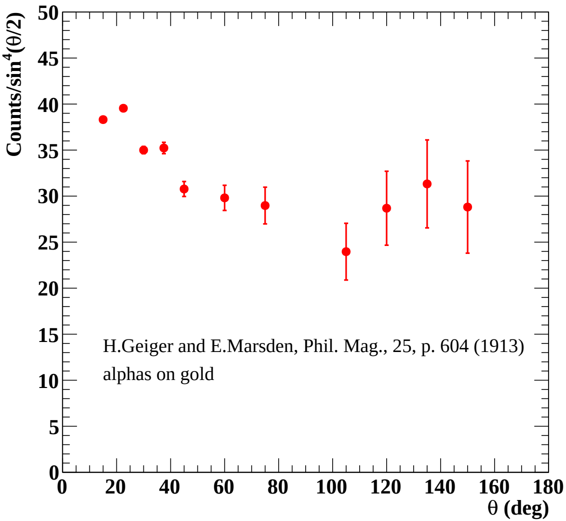



Rutherford trajectories for different
impact parameters
y/b
x

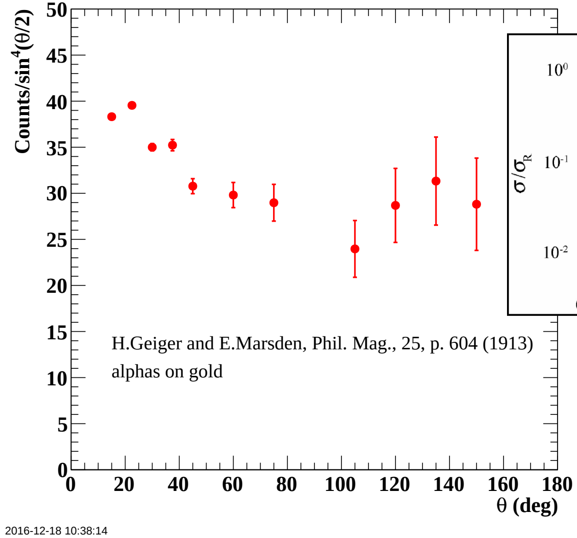

^{6}Li+^{208}Pb, E_{lab}= 73.7 MeV
PRC, 22 (4), p 1522 (1980)
$d\sigma/d\Omega$ (fm^2)
θ_s (deg)
10^5
10^4
1000
100
10
1
0.1
0
10
20
30
40
50

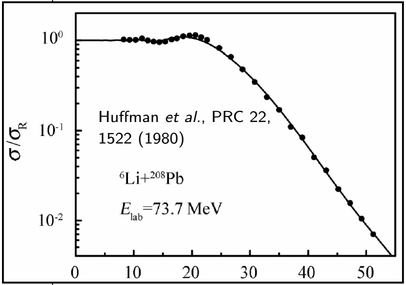


^{6}Li+^{208}Pb, E_{lab}= 73.7 MeV
Blue points – data
Red curve – σ_R
PRC, 22 (4), p 1522 (1980)
$d\sigma/d\Omega$ (fm^2)
10^5
10^4
1000
100
10
1
0.1
0
10
20
30
40
50
θ_s (deg)

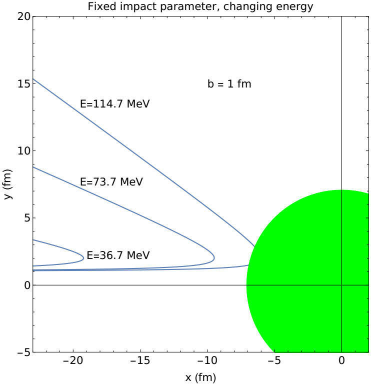


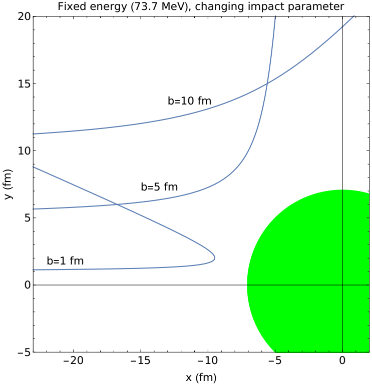
2016-12-18 10:38:14

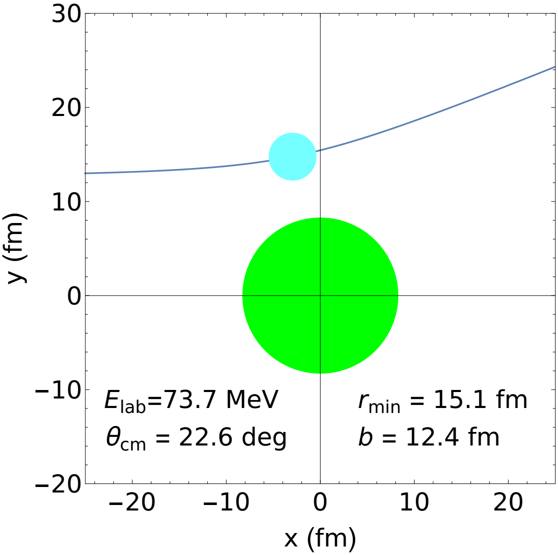

Counts/sin^4(θ/2)
50
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
θ (deg)
H.Geiger and E.Marsden, Phil. Mag., 25, p. 604 (1913)
alphas on gold
2016-12-18 10:38:14


σ/σR
10^0
10^-1
10^-2
0
10
20
30
40
50
Huffman et al., PRC 22, 1522 (1980)
6Li+208Pb
Elab=73.7 MeV

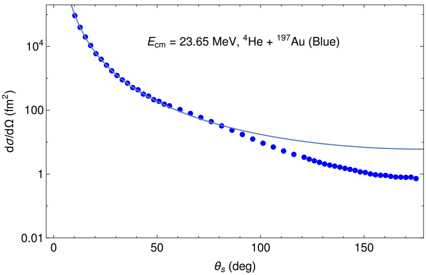
Plotting the Homework (Nuclear sizes)

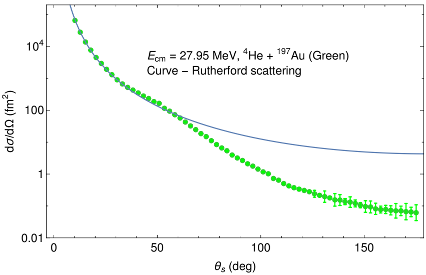






30
20
10
0
−10
−20
y (fm)
−20
−10
0
10
20
x (fm)
E_{lab}=73.7 MeV
θ_{cm} = 22.6 deg
r_{min} = 15.1 fm
b = 12.4 fm


E_{cm} = 23.65 MeV, ^{4}He + ^{197}Au (Blue)
10^4
100
1
0.01
0
50
100
150
$d\sigma/d\Omega$ (fm^2)
θ_s (deg)


E_{cm} = 27.95 MeV, ^{4}He + ^{197}Au (Green)
Curve – Rutherford scattering
10^4
100
1
0.01
0
50
100
150
$d\sigma/d\Omega$ (fm^2)
θ_s (deg)

Plotting the Homework (no. 10)