PHY 711 Classical Mechanics and Mathematical Methods
10-10:50 AM MWF in Olin 103

Lecture 2
Two particle interactions and scattering theory

Schedule for weekly one-on-one meetings?

Wells – Thursday at 3:15 PM (OK for this week)
Owen – Office hours

Fall 2021 Schedule
for N. A. W. Holzwarth

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00-10:00	Lecture Preparation	Physics Research	Lecture Preparation	Physics Research	Lecture Preparation
10:00-11:00	Classical Mechanics PHY711		Classical Mechanics PHY711		Classical Mechanics PHY711
11:00-12:00	Office Hours		Office Hours		Office Hours
12:00-4:00	Physics Research		Physics Research		Physics Research
4:00-5:00				Physics Colloquium	

Your questions –

b

From Owen –

1. For what different physical systems do the four two-particle interaction terms (V(r)) listed in the lecture notes apply?
2. Can a point particle have rotational energy? (More simply, can it rotate?)
3. Can classical scattering be used to analyze the internal structure of an object or does it require quantum mechanics? (For example, x-ray crystallography).

From Manikanta --

1. I have [questions] in the effective potential section. Its mentioned that centrifugal barrier is l^2/2mr^2, May I know more details of it ?
2. [What does the impact] parameter mean in assignment2.
3. bbb

From Can --

1. Question about details of quiz question #1.

From Ramesh –

1. We usually present an analogy between classical mechanics and quantum mechanics for any given phenomenon. In classical mechanics, the scattering results from the physical contact between two objects while in quantum mechanics the scattering is the result of the interaction of wavefunctions. To what extent, these classical scattering principles hold in quantum cases?

PHY 711 Classical Mechanics and Mathematical Methods

MWF 10 AM-10:50 AM	OPL 103	http://www.wfu.edu/~natalie/f21phy711/

Instructor: Natalie Holzwarth	Office:300 OPL	e-mail:natalie@wfu.edu

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Course schedule

(Preliminary schedule -- subject to frequent adjustment.)

	Date	F&W Reading	Topic	Assignment	Due
1	Mon, 8/23/2021	Chap. 1	Introduction	#1	8/27/2021
2	Wed, 8/25/2021	Chap. 1	Scattering theory	#2	8/30/2021
3	Fri, 8/27/2021	Chap. 1	Scattering theory		
4	Mon, 8/30/2021	Chap. 1	Scattering theory		
5	Wed, 9/01/2021	Chap. 1	Scattering theory		
6	Fri, 9/03/2021	Chap. 2	Non-inertial coordinate systems		

PHY 711 – Assignment #2

08/25/2021

1. Consider a particle of mass m moving in the vicinity of another particle of mass M where $m << M$. The particles interact with a conservative central potential of the form

$$V(r) = V_0\left(\left(\frac{r_0}{r}\right)^2 - \left(\frac{r_0}{r}\right)\right),$$

where r denotes the magnitude of the particle separation and V_0 and r_0 denote energy and length constants, respectively. The total energy of the system is V_0.

   (a) First consider the case where the impact parameter $b = 0$. Find the distance of closest approach of the particles.

   (b) Now consider the case where the impact parameter $b = r_0$. Find the distance of closest approach of the particles.

Comment on quiz questions

1. $$g(t)=\int_0^t\left(x^2+t\right)dx \qquad \frac{dg}{dt}=\int_0^t\frac{d\left(x^2+t\right)}{dt}dt+\left(x^2+t\right)\Big|_{x=t}$$

$$=\int_0^t dt+\left(t^2+t\right)=t^2+2t$$

2. Evaluate the integral $\oint\frac{dz}{z}$ for a closed contour about the origin.

Suppose that $z=e^{i\theta}$ $\qquad dz=e^{i\theta}id\theta \qquad \oint\frac{dz}{z}=\int_0^{2\pi}\frac{e^{i\theta}id\theta}{e^{i\theta}}=2\pi i$

3. $$\frac{df}{dx}=f \quad \Rightarrow\frac{df}{f}=dx \quad \Rightarrow d\left(\ln f\right)=dx \quad \Rightarrow f(x)=Ae^x$$

$$f(x=0)=A=1 \quad \Rightarrow A=1 \quad f(x)=e^x$$

4. $$\sum_{n=1}^N a^n=\frac{a-a^{N+1}}{1-a}$$

Let $S\equiv\sum_{n=1}^N a^n$ Note that $aS-S=a^{N+1}-a$

$$\Rightarrow S=\frac{a^{N+1}-a}{a-1}$$

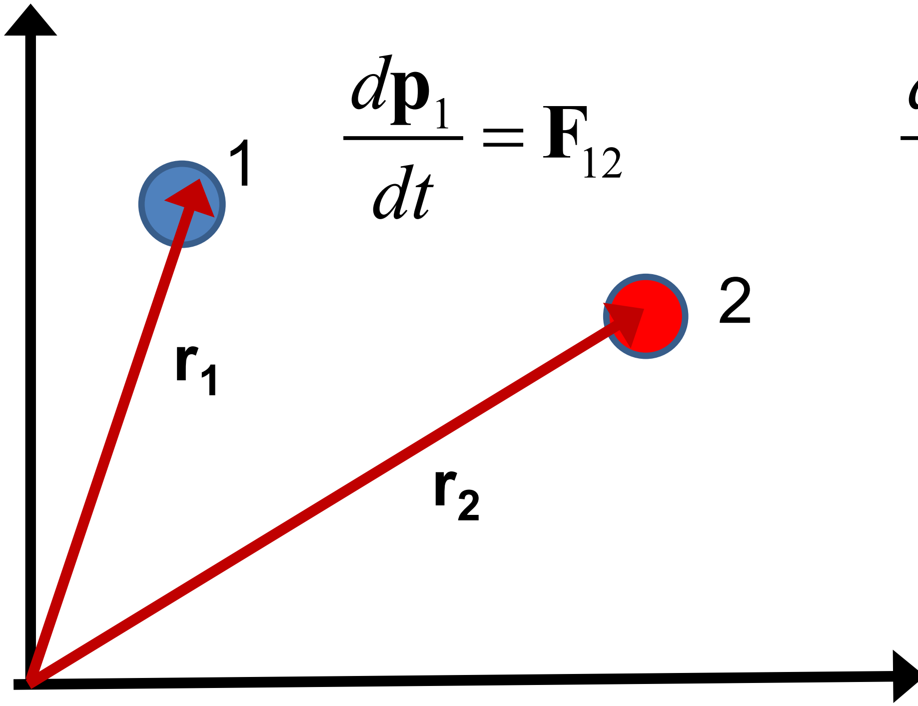
Suppose $$G(t)=\int_{A(t)}^{B(t)} f(x,t)\,dx$$

Then $$\frac{dG}{dt}=\int_{A(t)}^{B(t)} \frac{\partial f(x,t)}{\partial t}\,dx+\frac{dB}{dt} f(x=B(t),t)-\frac{dA}{dt} f(x=A(t),t)$$

First consider fundamental picture of particle interactions

Classical mechanics of a conservative 2-particle system.

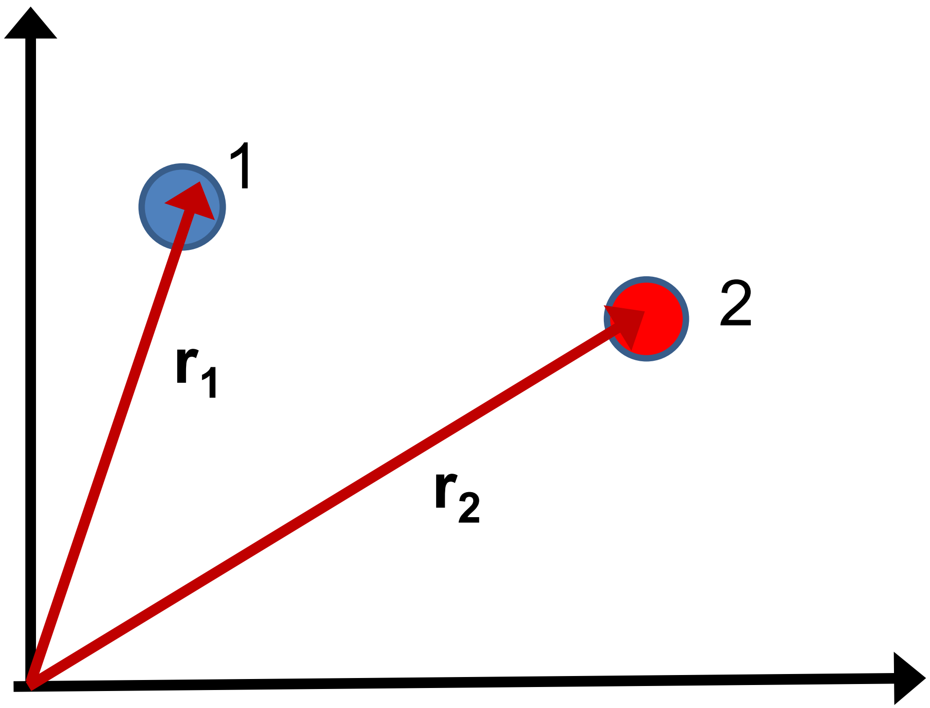
$$\frac{d\mathbf{p}_1}{dt} = \mathbf{F}_{12} \qquad \frac{d\mathbf{p}_2}{dt} = \mathbf{F}_{21}$$



$$\mathbf{F}_{12} = -\nabla_1 V\left(\mathbf{r}_1 - \mathbf{r}_2\right) \qquad \Rightarrow E = \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 + V\left(\mathbf{r}_1 - \mathbf{r}_2\right)$$

For this discussion, we will assume that $V(\mathbf{r})=V(r)$ (a central potential).

Energy is conserved: $$E = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 + V\left(\mathbf{r}_1 - \mathbf{r}_2\right)$$



For a central potential $V(\mathbf{r})=V(r)$, angular momentum is conserved. For the moment we also make the simplifying assumption that $m_2 >> m_1$ so that particle 1 dominates the motion.

Typical two-particle interactions –

Central potential: $V(\mathbf{r}_1 - \mathbf{r}_2) = V(|\mathbf{r}_1 - \mathbf{r}_2|) \equiv V(r)$

Hard sphere: $V(r) = \begin{cases} \infty & r \le a \\ 0 & r > a \end{cases}$

Coulomb or gravitational: $V(r) = \dfrac{K}{r}$

Lennard-Jones: $V(r) = \dfrac{A}{r^{12}} - \dfrac{B}{r^6}$

More details of two particle interaction potentials

Central potential: $$V(\mathbf{r}_1-\mathbf{r}_2)=V(|\mathbf{r}_1-\mathbf{r}_2|)\equiv V(r)$$

This means that the interaction only depends on the distance between the particles and not on the angle between them. This would typically be true of the particles are infinitesimal points without any internal structure such as two infinitesimal charged particles or two infinitesimal masses separated by a distance *r*:

$$V(r)=\frac{K}{r}$$

Example – Interaction between a proton and and an electron. Note we are treating the interactions with classical mechanics; in some cases, quantum effects are non-trivial.

Other examples of central potentials --

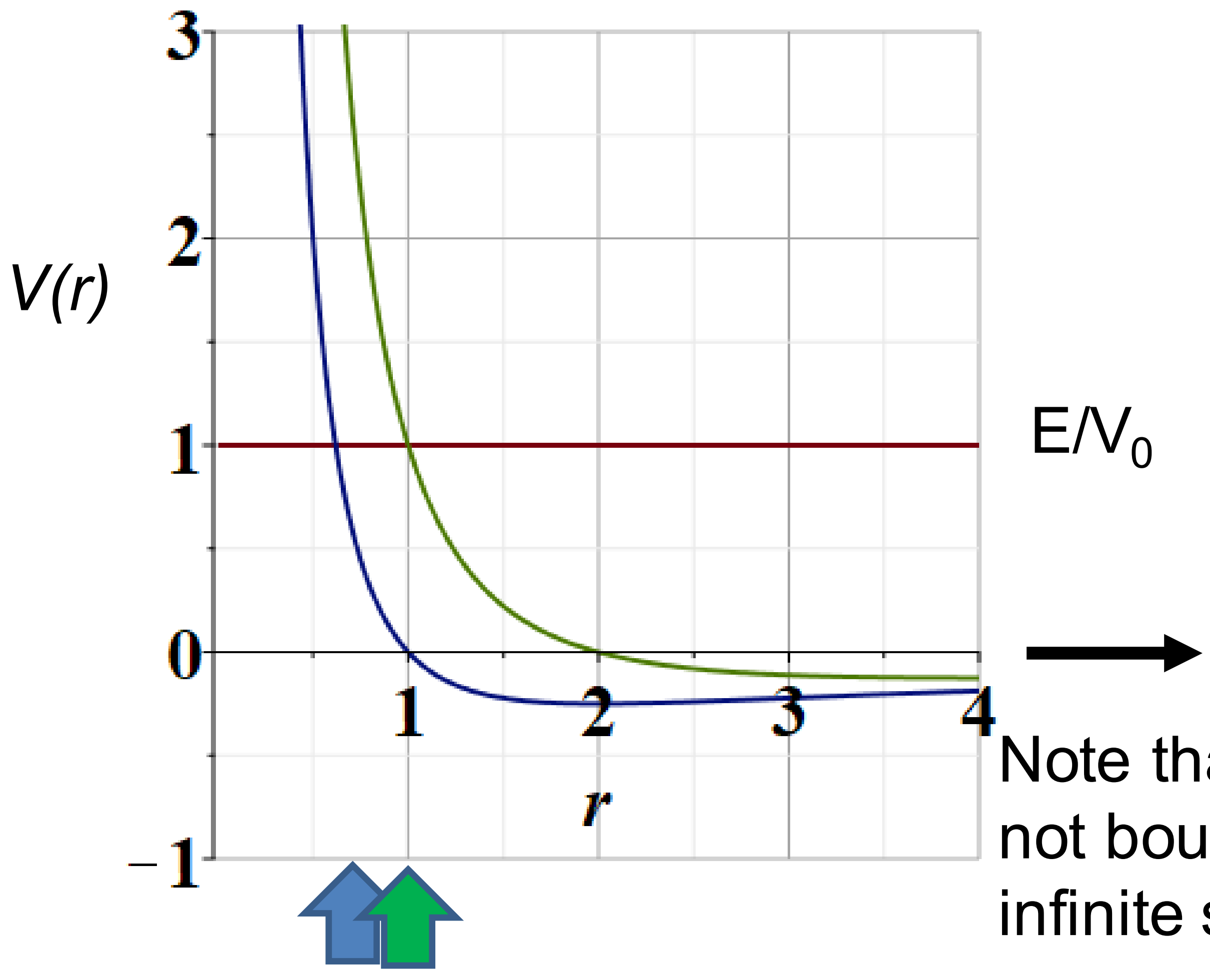
<u>Example</u>

Hard sphere:	$V(r)=\begin{cases}\infty & r\le a\\ 0 & r>a\end{cases}$	Two marbles
Lennard-Jones:	$V(r)=\frac{A}{r^{12}}-\frac{B}{r^{6}}$	Two Ar atoms

Note – not all systems are described by this form. Some counter examples:

1. Molecules (internal degrees of freedom)
2. Systems with more than two particles such as crystals

Representative plot of *V(r)*



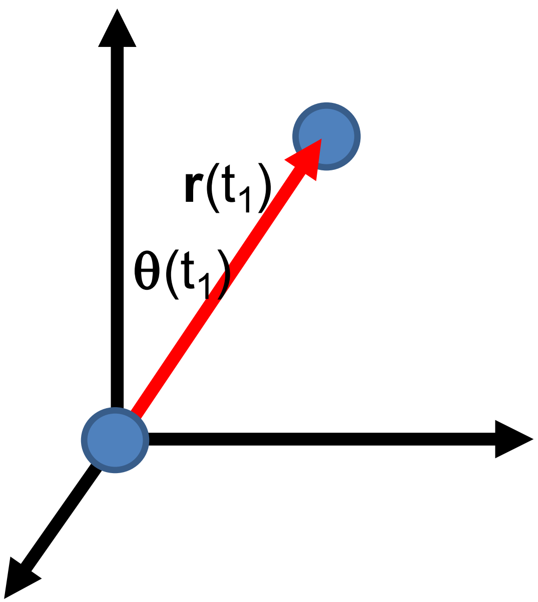
Note that particles are not bound; can reach infinite separation

Distances of closest approach

Some more details --

Here we are assuming that the target particle is stationary and $m_1 \equiv m$.

The origin of our coordinate system is taken at the position of the target particle.



Conservation of energy:

$$E = \frac{1}{2}m\left(\frac{d\mathbf{r}}{dt}\right)^2 + V(r)$$

$$= \frac{1}{2}m\left(\left(\frac{dr}{dt}\right)^2 + r^2\left(\frac{d\theta}{dt}\right)^2\right) + V(r)$$

Conservation of angular momentum:

$$L = mr^2\frac{d\theta}{dt}$$

Comments continued --

Conservation of energy:

$$E = \frac{1}{2} m \left(\frac{d\mathbf{r}}{dt} \right)^2 + V(r)$$

$$= \frac{1}{2} m \left(\left(\frac{dr}{dt} \right)^2 + r^2 \left(\frac{d\theta}{dt} \right)^2 \right) + V(r)$$

$$= \frac{1}{2} m \left(\frac{dr}{dt} \right)^2 + \boxed{\frac{L^2}{2mr^2} + V(r)} \Leftarrow V_{eff}(r)$$

Conservation of angular momentum:

$$L = mr^2 \frac{d\theta}{dt}$$

Also note that when $r \to \infty, \quad V(r) \to 0$

$$\mathbf{L} \equiv \mathbf{r} \times m \frac{d\mathbf{r}}{dt} \qquad L = b\sqrt{2mE}$$

For $r \to \infty, \quad \frac{d\mathbf{r}}{dt} \to v_\infty = \sqrt{\frac{2E}{m}}$

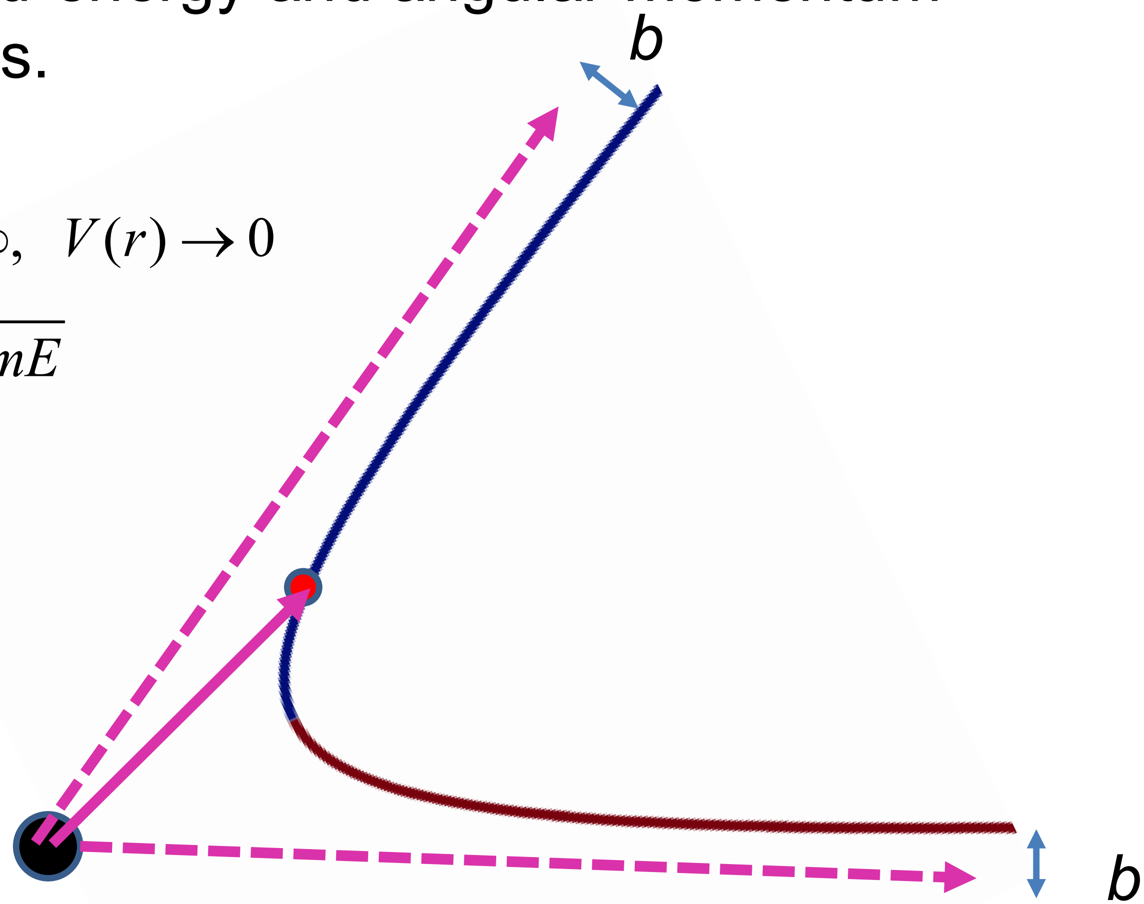
$$E = \frac{1}{2} m \left(\frac{dr}{dt} \right)^2 + \frac{b^2 E}{r^2} + V(r)$$

What is the impact parameter?

Briefly, a convenient distance that depends on the conserved energy and angular momentum of the process.

Also note that when $r \to \infty$, $V(r) \to 0$

$$\mathbf{L} \equiv \mathbf{r} \times m \frac{d\mathbf{r}}{dt} \qquad L = b\sqrt{2mE}$$



Which of the following are true:

a. The particle moves in a plane.
b. For any interparticle potential the trajectory can be determined/calculated.
c. Only for a few special interparticle potential forms can the trajectory be determined.

Why should we care about this?

a. We shouldn’t really care.
b. It is only of academic interest
c. It is of academic interest but can be measured.
d. Many experiments can be analyzed in terms of the particle trajectory.

Scattering theory:

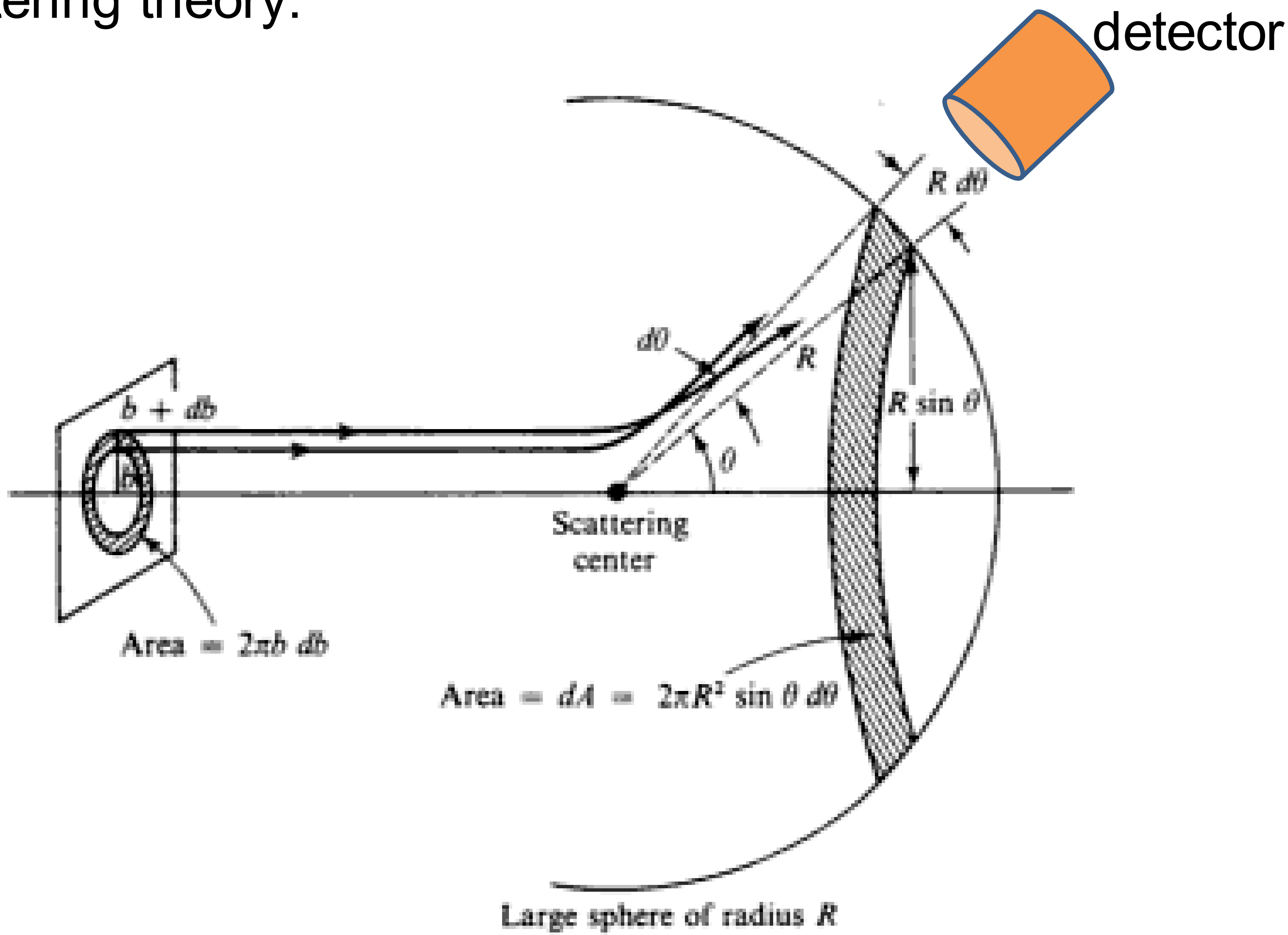
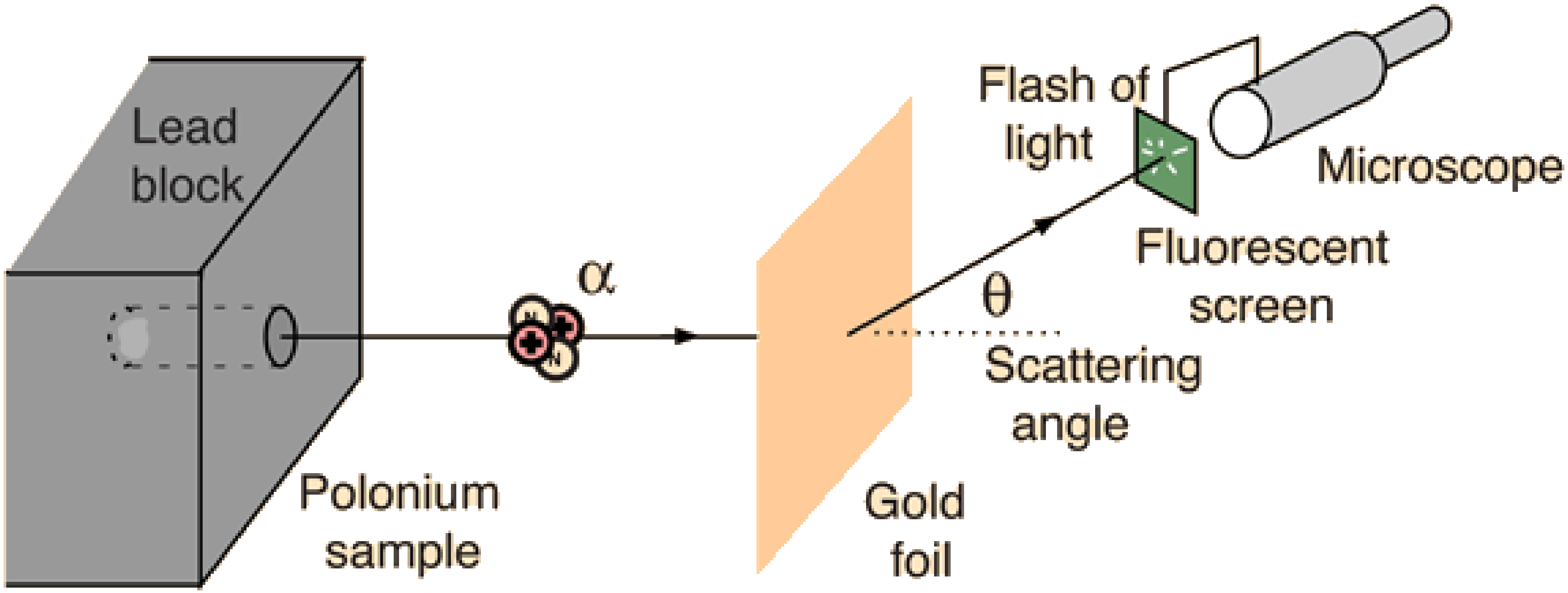
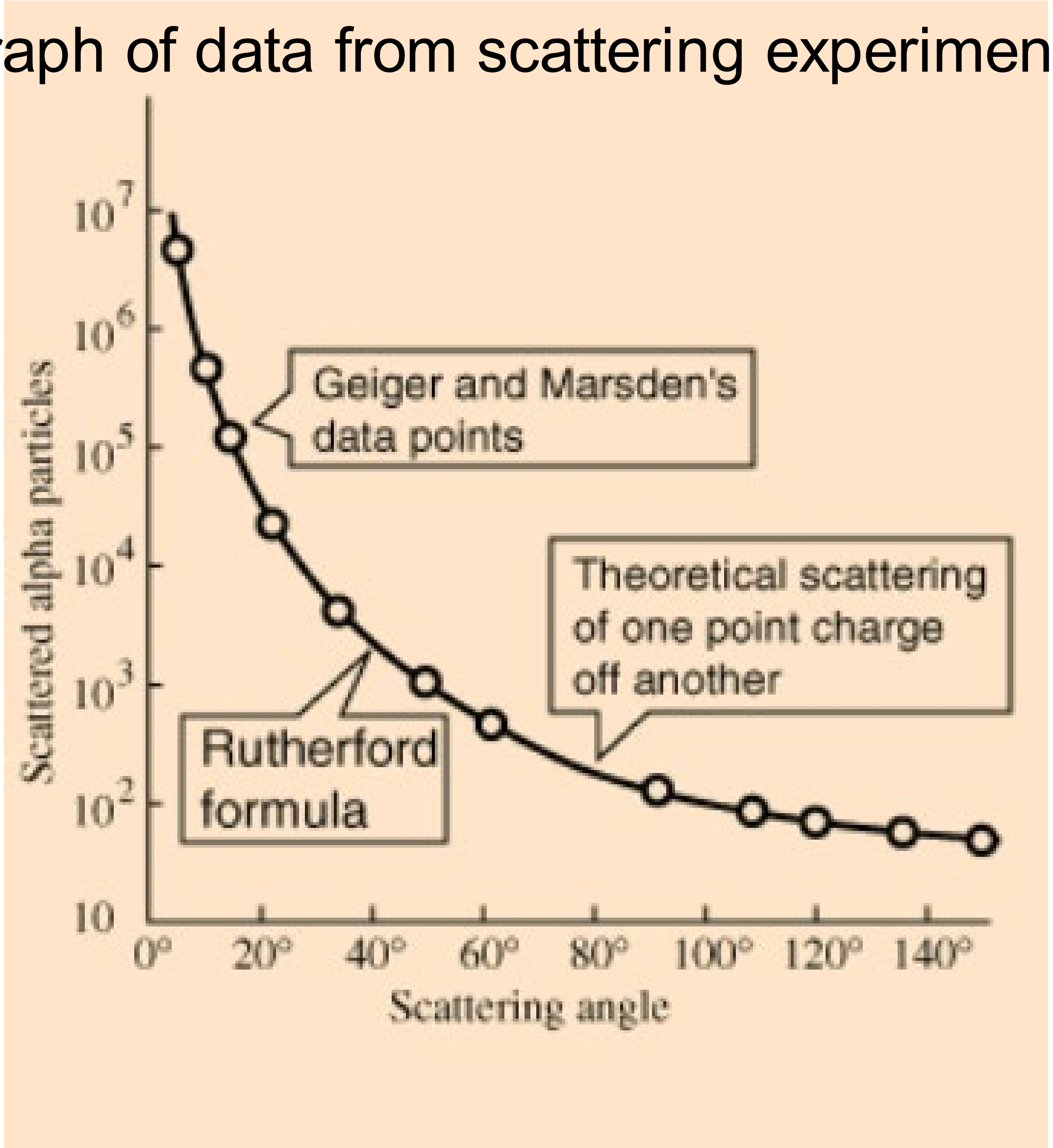


Figure 5.5 The scattering problem and relation of cross section to impact parameter.

Example: Diagram of Rutherford scattering experiment
http://hyperphysics.phy-astr.gsu.edu/hbase/rutsca.html



Graph of data from scattering experiment



From website: http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/rutsca2.html

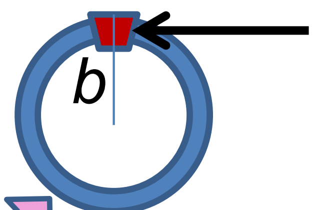
Standardization of scattering experiments --

Differential cross section

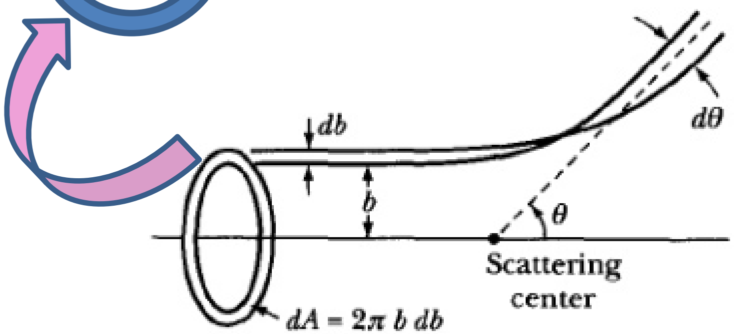
$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\text{Number of detected particles at } \theta \text{ per target particle}}{\text{Number of incident particles per unit area}}$$

$$= \text{Area of incident beam that is scattered into detector at angle } \theta$$

Impact parameter: *b*



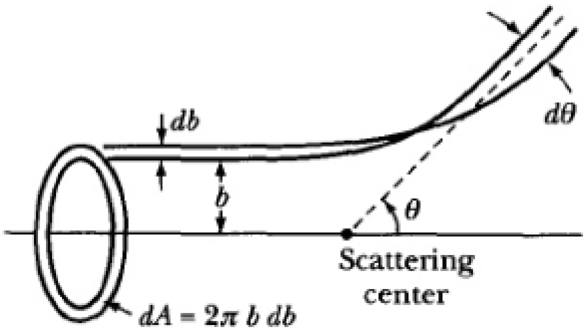
$$d\varphi b db$$



$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{d\varphi\, b\, db}{d\varphi \sin\theta\, d\theta} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

Figure from Marion & Thorton, Classical Dynamics

Note: The notion of cross section is common to many areas of physics including classical mechanics, quantum mechanics, optics, etc. Only in the **classical mechanics** can we calculate it from a knowledge of the particle trajectory as it relates to the scattering geometry.



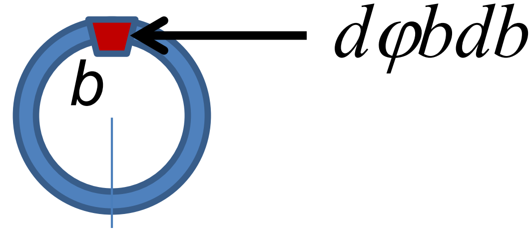
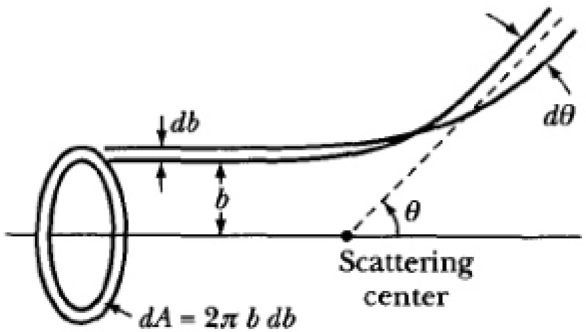


Figure from Marion & Thorton, Classical Dynamics

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{d\varphi\, b\, db}{d\varphi \sin\theta\, d\theta} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

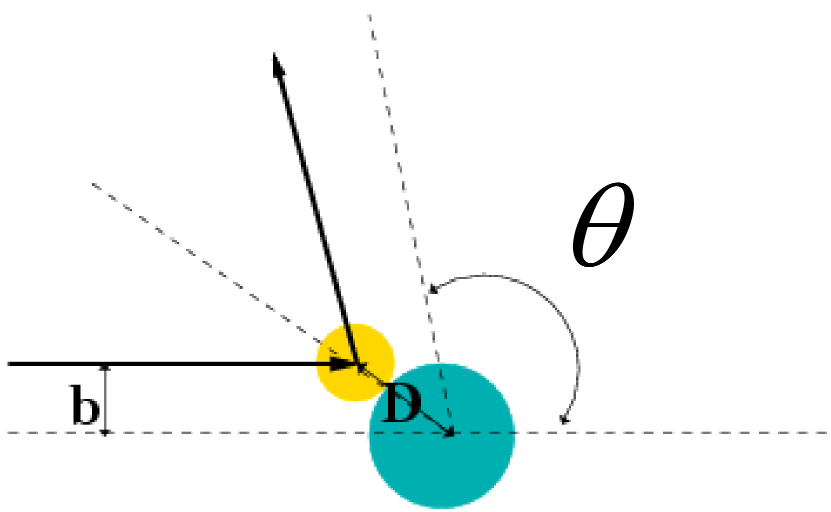
Note: We are assuming that the process is isotropic in φ

Simple example – collision of hard spheres having mutual radius D; very large target mass



$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

Microscopic view:

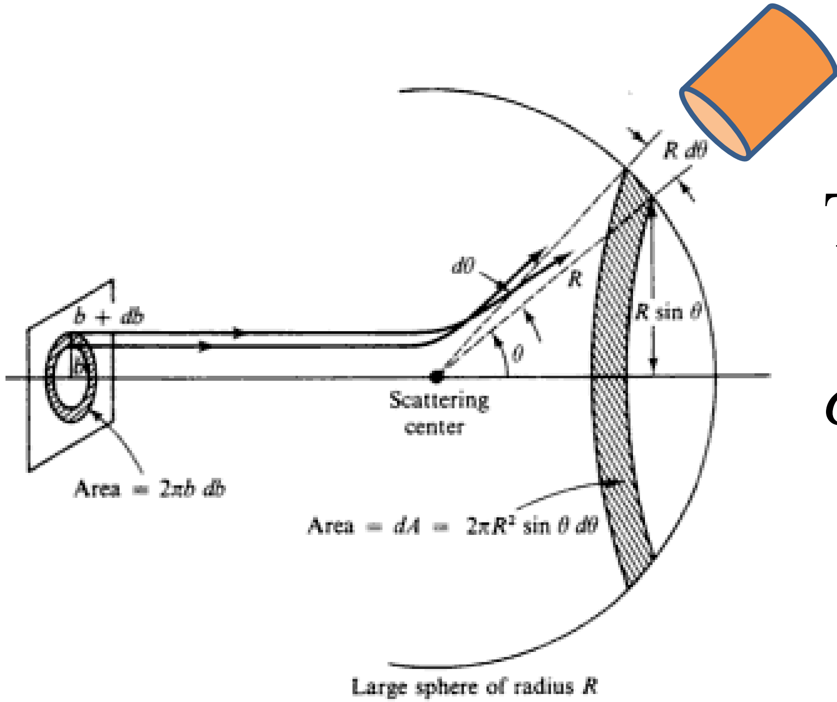


$$b(\theta) = ?$$

$$b(\theta) = D\sin\left(\frac{\pi}{2} - \frac{\theta}{2}\right)$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{D^2}{4}$$

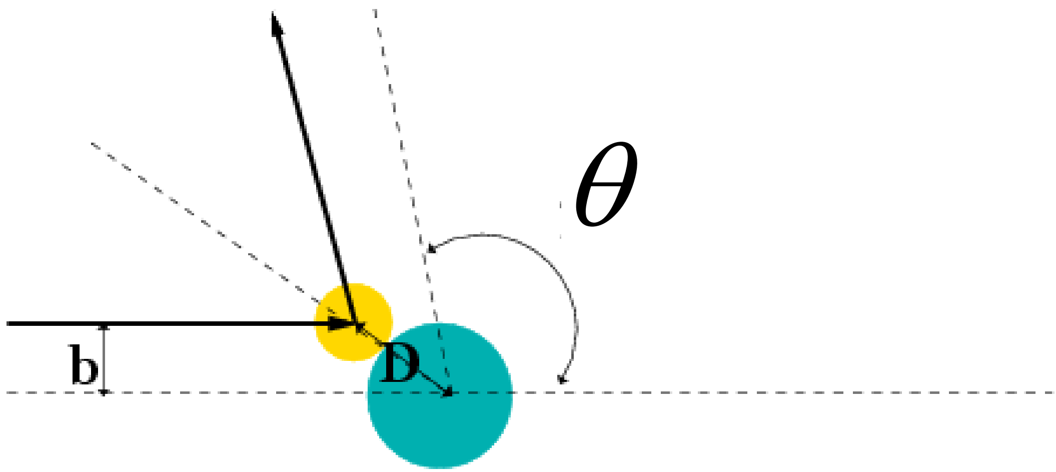
Simple example – collision of hard spheres -- continued



Total scattering cross section:

$$\sigma = \int \left(\frac{d\sigma}{d\Omega} \right) d\Omega$$

Hard sphere:



$$\left(\frac{d\sigma}{d\Omega} \right) = \frac{D^2}{4}$$

$$\sigma = \pi D^2$$

More details of hard sphere scattering –

Hidden in the analysis are assumptions about the scattering process such as:

- No external forces ➔ linear momentum is conserved
- No dissipative phenomena ➔ energy is conserved
- No torque on the system ➔ angular momentum is conserved
- Target particle is much more massive than scattering particle
- Other assumptions??

Note that for quantum mechanical hard spheres at low energy the total cross section is 4 times as large.