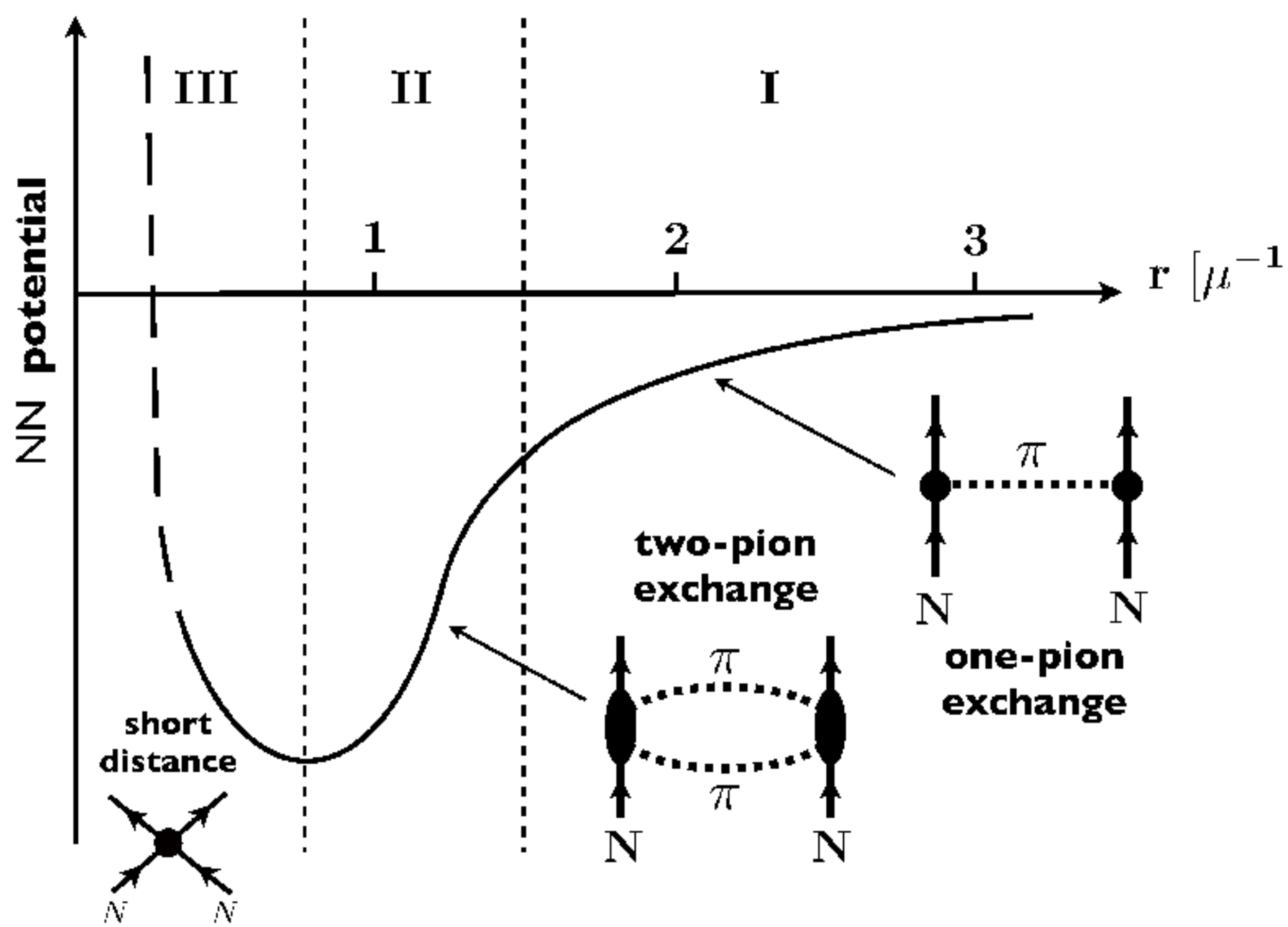
History of the NN potentials



largely based on R. Machleidt, "*Historical perspective and future prospects for nuclear interactions*"

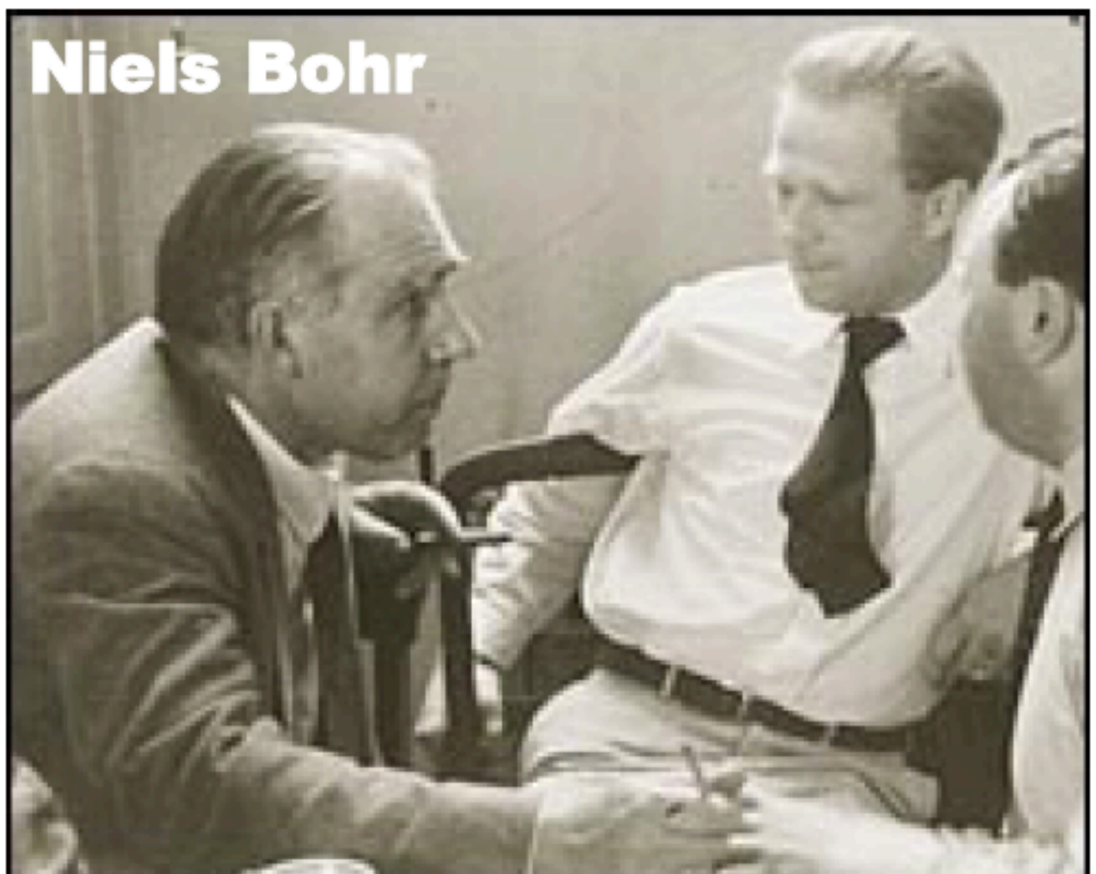
Chronology

- 1930/1940 Phenomenological approaches
- 1947/1960 Discovery of the pion
- 1960/1970 Discovery of the vector bosons
- 1970/1990 Realistic potentials
- 2000/now Chiral potentials

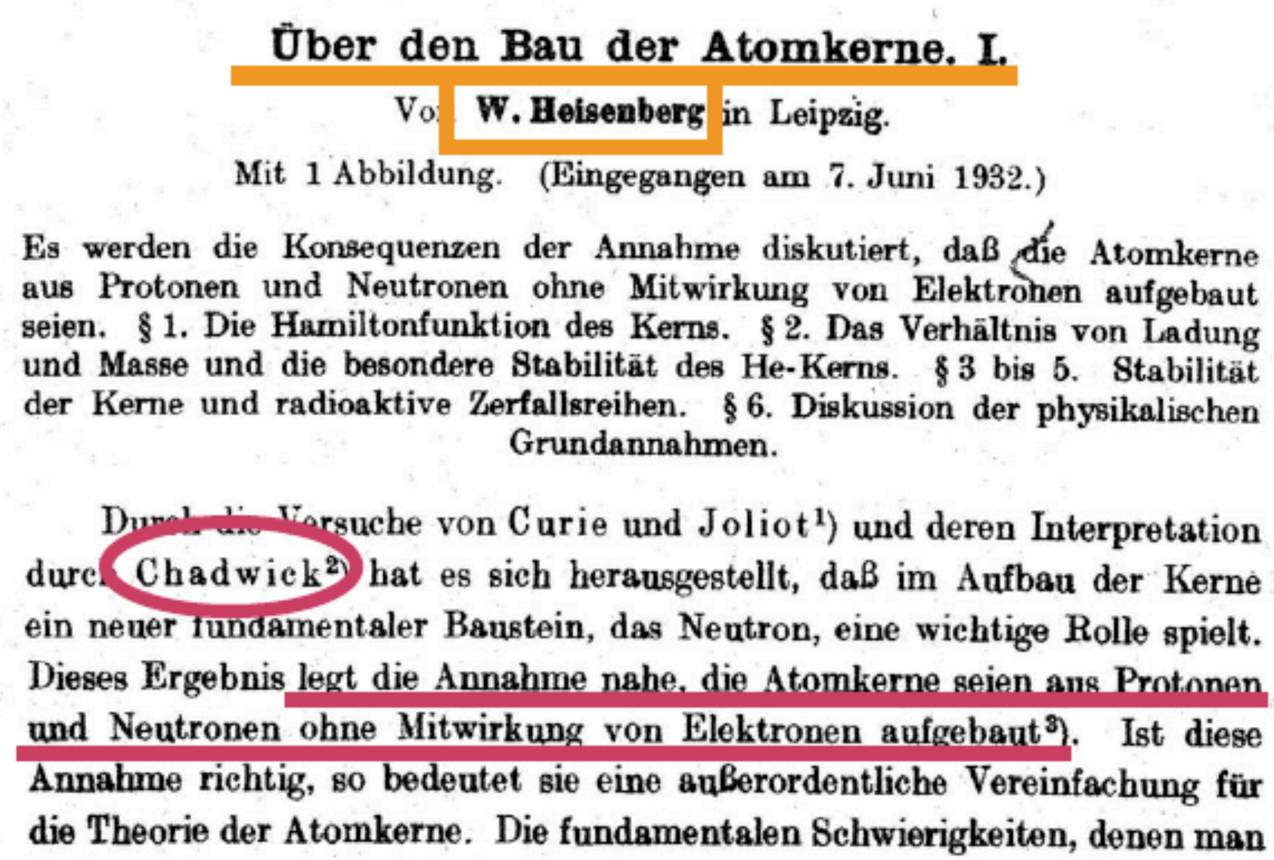
The origins..

- Chadwick: discovery of the neutron (1932)
- Heisenberg: introduction of the isospin (1932)

Heisenberg



Pauli



Über den Bau der Atomkerne. I.

Von **W. Heisenberg** in Leipzig.

Mit 1 Abbildung. (Eingegangen am 7. Juni 1932.)

Es werden die Konsequenzen der Annahme diskutiert, daß die Atomkerne aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut seien. § 1. Die Hamiltonfunktion des Kerns. § 2. Das Verhältnis von Ladung und Masse und die besondere Stabilität des He-Kerns. § 3 bis 5. Stabilität der Kerne und radioaktive Zerfallsreihen. § 6. Diskussion der physikalischen Grundannahmen.

Durch die Versuche von Curie und Joliot[1]) und deren Interpretation durch Chadwick[2]) hat es sich herausgestellt, daß im Aufbau der Kerne ein neuer fundamentaler Baustein, das Neutron, eine wichtige Rolle spielt. Dieses Ergebnis legt die Annahme nahe, die Atomkerne seien aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut[3]). Ist diese Annahme richtig, so bedeutet sie eine außerordentliche Vereinfachung für die Theorie der Atomkerne. Die fundamentalen Schwierigkeiten, denen man

Chadwick…suggests the idea that nuclei are composed by protons and neutrons

Zeitschrift f. Physik, 77 (1932) 1

The origins..

- Yukawa hypothesis about the mesotron (1935)

Hypothesis of a particle with intermediate mass (compared to the electron and proton) responsible for the interaction between nucleons

↓

The particle is massive, so the interaction range is finite → that the range of interaction should be finite was already clear from the saturation properties of finite nuclei

On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

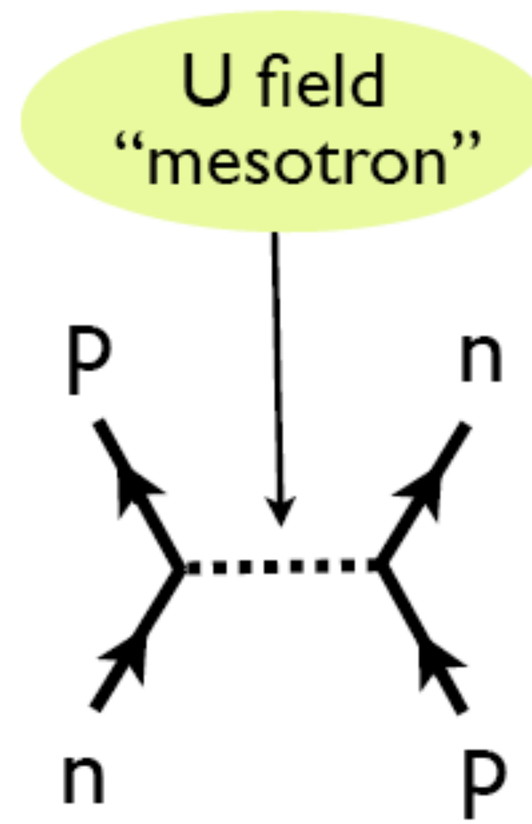
§ 1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction of elementary particles. Heisenberg considered the interaction of "Platzwechsel" between the neutron and the proton to be of importance to the nuclear structure.(1)

Recently Fermi treated the problem of β-disintegration on the hypothesis of "neutrino"(2). According to this theory, the neutron and the proton can interact by emitting and absorbing a pair of neutrino and electron. Unfortunately the interaction energy calculated on such assumption is much too small to account for the binding energies of neutrons and protons in the nucleus.(3)

To remove this defect, it seems natural to modify the theory of Heisenberg and Fermi in the following way. The transition of a heavy particle from neutron state to proton state is not always accompanied by the emission of light particles, i. e., a neutrino and an electron, but the energy liberated by the transition is taken up sometimes by another heavy particle, which in turn will be transformed from proton state into neutron state. If the probability of occurrence of the latter process is much larger than that of the former, the interaction between the neutron and the proton will be much larger than in the case of Fermi, whereas the probability of emission of light particles is not affected essentially.

Proceedings of the Physico-Mathematical Society of Japan
17 (1935) 48



Now, if we introduce the matrices[4]

$$\tau_1=\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix},\quad \tau_2=\begin{pmatrix}0 & -i\\ i & 0\end{pmatrix},\quad \tau_3=\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

and denote the neutron state and the proton state by $\tau_3=1$ and $\tau_3=-1$ respectively, the wave equation is given by

$$\boxed{\left\{\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\lambda^2\right\}U=-4\pi g\tilde{\Psi}\frac{\tau_1-i\tau_2}{2}\Psi,}\qquad (4)$$

where Ψ denotes the wave function of the heavy particles, being a function of time, position, spin as well as τ_3', which takes the value either 1 or -1.

Next, the conjugate complex function $\tilde{U}(x,y,z,t)$, satisfying the equation

$$\boxed{\left\{\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\lambda^2\right\}\tilde{U}=-4\pi g\tilde{\Psi}\frac{\tau_1+i\tau_2}{2}\Psi,}\qquad (5)$$

is introduced, corresponding to the inverse transition from proton to neutron state.

Similar equation will hold for the vector function, which is the analogue of the vector potential of the electromagnetic field. However, we disregard it for the moment, as there's no correct relativistic theory for the heavy particles. Hence simple non-relativistic wave equation neglecting spin will be used for the heavy particle, in the following way

$$\boxed{\begin{aligned}\Bigg\{\frac{h^2}{4}\left(\frac{1+\tau_3}{M_N}+\frac{1-\tau_3}{M_P}\right)\Delta+ih\frac{\partial}{\partial t}-\frac{1+\tau_3}{2}M_Nc^2-\frac{1-\tau_3}{2}M_Pc^2\\ -g\left(\tilde{U}\frac{\tau_1-i\tau_2}{2}+U\frac{\tau_1+i\tau_2}{2}\right)\Bigg\}\Psi=0,\end{aligned}}\qquad (6)$$

Yukawa's early U field:

Scalar Isovector

Estimate of **mass**:

$m_U \sim 200\, m_e$

- 1937: U particle of Yukawa erroneously identified with the muon (Anderson *et al.*, Nishina *et al.*)

- 1947: π meson discovered into cosmic rays
(Occhialini, Powell, Lattes and Muirhead; Nature 159 (1947) 186, 694)

- 1948: π produced into the Berkeley cyclotron
(Gardner and Lattes; Science 107 (1948) 270)

- 1949: Yukawa wins the Nobel prize

π correctly identified
with pseudoscalar mesons
with mass

$$m_\pi \simeq 140\ MeV/c^2$$

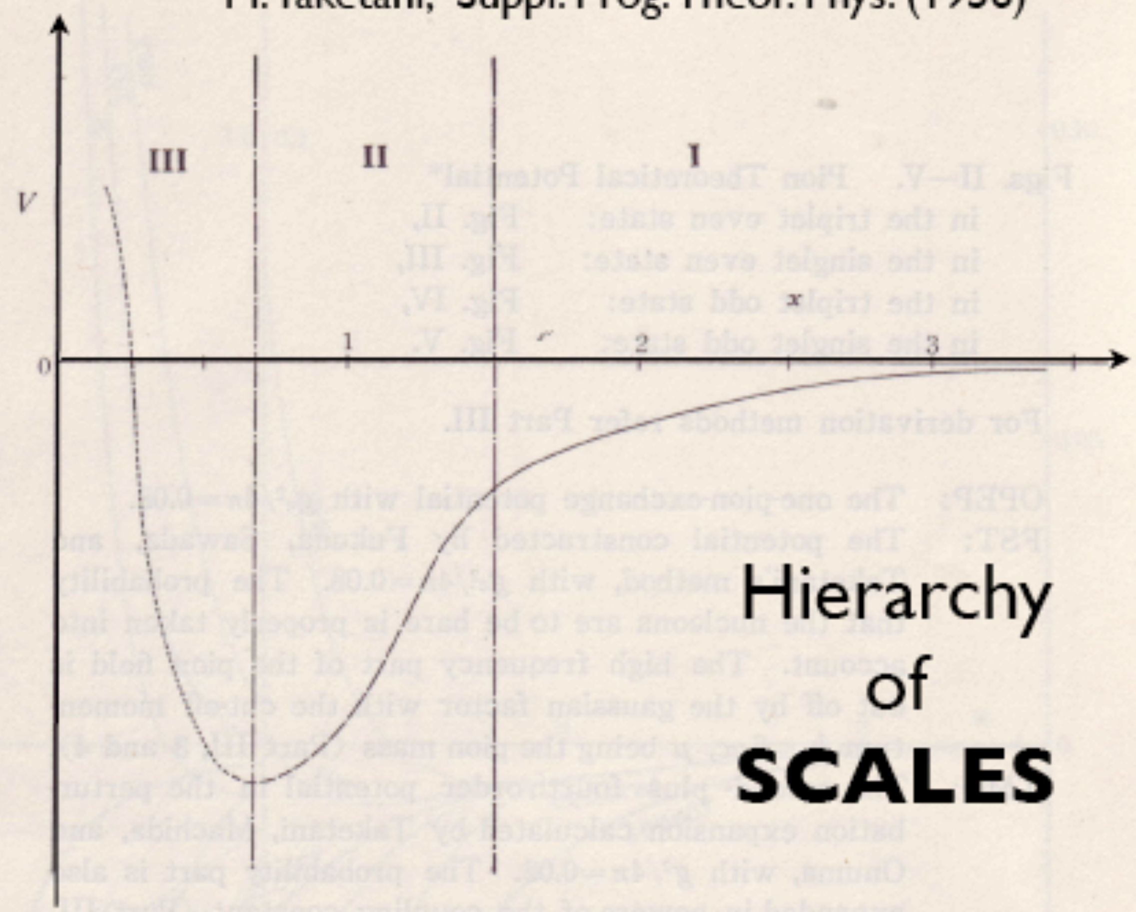
Pion-exchange

- Hypothesis: the strong nuclear force is mediated by the pion
- Problem: the pion is only responsible of the long-range part
- Multi-pion exchange hypothesis
- Problem: very difficult calculations and numerous ambiguities

Nucleon-Nucleon Interaction

M. Taketani, S. Nakamura, M. Sasaki
Prog. Theor. Phys. **6** (1951) 581

M. Taketani, Suppl. Prog. Theor. Phys. (1956)



Hierarchy
of
SCALES

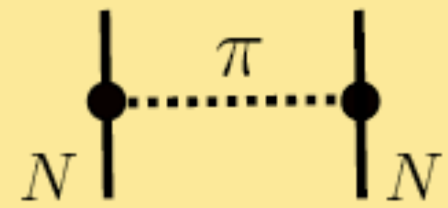
Fig. I. Three Regions of Nuclear Potential.*

Region I. *Classical region*, $r \lesssim 1.5\kappa^{-1}$, ($\kappa^{-1}$ is the pion Compton wave length) where the one-pion-exchange potential dominates and the quantitative behavior of the potential has been established.

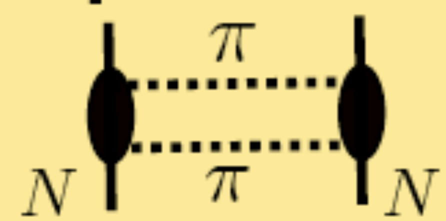
Region II. *Dynamical region*, $0.7\kappa^{-1} \lesssim r \lesssim 1.5\kappa^{-1}$, where the two-pion-exchange potential competes with and exceeds the one-pion-exchange potential. The recoil effect is also appreciable in this region. The qualitative behavior, however, has been clarified.

Region III. *Phenomenological region*, $r \lesssim 0.7\kappa^{-1}$, where exist so many complicated effects, e.g., the relativistic effect, the isobar effect, the effect of new particles, etc., that at present we may have no means but some phenomenological treatment to fit with experiments.

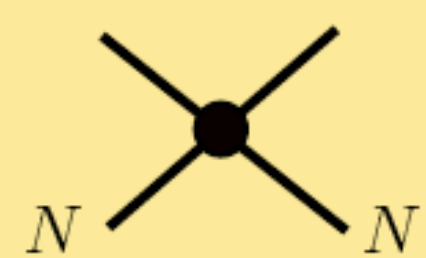
region I
long distance:
one-pion exchange



region II
intermediate distance:
two-pion exchange



region III
short distance: unresolved



What about *pion theories*?

SCIENTIFIC AMERICAN, September 1953

What Holds the Nucleus Together?

by Hans A. Bethe

In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem – probably more man-hours than have been given to any other scientific question in the history of mankind.

A failure!

What about *pion theories*?

"There are few problems in nuclear theoretical physics which have attracted more attention than that of trying to determine the fundamental interaction between two nucleons. It is also true that scarcely ever has the world of physics owed so little to so many …
… It is hard to believe that many of the authors are talking about the same problem or, in fact, that they know what the problem is."

M. L. Goldberger

Midwestern Conference on Theoretical Physics, Purdue University, 1960

A failure!

An alternative approach: pure phenomenology

The most general functional form

$$V_c(r) = V_0(r) + V_\sigma(r)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + V_\tau(r)\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + V_{\sigma\tau}(r)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

$$V_T(r) = [V_T(r) + V_{T\tau}(r)]S_{12}(\hat{r})$$

$$S_{12}(\hat{r}) = \frac{3}{r^2}(\boldsymbol{\sigma}_1 \boldsymbol{r}) \cdot (\boldsymbol{\sigma}_2 \boldsymbol{r}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$V_{LS}(r) = V_{LS0}\boldsymbol{L} \cdot \boldsymbol{S}$$

Gammel e Thaler (57), Jastrow (hard core at short distance, 51), Hamada e Johnston (62) e Yale group (65)

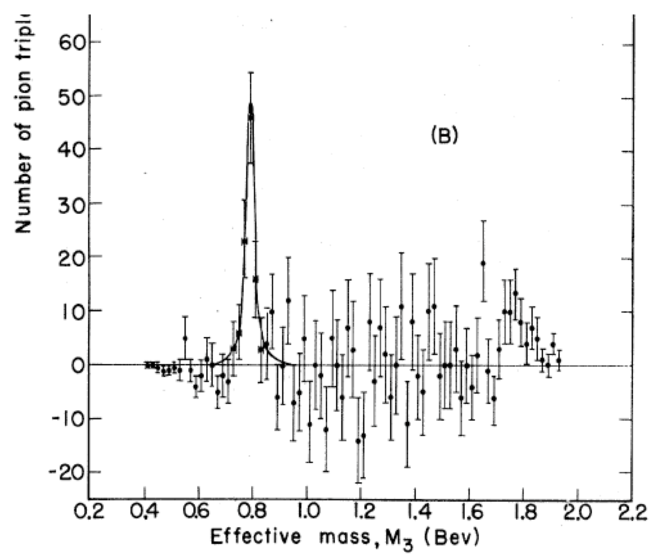
<u>Long range: pion exchange</u>

End of 60, *Reid potentials: soft core introduction*

→ Large number of parameters (~50)

Meson-exchange models

- Discovery of the ω meson (1961)

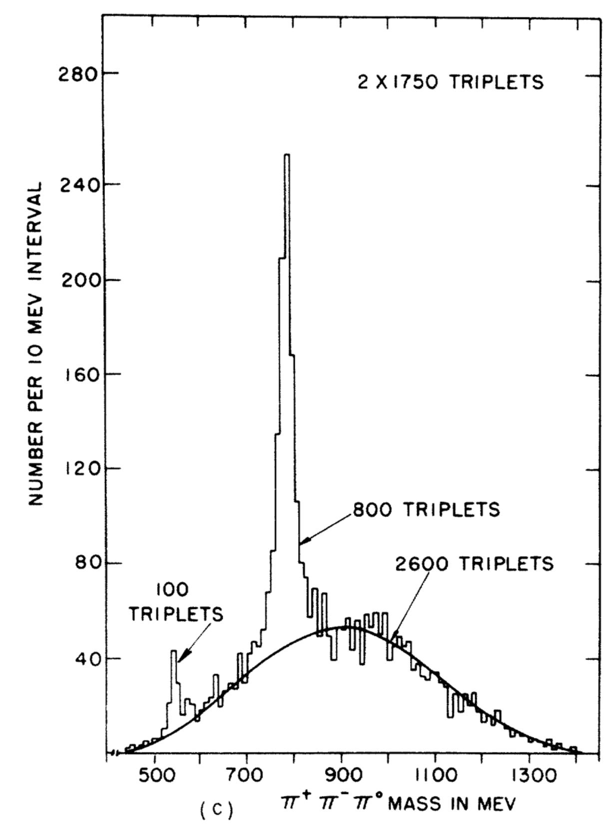


The peak in Fig. 2(B) appears to have a half-width $\Gamma/2<15$ Mev. This is so close to our resolution, $\Gamma_{resol}/2$, of 12 Mev that we cannot unfold it without further study and at present can only conclude that

$$M_\omega = 787 \text{ Mev},$$

and

$$\Gamma/2 < 15 \text{ Mev}.$$



- Discovery of the ρ meson (1962)

Table II. Masses and widths of resonant states.

	Mass	Full width at half max
ρ^+	770 ± 10 MeV	Γ = 130 ± 10 MeV
ρ^0	750 ± 10 MeV	Γ = 100 ± 10 MeV
ω^0	782 ± 1 MeV	Γ ≤ 20 MeV
η^0	548 ± 1 MeV	Γ ≤ 10 MeV

- Rediscovery of the idea that the nuclear force is mediated by mesons: calculations much simpler than in the multi-pion approach

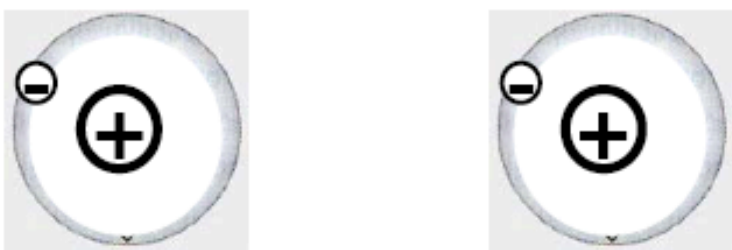
- Development of OBE (one boson exchange) model

Nijmegen (Rijken,...) e Bonn group (Holinde e Machleidt)

How to interpret meson-exchange?

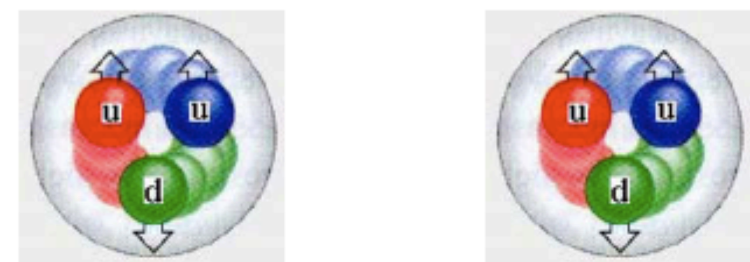
The analogy

Van der Waals force



Residual force between two electric charge-neutral atoms

Nuclear force



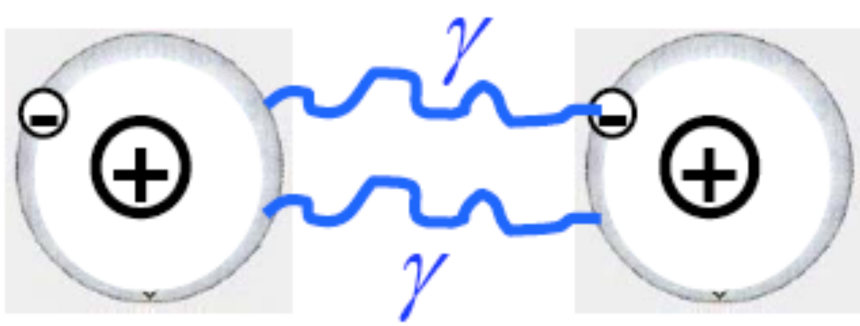
Residual force between two color charge-neutral nucleons

Note that residual forces are typically weak as compared to the "pure" version of the force (order of magnitude weaker).

R. Machledit talks [www.phys.uidaho.edu/machleidt]

How to interpret meson-exchange?

The analogy

Van der Waals force	Nuclear force
	
Residual force between two electric charge-neutral atoms	**Residual force between two color charge-neutral nucleons**

Two-photon exchange (=dipole-dipole interaction)

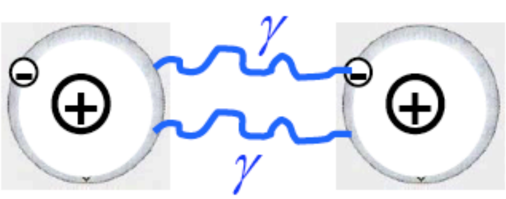
The perfect analogy would be a two-gluon exchange.

http://en.wikipedia.org/wiki/Van_der_Waals_force

R. Machledit talks [www.phys.uidaho.edu/machleidt]

How to interpret meson-exchange?

Van der Waals force	Nuclear force



However, this picture cannot be true, because it would create a force of infinite range (gluons are massless), while the nuclear force is of finite range.

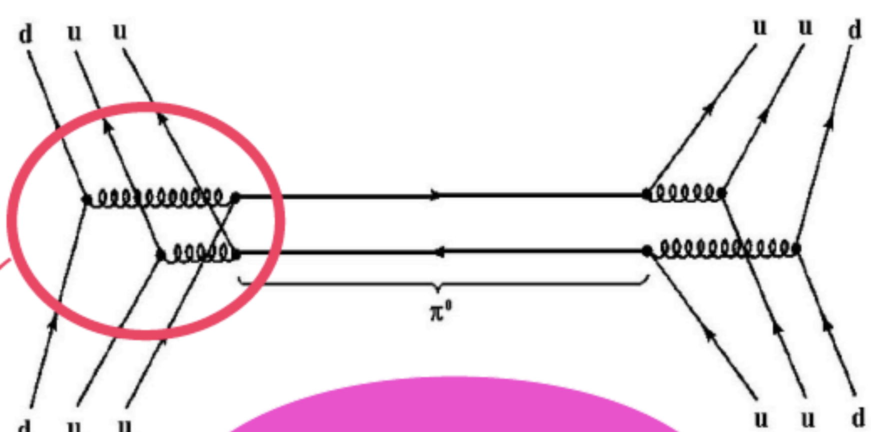
Residual force between two electric charge-neutral atoms

Two-photon exchange (=dipole-dipole interaction)

The perfect analogy would be a two-gluon exchange.

Quark anti-quark exchange

= meson exchange!



This is meson exchange!

But notice that if you want to claim to do QCD, then you have to calculate this vertex from quark and gluon exchanges. Good luck!

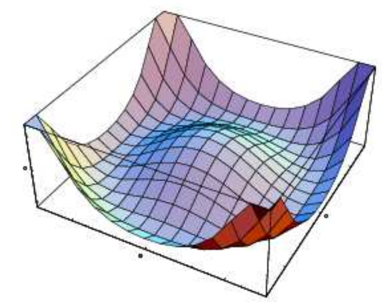
R. Machledit talks [www.phys.uidaho.edu/machleidt]

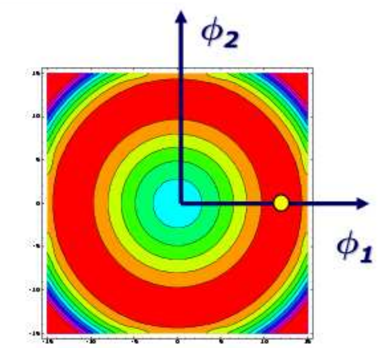
Meson-exchange models

- 1970 - 80 - Good agreement with exp. data
  - Paris Potential (Lacombe *et al.*) PRC 21, 861 (1980)
  - Bonn Potential (Machleidt *et al.*) Phys. Rep. 149, 1 (1987)
- 1993: Nijmegen phase-shifs analysis
- Realistic potentials ($\chi^2 \sim 1.0$)
  - CD-Bonn (Machleidt et al. 1996, 2001)
  - Argonne 18 (Wiringa et al, 1995)
  - Nijmegen I,II, Reid93 (Stoks et al. 1994)

Chiral potentials (2000 - …)

- Step back: pion-exchange theories constrained by symmetries, i.e. chiral symmetry





- Nuclear physics, with nucleons as d.o.f., is a “low-energy” limit of QCD
- The interaction is mediated by pions, as the Goldstone bosons of the theory, that weakly interact with nucleons (aka perturbation theory can be applied)
- The theory is non-renormalizable, an explicit cutoff is introduced

R. Machledit talks [www.phys.uidaho.edu/machleidt]

Chiral potentials (2000 - ...)