Nuclear Physics and Astrophysics

PHY-302

Dr. E. Rizvi

Lecture 9 - Scattering

Queen Mary
University of London

Nucleon - Nucleon Scattering

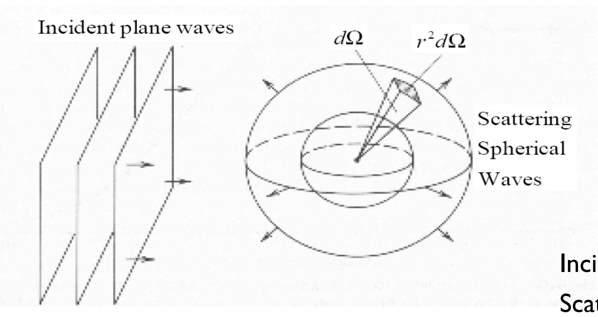
Studying deuterons has provided some understanding of nuclear force

More can be learned from nucleon-nucleon scattering

Hydrogen is the cleanest target - one nucleon: H = p^+

A quantum mechanical approach is needed...

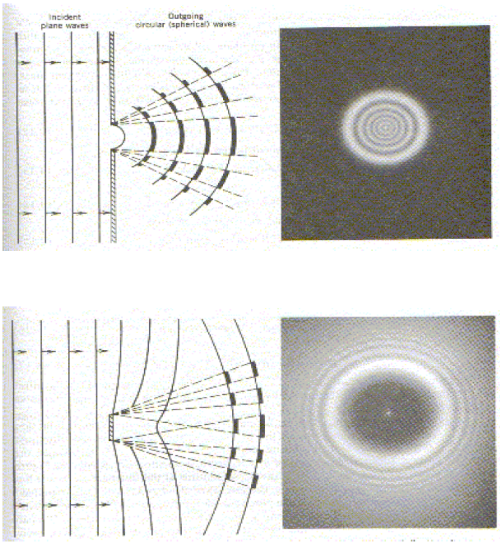
Very similar to optical diffraction - use this as analogy



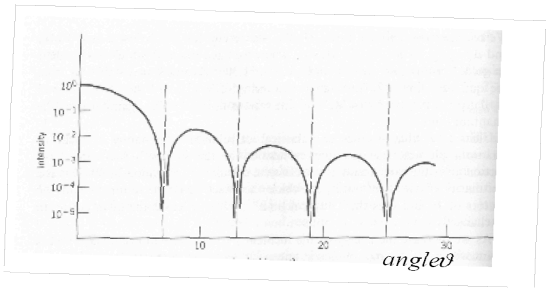
Incident particle is a plane wave

Scattered wave fronts are spherical

Intensity variations on wave-front due to diffraction

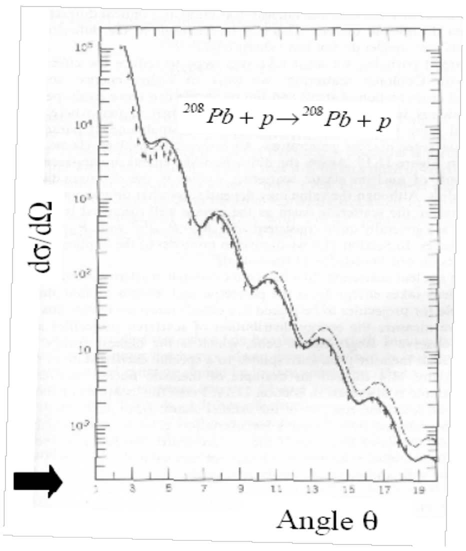


Diffraction pattern observed from plane wave striking a target



Light intensity measured vs angle

scattering 500 MeV p^+ off ^{208}Pb



Very similar pattern observed when elastically scattering p^+ off ^{208}Pb

Nuclei act as sources of spherical waves of scattered p^+ -- similar to optical diff.

In optical diffraction first minimum occurs at

$$\sin\theta = 1.22\,\lambda/d$$

Properties of Nuclear Force

Lets summarise what we know about the Nuclear force:

- At short distance: stronger than Coulomb force
Overcomes coulomb repulsion of protons in nucleus

No need for A(A-1) term in SEMF

- At long distance (atomic sizes): nuclear force is feeble
Molecular nuclei interactions require only Coulomb force

low energy ep scattering requires only a Coulomb force description

- Some particles immune from nuclear force
No evidence that electrons feel this force

- 2 Nucleons interact via an attractive central potential
Square well potential model works to lowest order

V=V(r)
else could not use $\langle l^2\rangle=\hbar^2 l(l+1)$
for deuteron

Properties of Nuclear Force

- The nuclear force is "charge" symmetric
Interactions of pp and nn scattering experiments are identical after Coulomb effects are corrected for

Does not refer to electric charge!

- The nuclear force is "charge" independent
Interactions of nn, pp, np are identical once correction for the Coulomb force (data less conclusive!)

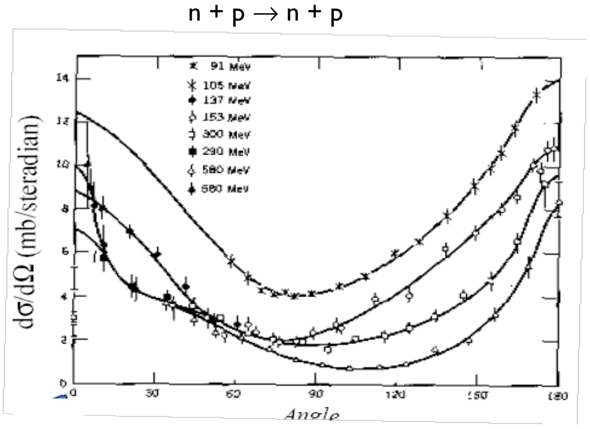
- Nuclear force is repulsive at very short distances
This arises from the fact nuclear density is constant - something keeps nucleons from dense crowding

- The nucleon-nucleon interaction is strongly Spin dep.
This arises from failure to observe a singlet bound state of deuteron (spins anti-parallel, s=0)

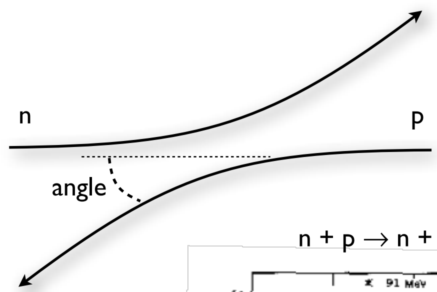
(Only $^3S_1$ and $^3D_1$ states of deuteron exist)

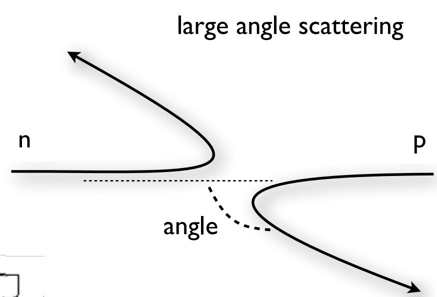
Perform np / nn / pp Scattering Experiments

n + p → n + p



- similar thing happens with nn or pp scattering
- NOT like Rutherford's results!
- nn / pp scattering particles are indistinguishable!





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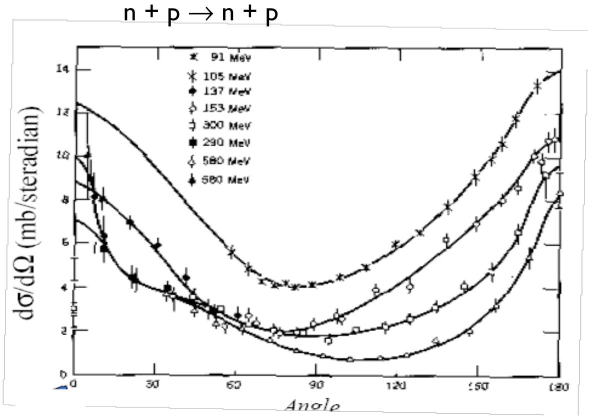

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The Exchange Model

When scattering n-p at high energies strong peak in cross-section at 0°
Also strong peak seen at 180° - not explained by standard elastic processes

• In Exchange Model n and p exchange places in interaction

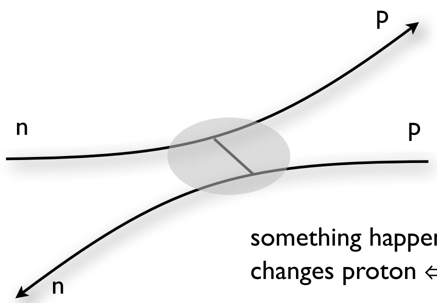
n becomes p & p becomes n

• Fits in with field theory concept of forces

• Quantum field theory interprets force as exchange of quanta - particles of the field

• In the interaction a particle emits a field quanta, other absorbs it

• n and p are continuously emitting field quanta



Such particle exchange should be forbidden: why?

consider proton emitting particle in rest frame...

np scattering

To change n↔p need exchange of particle with spin 0 or 1 integer charge

To apply model to nn and pp scattering need charge neutral exchange
Limited range of particle provides mass limit:

$$\Delta E \Delta t \simeq \hbar$$

If particle travels at velocity close to c and has ~ 1 fm range, then

$$R = c\Delta t \simeq 1 \;\; \text{fm}$$

$$\Delta mc^2 \simeq \frac{\hbar c}{c\Delta t} \simeq \frac{200 \;\; \text{MeV} \;\; \text{fm}}{c\Delta t}$$

Particle is expected to have mass ~ 200 MeV/c^2

compare to p^+ and n^o masses ~ 900 MeV/c^2 e^- ~ 0.5 MeV/c^2

Yukawa Theory of Exchange Force Model

- In 1934 Hideki Yukawa proposed nucleon force is due to massive boson exchange between nucleons

- Further demonstrated that Coulomb potential with 1/r dependence could be described by massless boson exchange

- Calculations showed nucleon boson exchange with mass m leads to a potential:

$$V(r) = \frac{1}{r} e^{-mcr/\hbar}$$

central potential!

In 1947 three particles discovered

particle	charge	mass
π^0	0	135.0
π^+	+1	139.6
π^-	-1	139.6

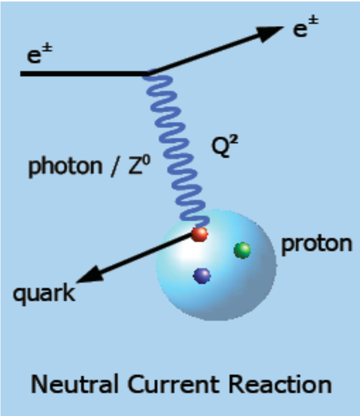
all have spin 0

may explain possible discrepancy in nuclear charge independence:

nn and pp interactions only occur via π^0 exchange

np interactions can occur via π^- and π^0 exchange this scattering is still being done in particle physics

Use electrons as probe: with momentum-transfer-squared is Q^2



Q^2 is Lorentz invariant

Larger Q^2 means smaller λ photon

Can resolve smaller structures (quarks)

Measure momentum distribution of quarks inside proton

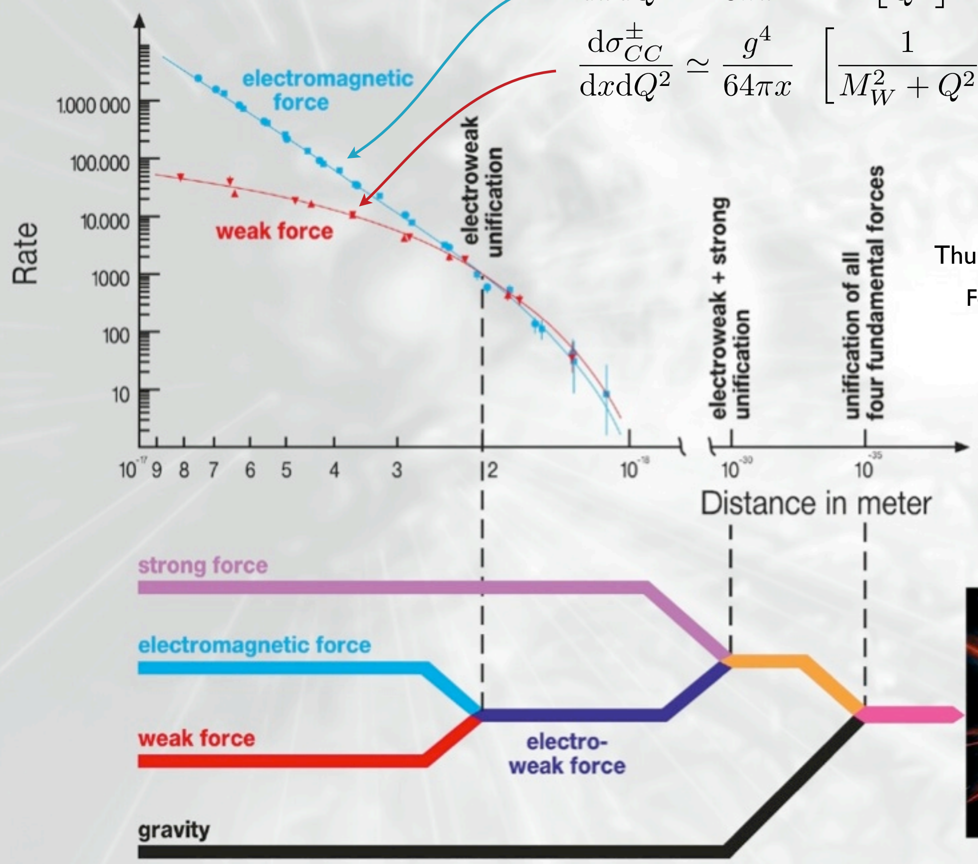
$$\frac{d\sigma^{\pm}_{NC}}{dx dQ^2} \simeq \frac{e^4}{8\pi x} \left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3\right]$$

$$\frac{d\sigma^{\pm}_{CC}}{dx dQ^2} \simeq \frac{g^4}{64\pi x} \left[\frac{1}{M_W^2 + Q^2}\right]^2 \left[Y_+\tilde{W}_2 \mp Y_- x\tilde{W}_3\right]$$

$$\lambda \simeq \frac{hc}{E}$$

Thus high energy ≡ small distance

Forces are equal at high energy



big bang