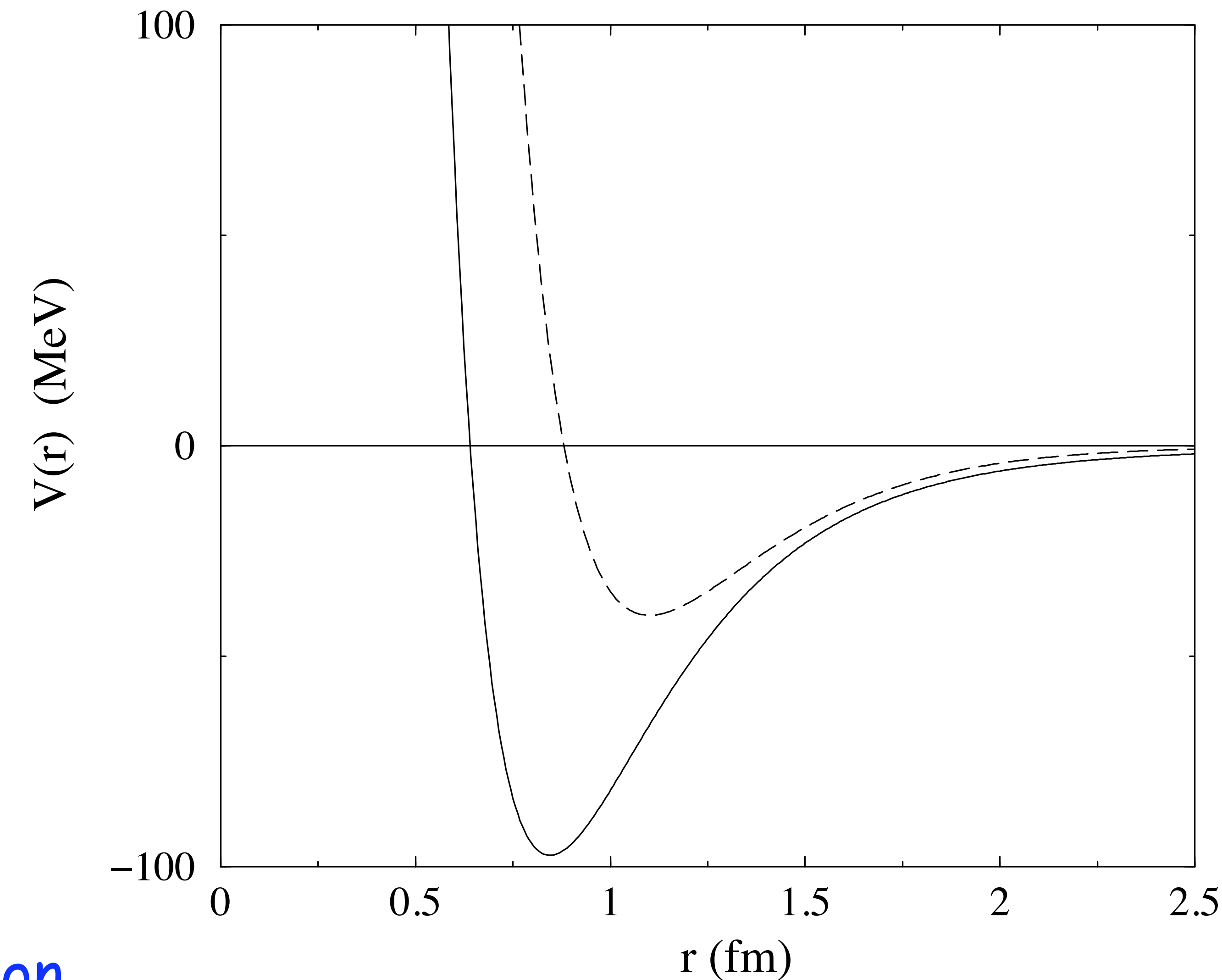
Example

- Reid soft-core interaction (1968)

- solid $^1S_0$
- no bound state

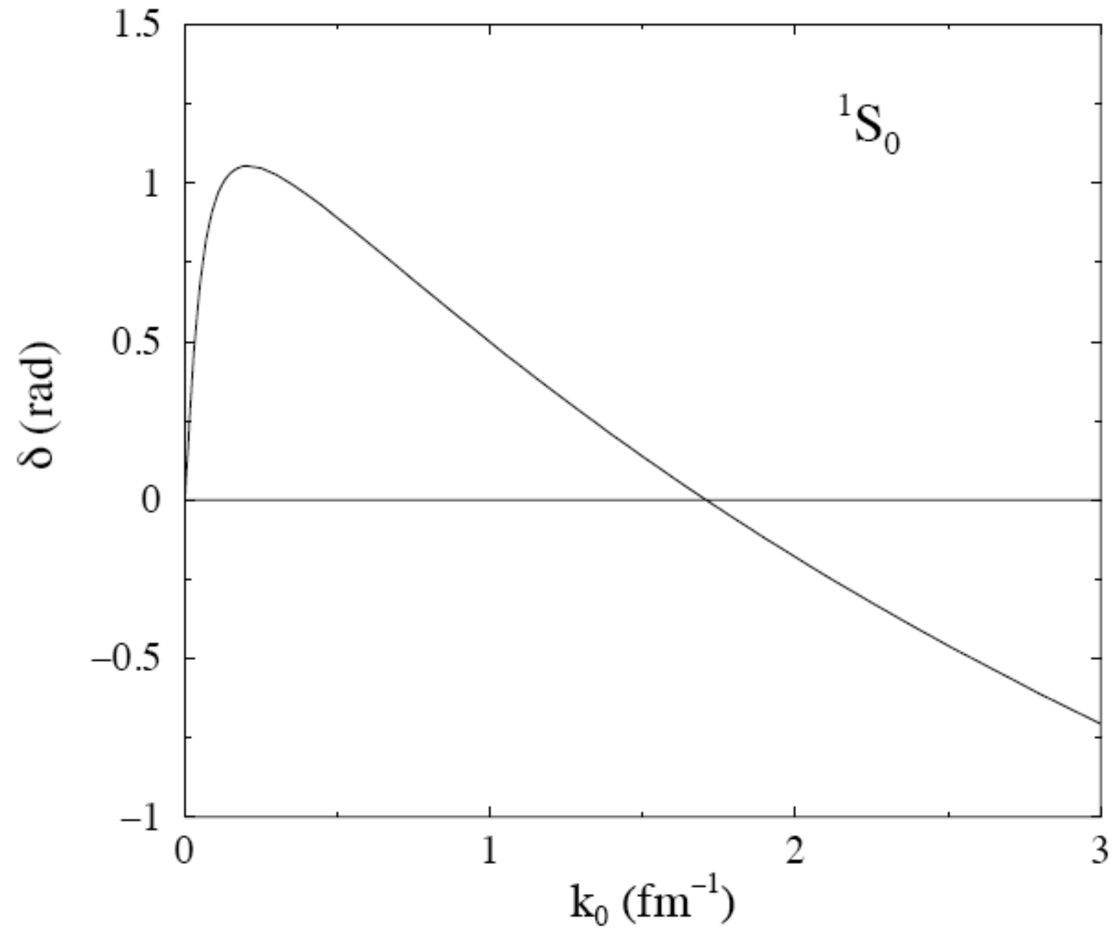
- dashed $^3S_1$
- deuteron
- ??

note similarity to
atom-atom interaction



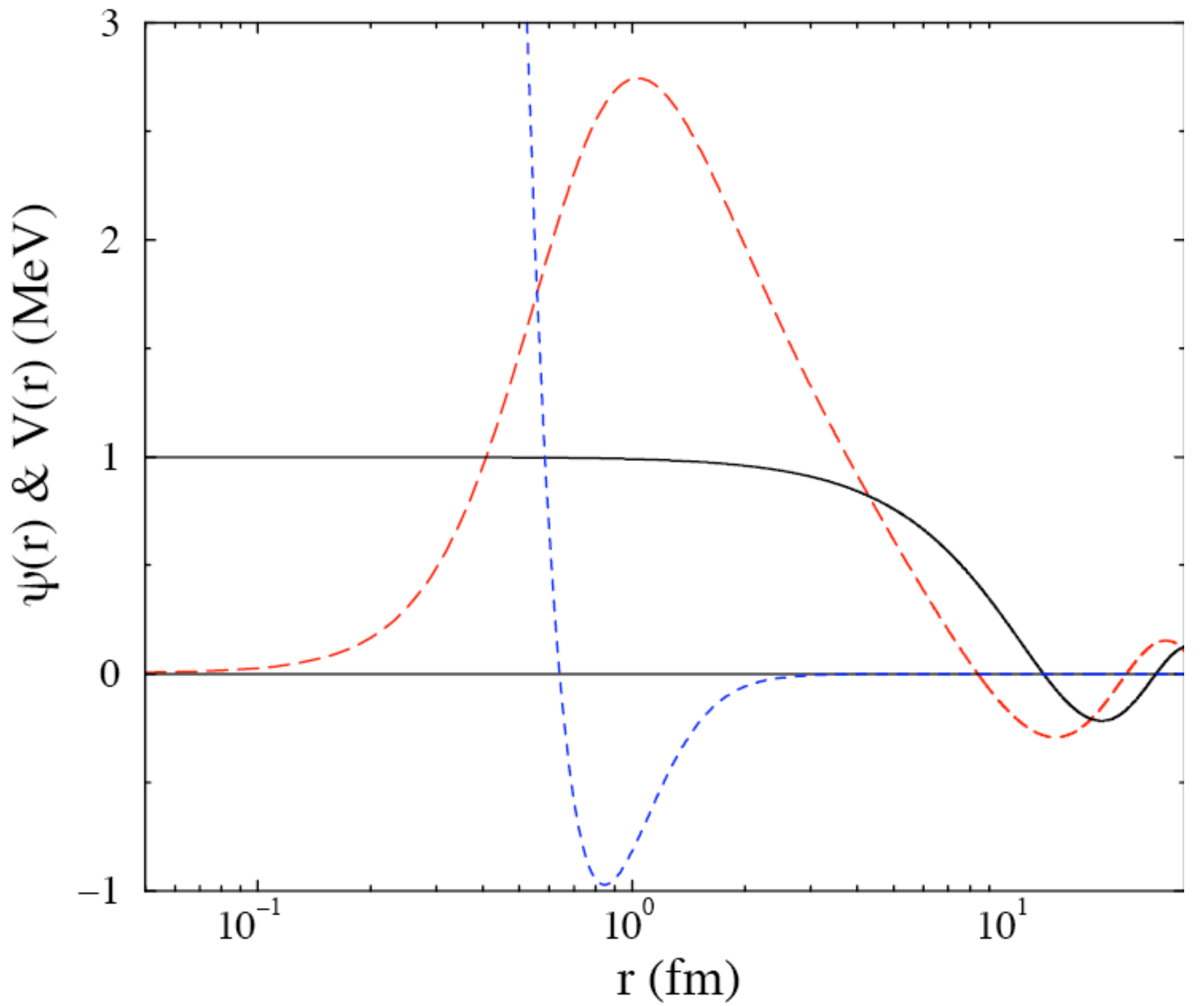
Some results

- Discretize integration --> matrix inversion
- Already sufficient only to iterate principal value part (R-matrix)
- $^1S_0$ phase shift from Reid-soft-core NN interaction
- Attraction at low energy
- Repulsion at higher energy



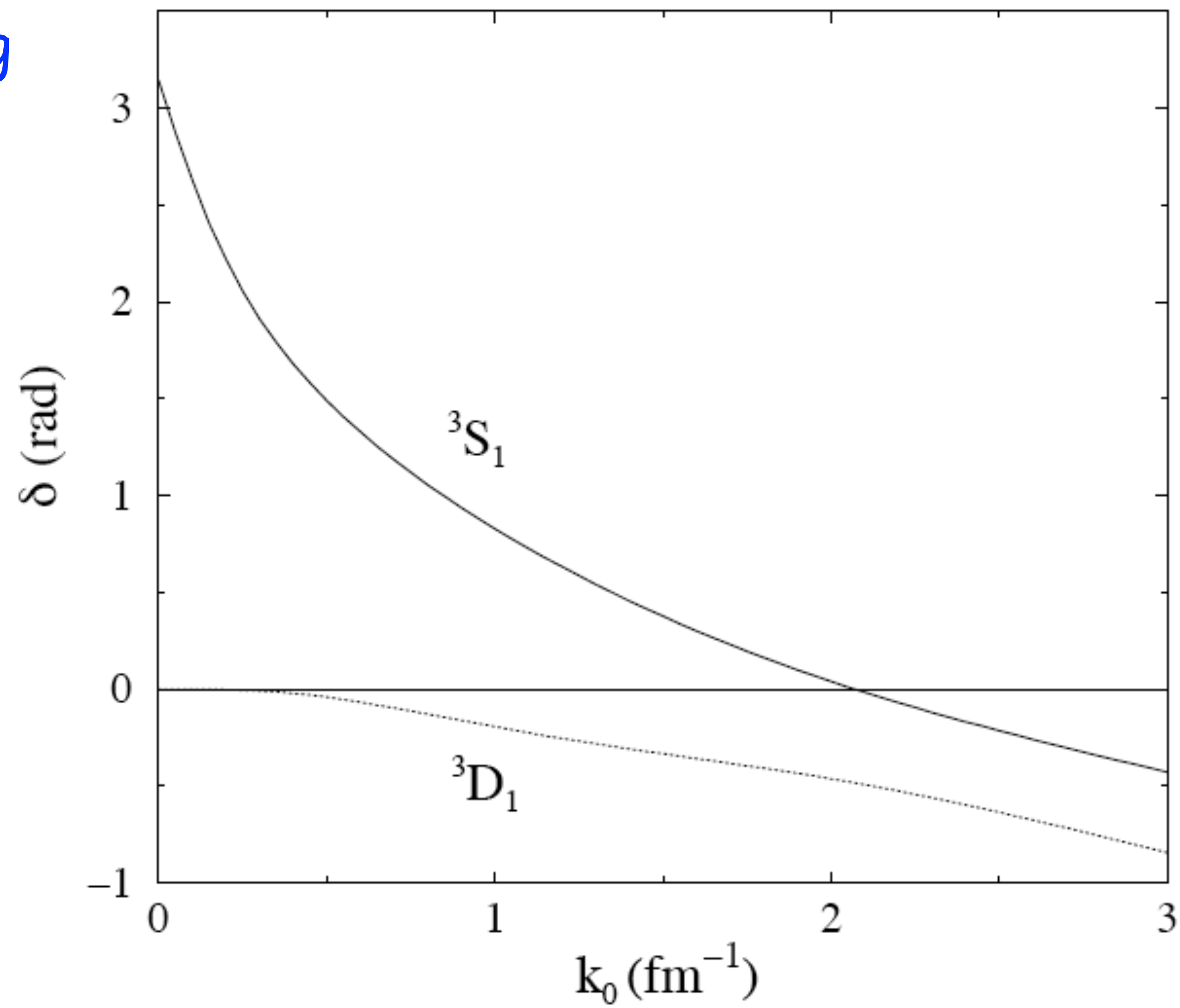
Wave function

- Scattering energy --> k_0 = 0.25 fm^{-1}
- Free wave function - solid
- Correlated - long dashes
- Potential/100 - short dashes
- Note logarithmic scale horizontal axis
- Correlated wave function disappears where interaction strongly repulsive



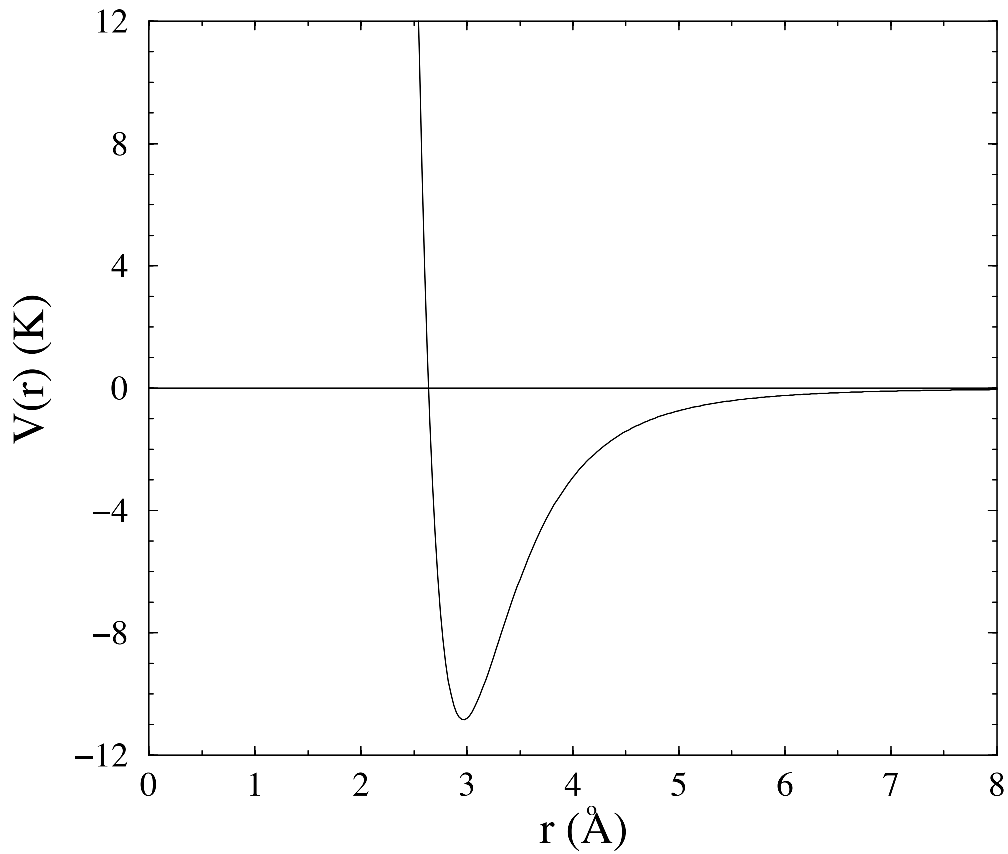
Example

- $^3S_1$-$^3D_1$ coupled channel has a bound state (deuteron)
- One phase shift must start at π
- Considerable mixing
- Still old notation



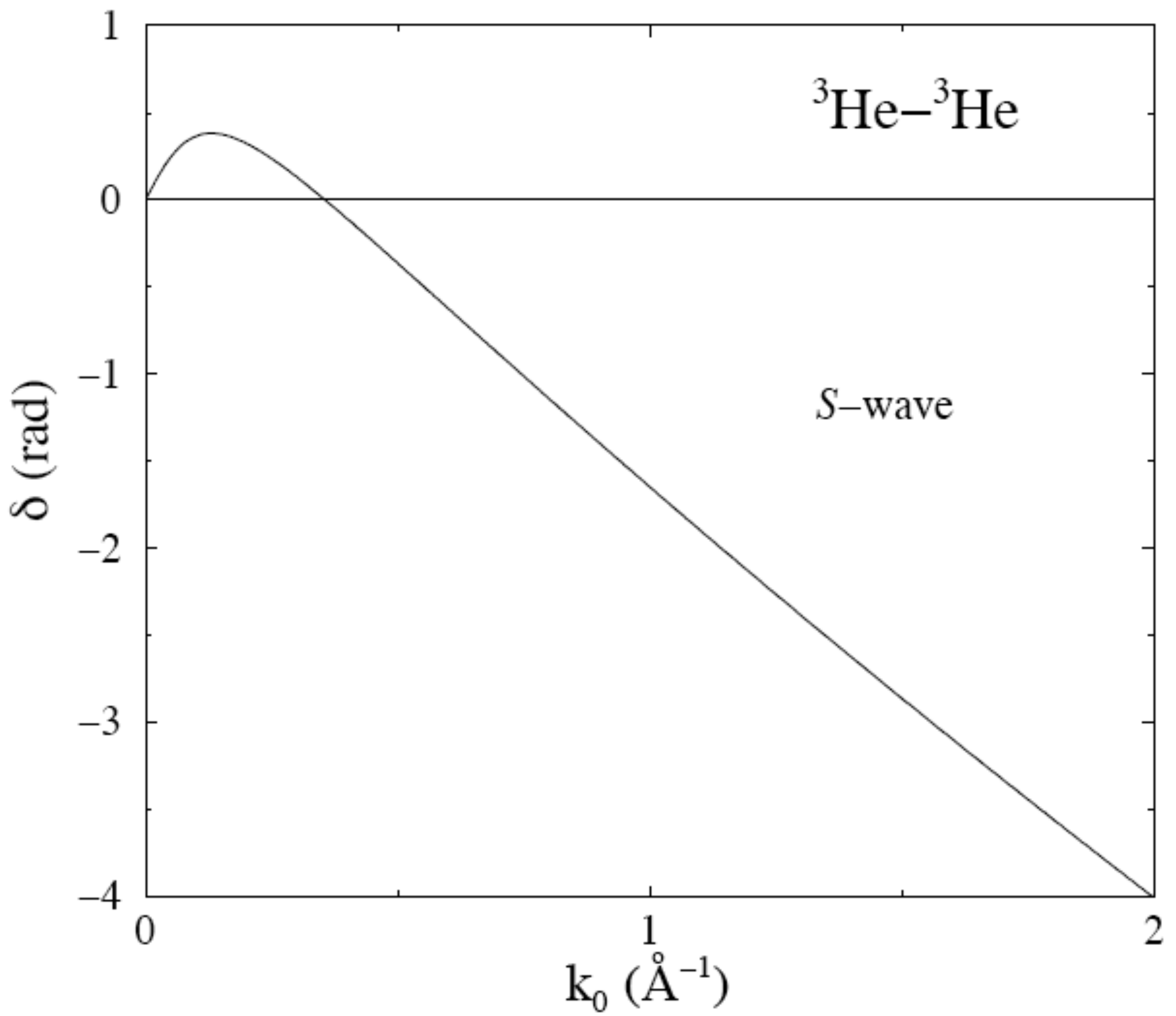
Example

- He-He interaction
- partly theoretical
- partly "experimental"
- 1 eV = 1.16045 x 10^4 K

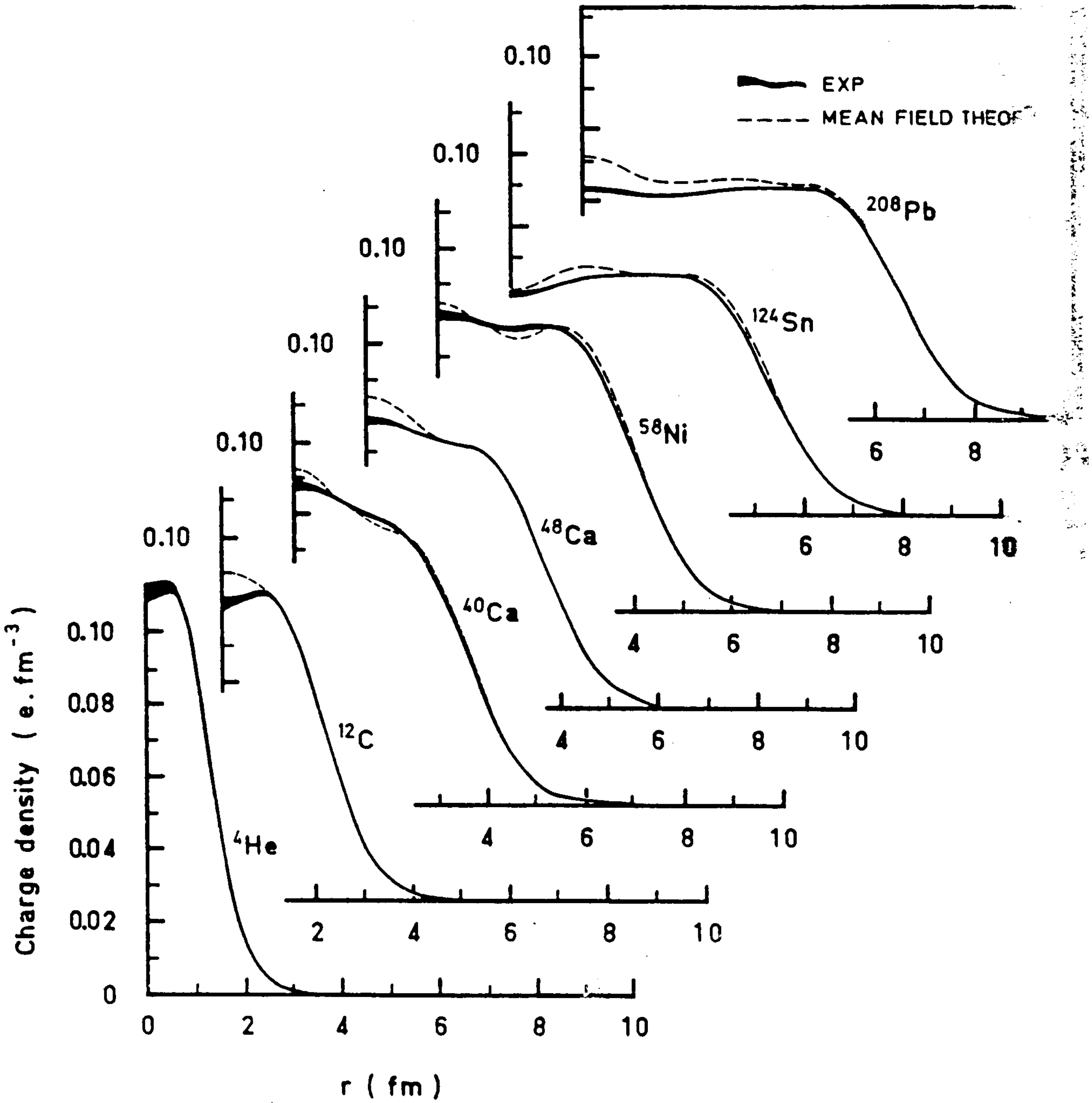


Example

- Phase shifts for S-wave ^{3}He-^{3}He interaction
- Compare with NN $^1S_0$
- Less attractive
- Much more repulsive

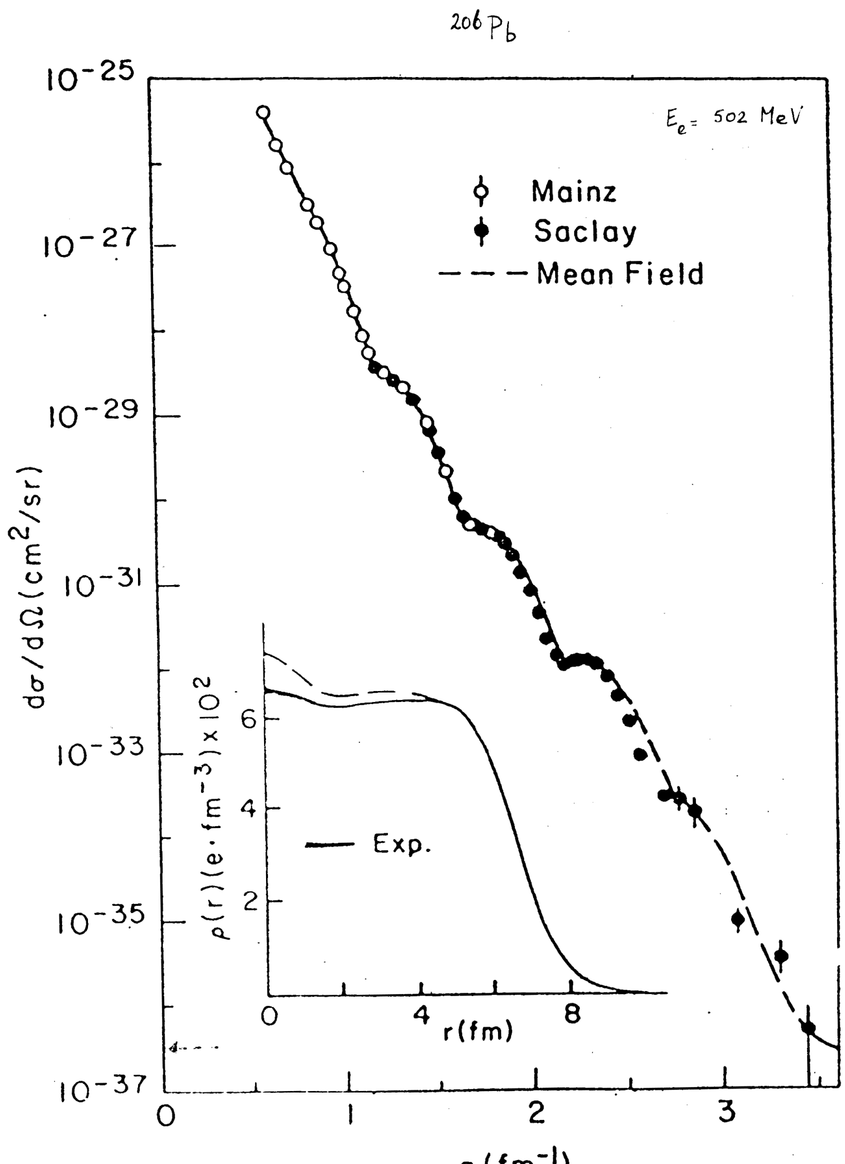


Experimental data across the chart



Role of the last proton identified

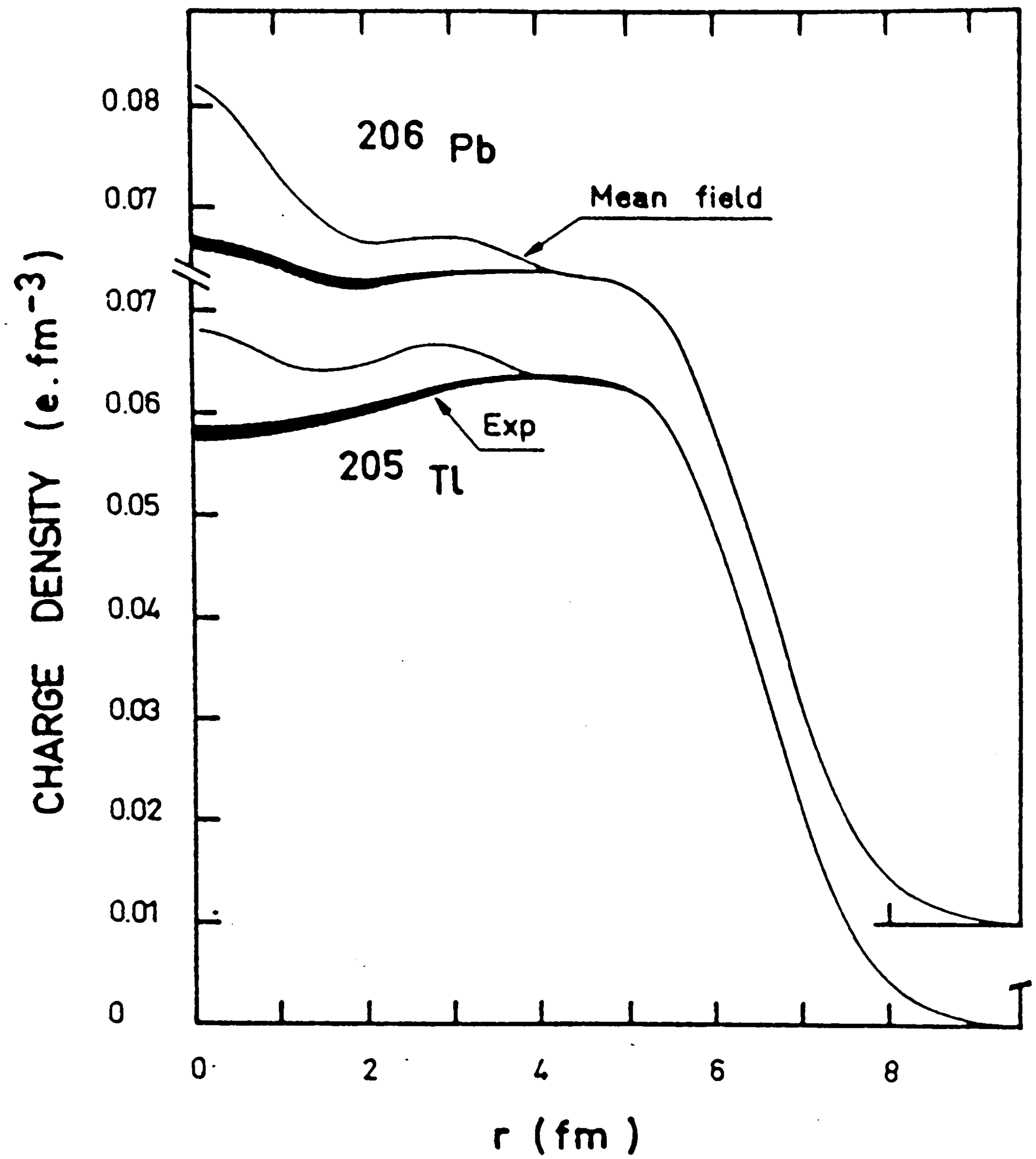
- Consider charge density of ^{206}Pb
- Compare to charge density of ^{205}Tl



J.M. Cavedon et al., Phys. Rev. Lett. 58 (1987) 195

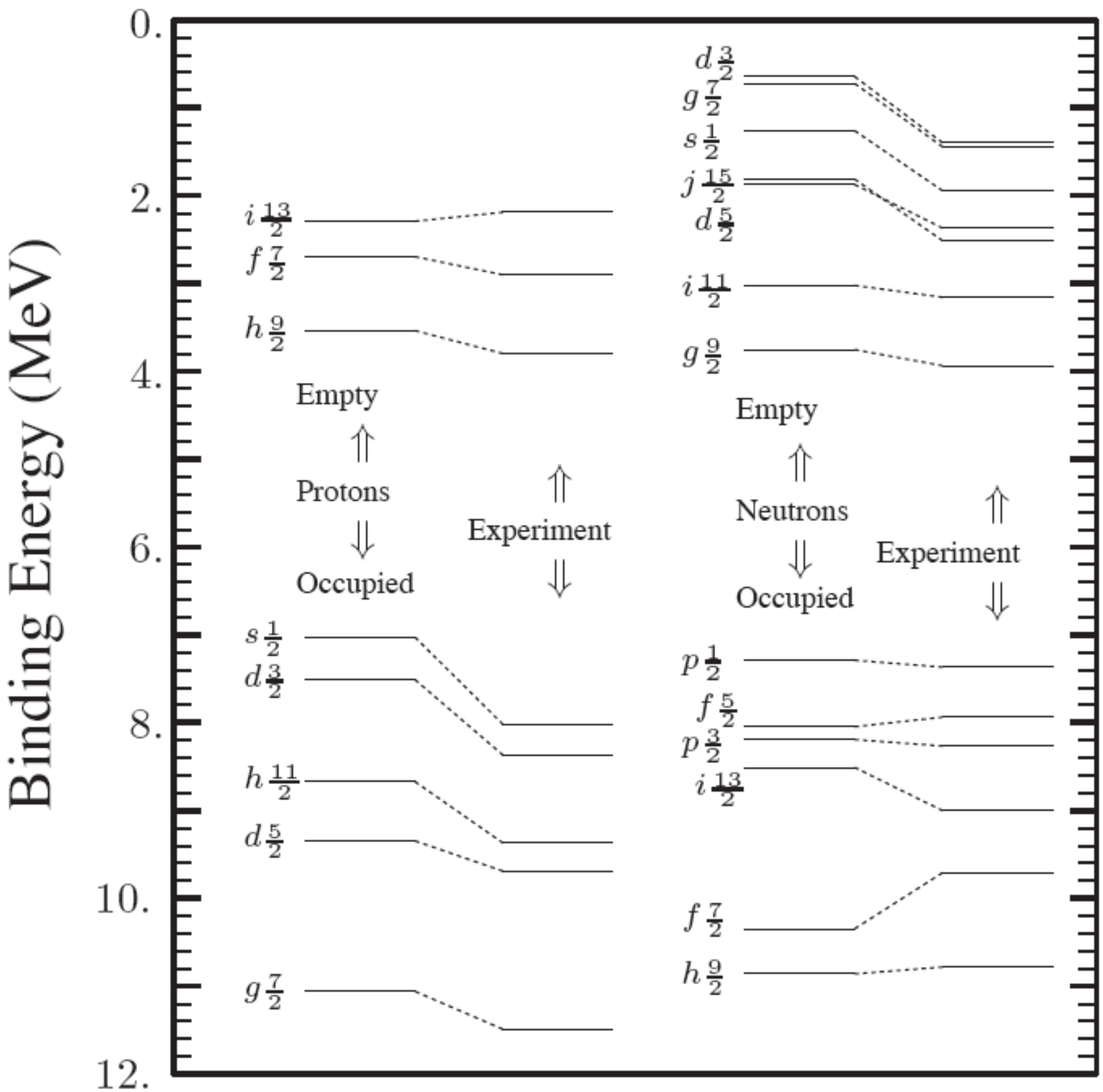
206-205

- Not possible for ^{208}Pb and ^{207}Tl



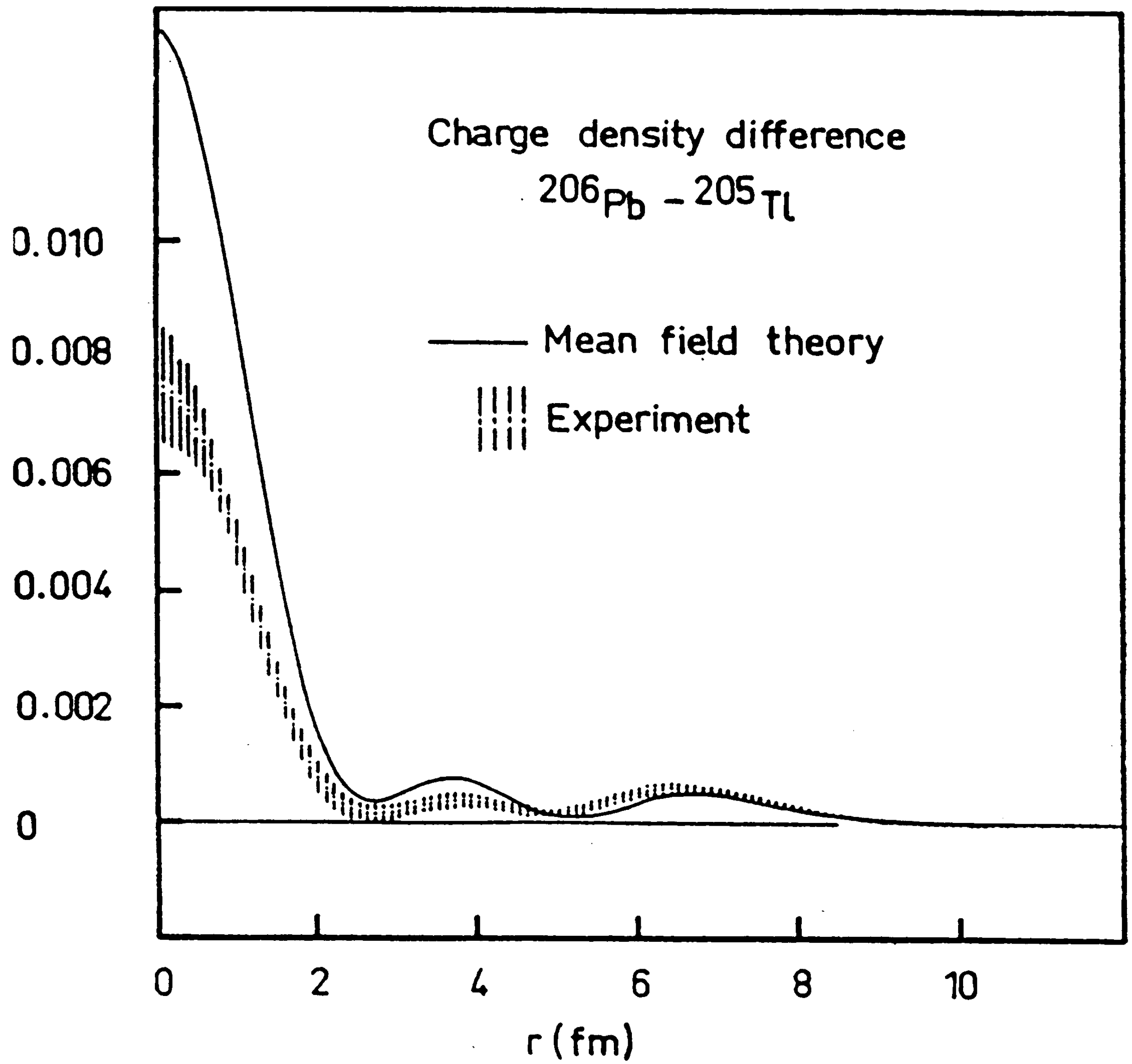
Comparison with experiment

- Now how to explain this potential …



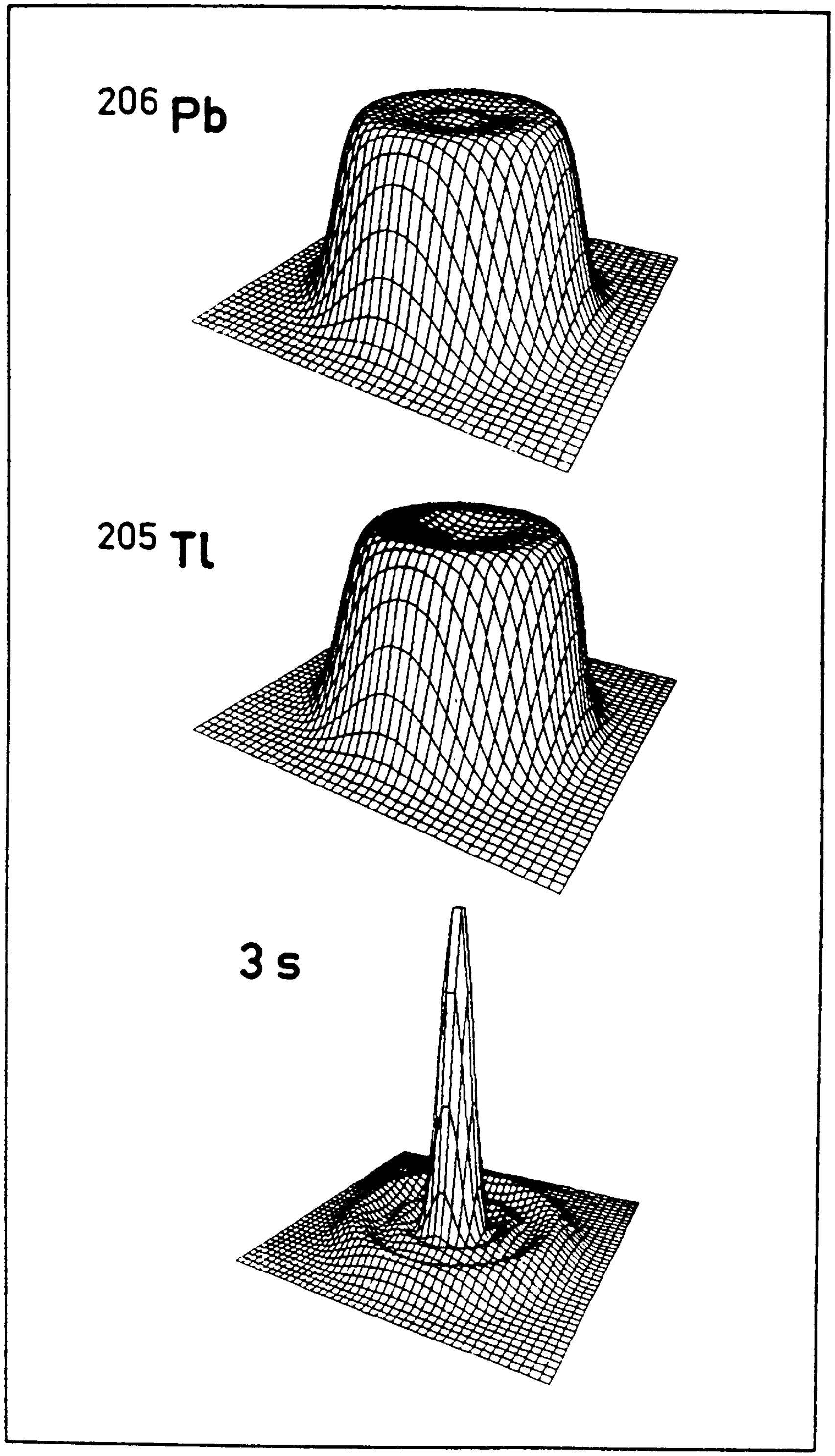
Difference in r-space

- Qualitatively suggestive



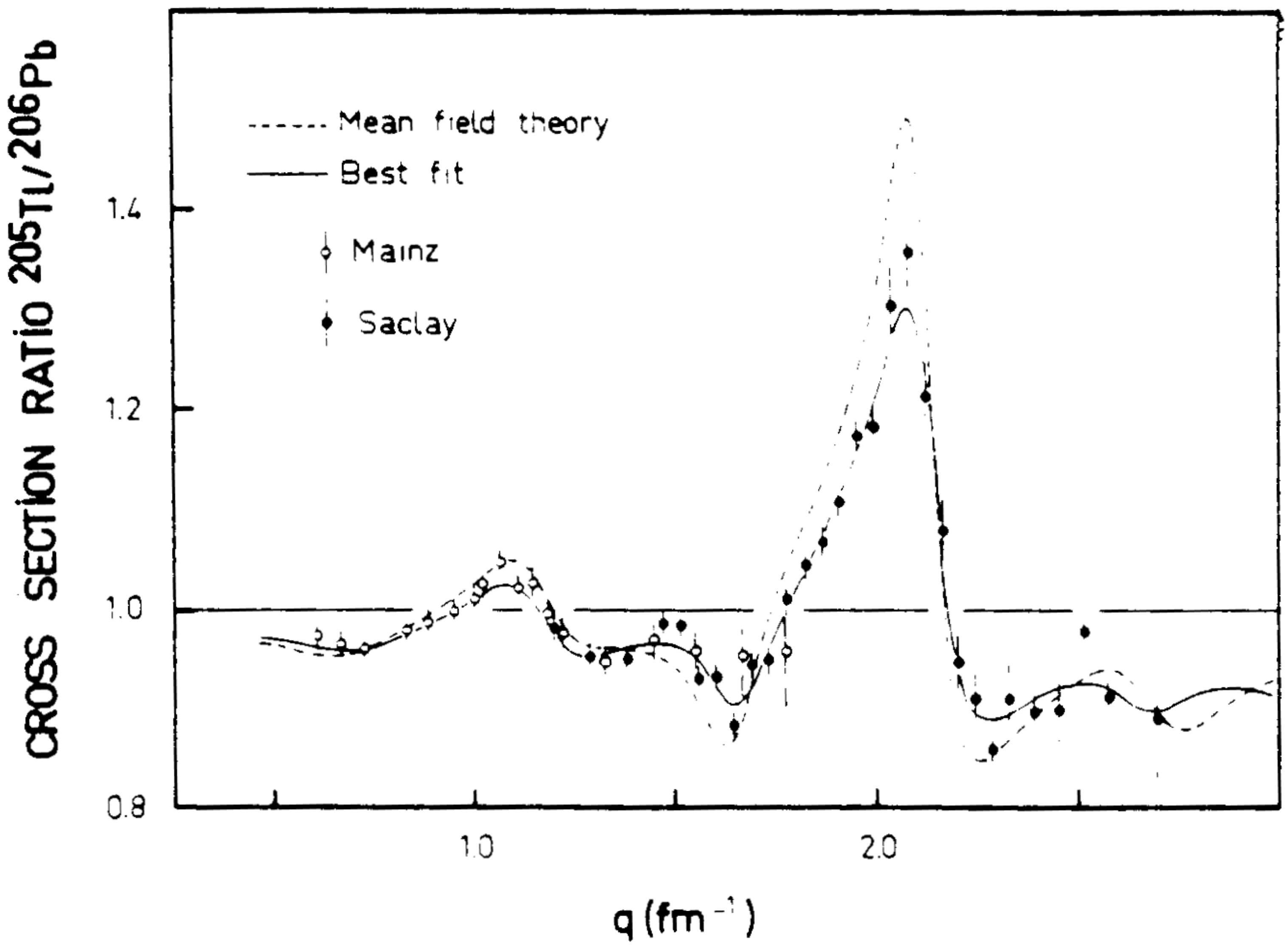
Fun picture

- Arbitrary units



Cross section ratio

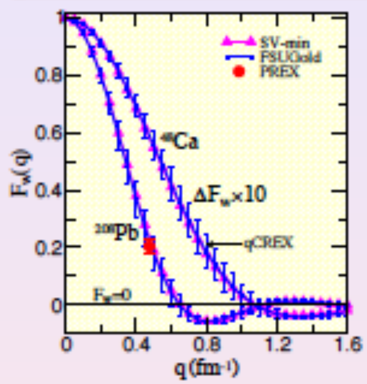
- But … requires a factor!

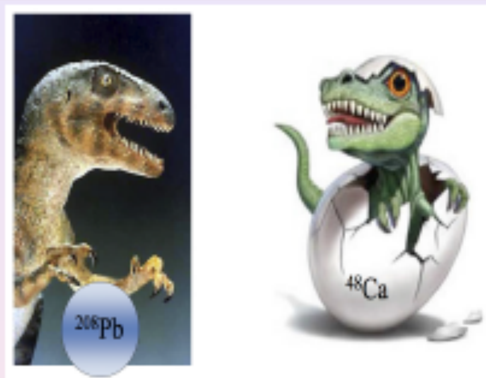


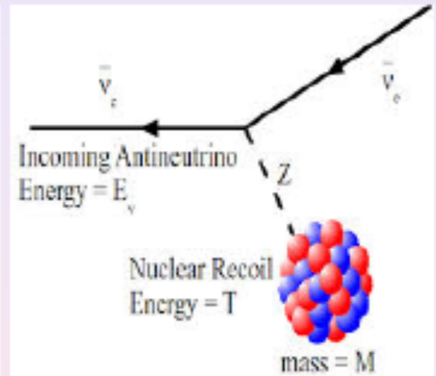
How about neutrons?

PREX: The Lead Radius EXperiment Abrahamyan et al., PRL 108, (2012) 112502

- **Ran for 2 months: April-June 2010**
- First electroweak observation of a neutron-rich skin in ^{208}Pb
- Promised a 0.06 fm measurement of R_n^{208}; error 3 times as large!







We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_n). The result $A_{PV} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

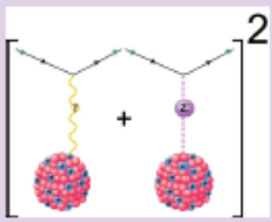
A Physics case for PREX-II, CREX, and ...
Coherent ν-nucleus scattering

Weak interaction helps!

- Difficult experiment

Parity Violation in Elastic e-Nucleus Scattering (JLab and Mainz)

- Charge (proton) densities known with exquisite precision
  charge density probed via parity-conserving eA scattering
- Weak-charge (neutron) densities very poorly known
  weak-charge density probed via parity-violating eA scattering



$$A_{\rm PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- Use parity violation as Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (R_n^{208})

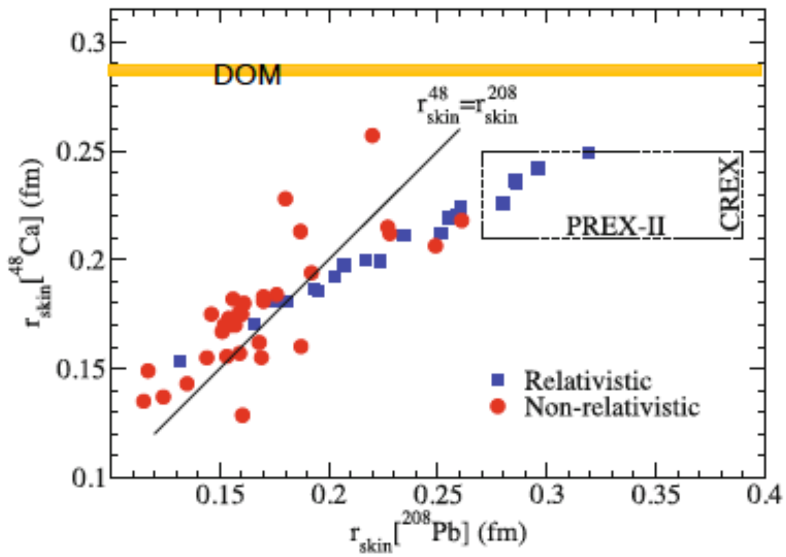
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

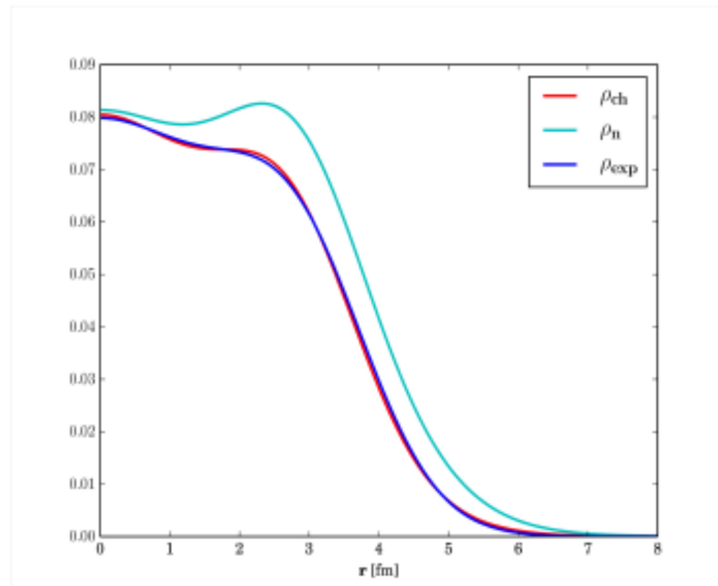
$$g_v = 2t_z - 4Q\sin^2\theta_W \approx 2t_z - Q$$

Hossein Mahzoon's thesis work

- Use scattering data to predict properties of neutrons!

^{48}Ca Charge Density

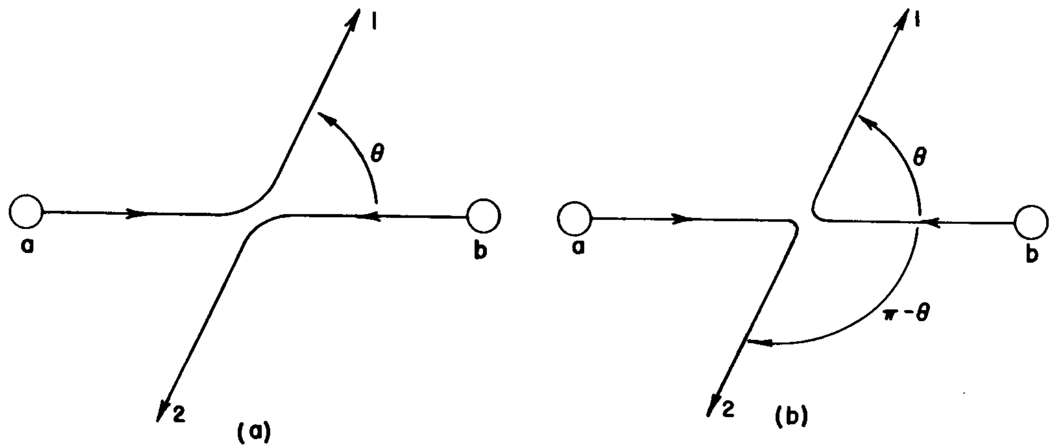




Eur. Phys. J. A (2014) 50: 48
C.J. Horowitz, K.S. Kumar, and R. Michaels

Scattering of identical particles

Nonidentical particles



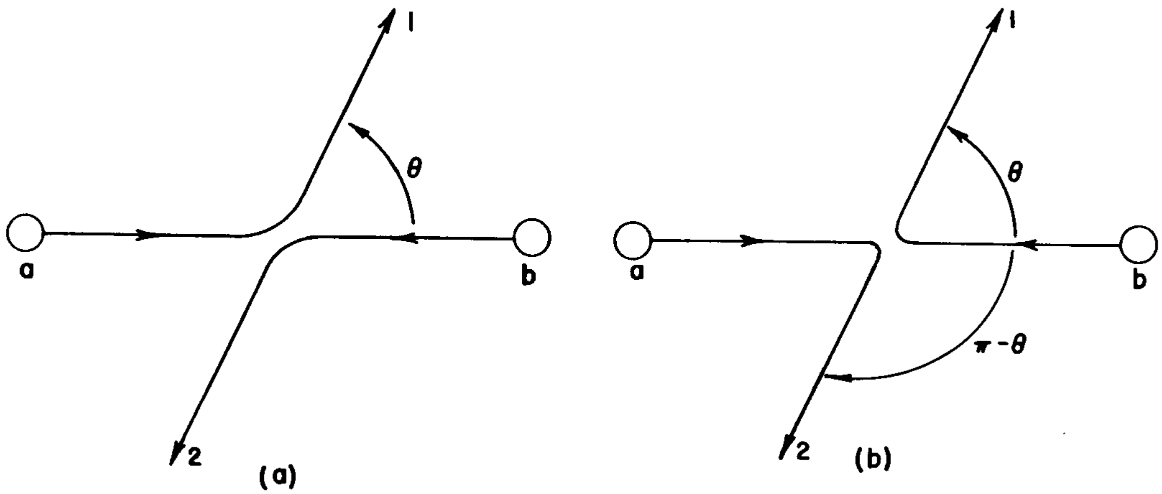
particle a in D1 (a) $$\frac{d\sigma}{d\Omega}(a\ in\ D_1, b\ in\ D_2) = \ |f(\theta)|^2$$

particle a in D2 (b) $$\frac{d\sigma}{d\Omega}(a\ in\ D_2, b\ in\ D_1) = \ |f(\pi - \theta)|^2$$

any particle in D1 $$\frac{d\sigma}{d\Omega}(particle\ in\ D_1) = \ |f(\theta)|^2 + |f(\pi - \theta)|^2$$

Identical bosons

- Cannot distinguish (a) and (b)



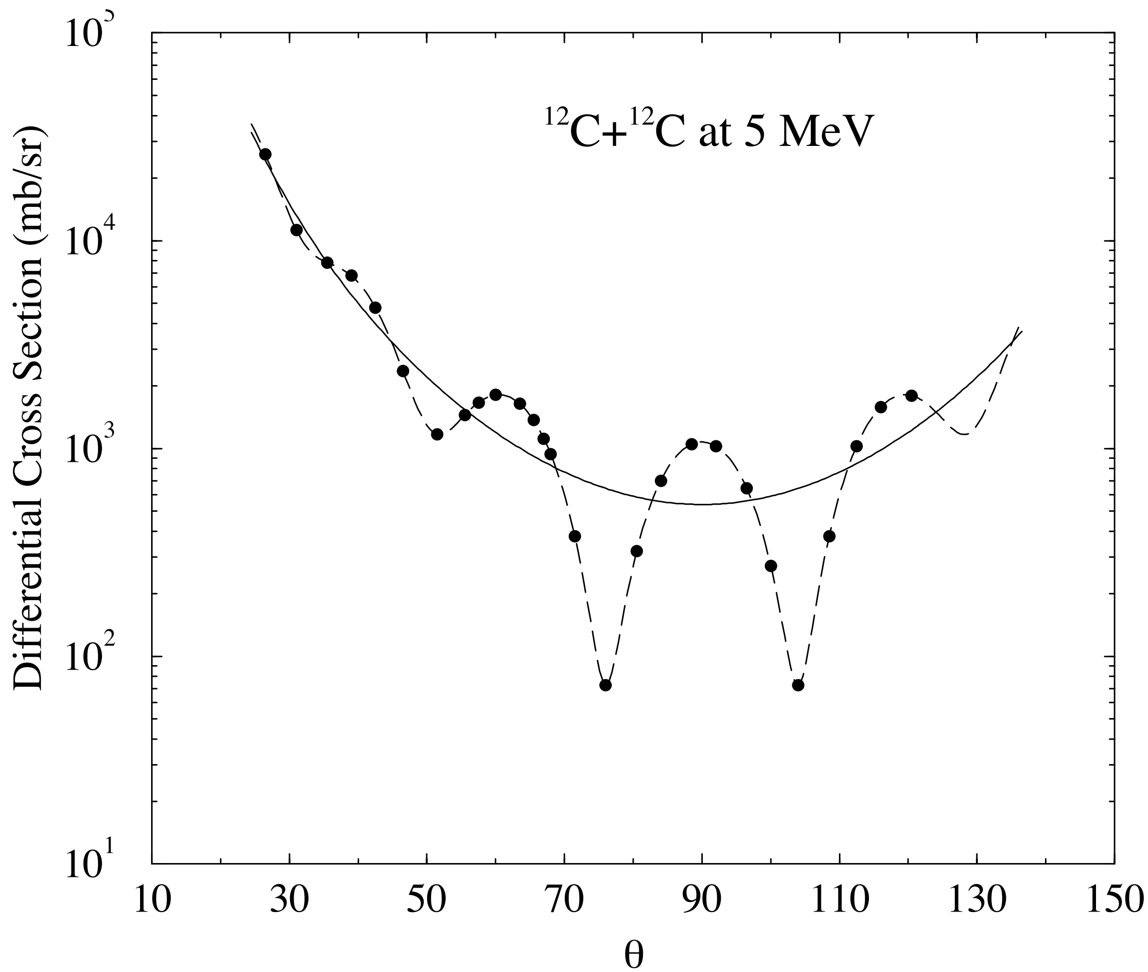
- Rule for bosons: add amplitudes then square!

$$\frac{d\sigma}{d\Omega}(bosons) = \left|f(\theta) + f(\pi - \theta)\right|^2$$

- Interference
- 90 degrees: factor of 2 compared to "classical" cross section

$^{12}C + ^{12}C$

Low-energy boson-boson scattering

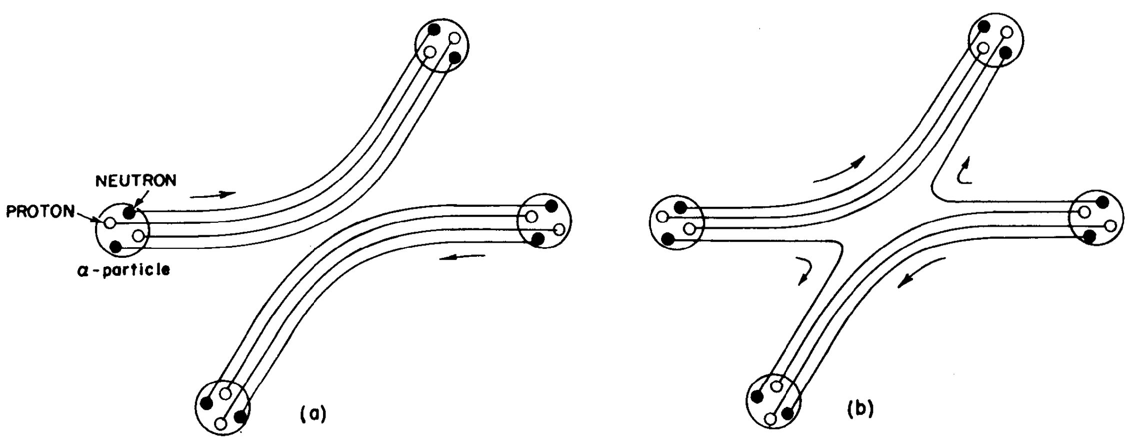


Phys. Rev. **123**, 878 (1961)

^{12}C a boson?

- 6 protons and 6 neutrons
- total angular momentum integer (made of 12 spin-$\frac{1}{2}$ particles)
- ground state 0^+
- first excited state above 4 MeV

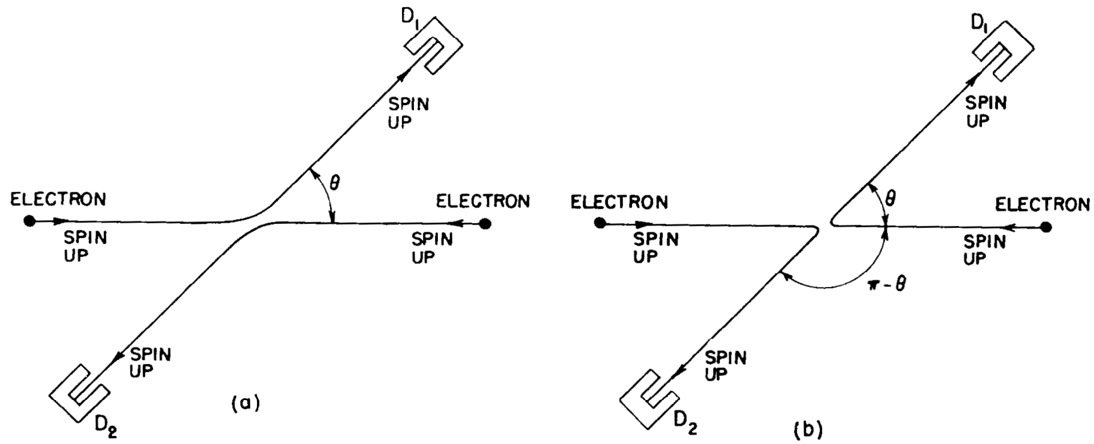
- ^{4}He atom: 2p + 2n + 2e ⇒**boson**
- ^{3}He atom: 2p + 1n + 2e ⇒**fermion**



Fermion-fermion scattering

- Identical fermions: electrons with spin up

$$\frac{d\sigma}{d\Omega}(fermions) = \left| f(\theta) - f(\pi - \theta) \right|^2$$



- What about