Physics Department, Tohoku University,
June 30 – July 2, 2014

Nuclear Forces
- Lecture 1 -

Historical Perspective

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Nuclear Forces
- Overview of all lectures -

- Lecture 1: Historical perspective
- Lecture 2: Properties and phenomenology of the nuclear force
- Lecture 3: The meson theory of nuclear forces
- Lecture 4: QCD and nuclear forces; the symmetries of low-energy QCD
- Lecture 5: Effective field theory (EFT) for low-energy QCD and nuclear two-body forces
- Lecture 6: Nuclear many-body forces from chiral EFT

Lecture 1: Historical perspective

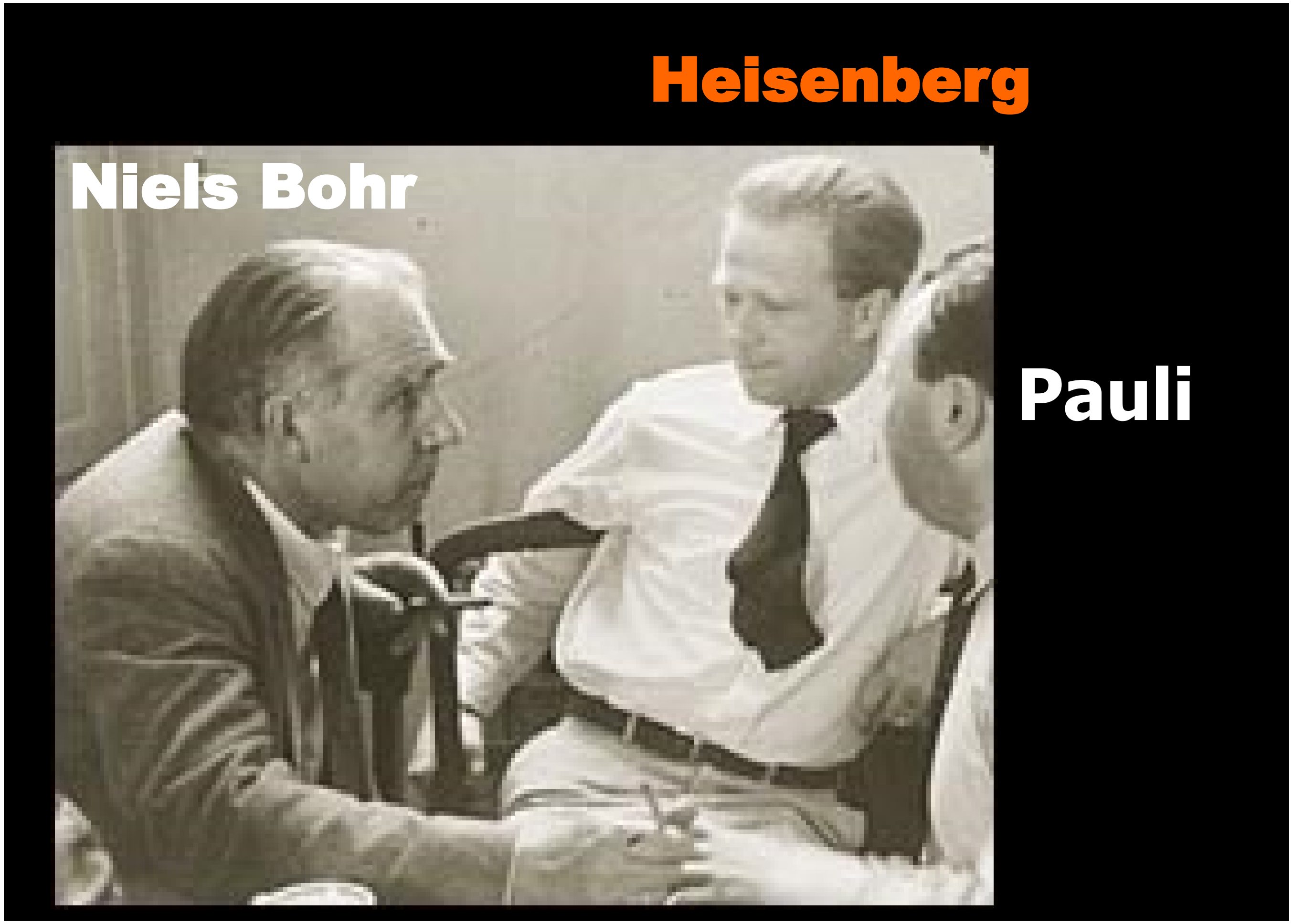
History of Nuclear Forces: Phase I

1930's

Chadwick (1932): Neutron

Heisenberg (1932): First Phenomenology (Isospin)

Heisenberg and his contribution of 1932



Zeitschrift fuer Physik 77, 1 (1932)

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

On the Structure of Atomic Nuclei. I.

....

… Chadwick …

… suggests the assumption that atomic nuclei are built from protons and neutrons without electrons …

Zeitschrift fuer Physik 77, 1 (1932), cont' d

Von den Kraftwirkungen der elementaren Kernbausteine aufeinander betrachten wir zunächst die zwischen Neutron und Proton. Bringt man Neutron und Proton in einen mit Kerndimensionen vergleichbaren Abstand, so wird — in Analogie zum H_2^+-Ion — ein Platzwechsel der negativen Ladung eintreten, dessen Frequenz durch eine Funktion $\frac{1}{h} J(r)$ des Abstandes r der beiden Teilchen gegeben ist. Die Größe $J(r)$ entspricht dem Austausch- oder richtiger Platzwechselintegral der Molekültheorie. Diesen Platzwechsel kann man wieder durch das Bild der Elektronen, die keinen Spin haben und den Regeln der Bosestatistik folgen, anschaulich machen. Es ist aber wohl richtiger, das Platzwechselintegral $J(r)$ als eine fundamentale Eigenschaft des Paares Neutron und Proton anzusehen, ohne es auf Elektronenbewegungen reduzieren zu wollen.

… the force … between proton and neutron …

…. in analogy to the H_2^+ -ion --- an exchange of negative charge will take place, …

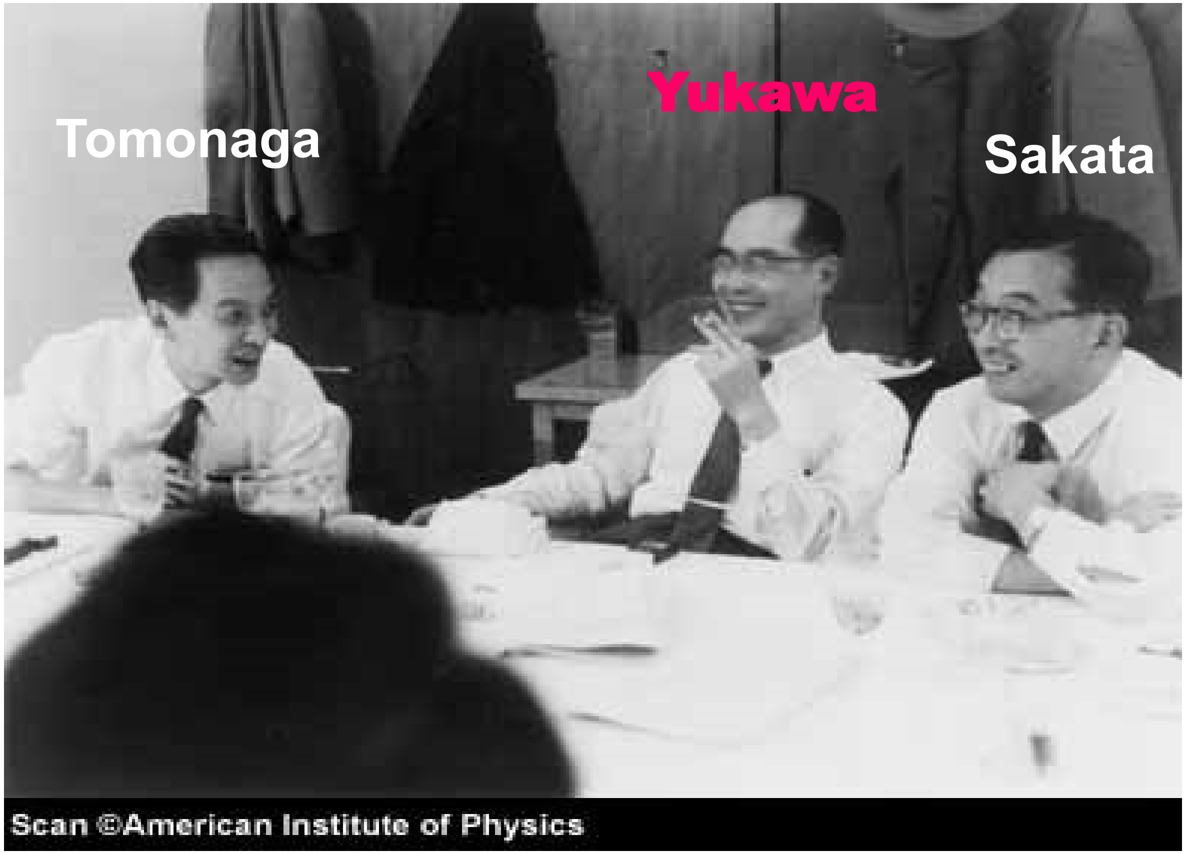
This exchange can be visualized by electrons which do not have spin and follow the rules of bose statistics …

Precursor of the idea of Boson Exchange!

History, Phase I cont’d

1930’s	Chadwick (1932): Neutron Heisenberg (1932): First Phenomenology (Isospin) **Yukawa (1935): Meson Hypothesis**

Yukawa and his idea



S. Tomonaga, H. Yukawa, and S. Sakata in the 1950s.

From:

H. Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935).

§ 2. Field describing the interaction

In analogy with the scalar potential of the electromagnetic field, a function $U(x, y, z, t)$ is introduced to describe the field between the neutron and the proton. This function will satisfy an equation similar to the wave equation for the electromagnetic potential.

Now the eqnation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right\} U = 0 \qquad (1)$$

has only static solution with central symmetry $\frac{1}{r}$, except the additive and the multiplicative constants. The potential of force between the neutron and the proton should, however, not be of Coulomb type, but decrease more rapidly with distance. It can be expressed, for example, by

$$+ \text{ or } -g^2\frac{e^{-\lambda r}}{r}, \qquad (2)$$

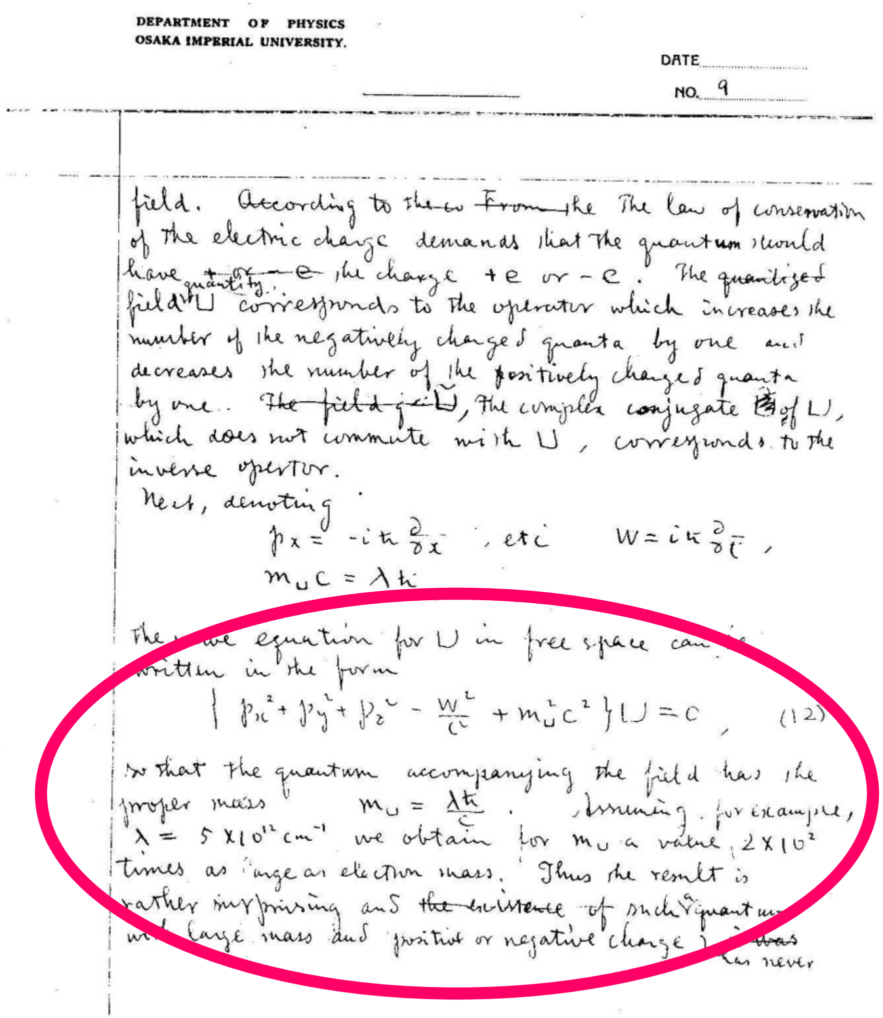
where g is a constant with the dimension of electric charge, i. e., cm.$^{\frac{3}{2}}$ sec.$^{-1}$ gr.$^{\frac{1}{2}}$ and λ with the dimention cm.$^{-1}$

Since this function is a static solution with central symmetry of the wave equation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} U = 0, \qquad (3)$$

let this equation be assumed to be the correct equation for U in vacuum. In the presence of the heavy particles, the U-field interacts with them and causes the transition from neutron state to proton state.

R. Machleidt



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field. ~~According to the~~ ~~From the~~ The law of conservation of the electric charge demands that the quantum should have ~~+ or − e~~ the charge +e or −e. The quantized field U corresponds to the operator which increases the number of the negatively charged quanta by one and decreases the number of the positively charged quanta by one. ~~The field~~ $\tilde{U}$, the complex conjugate of U, which does not commute with U, corresponds to the inverse operator.

Next, denoting

$$p_x = -i\hbar\frac{\partial}{\partial x}, \text{ etc} \qquad W = i\hbar\frac{\partial}{\partial t},$$

$$m_U c = \lambda\hbar$$

the wave equation for U in free space can be written in the form

$$\left\{p_x^2+p_y^2+p_z^2-\frac{W^2}{c^2}+m_U^2c^2\right\}U=0, \qquad (12)$$

so that the quantum accompanying the field has the proper mass $m_U = \frac{\lambda\hbar}{c}$. Assuming, for example, $\lambda = 5\times10^{12}\,\text{cm}^{-1}$ we obtain for m_U a value 2×10^2 times as large as electron mass. Thus the result is rather surprising and ~~the existence~~ of such quantum with large mass and positive or negative charge ... has never

H. Yukawa: manuscript of the first paper showing the mass-range formula (November 1934). Reproduced by permission of Yukawa Hall Archival Library.

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Yukawa (1935): Meson Hypothesis

1940’s

Discovery of the pion in cosmic ray (1947) and in the Berkeley Cyclotron Lab (1948).
Nobelprize awarded to Yukawa (1949).

1950’s

“Pion Theories”

Taketani, Nakamura, Sasaki (1951): 3 ranges.

One-Pion-Exchange (OPE): o.k.

Multi-pion exchanges: Problems!

Taketani, Machida, Onuma (1952);

Brueckner, Watson (1953).

Quotes by Bethe (1953) and Goldberger (1960)

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.

"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

History, **Phase I** (The first pion period)

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The first pion period: results in a disaster

Phase II: The meson period

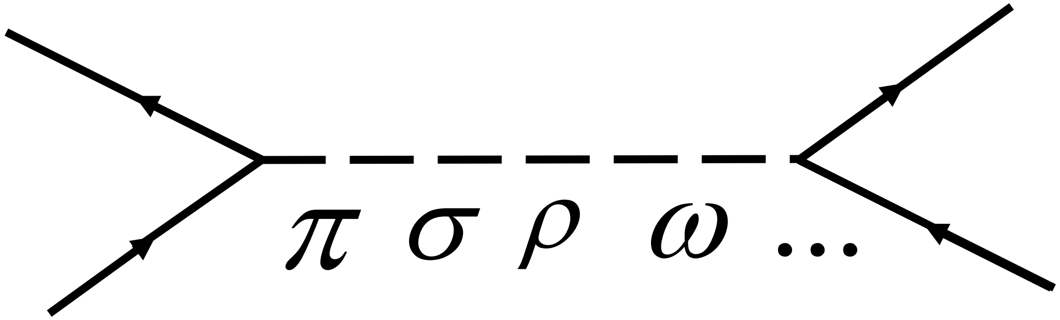
1960's

Many pions = multi-pion resonances:

$$\sigma(600), \rho(770), \omega(782) \ldots$$

One-Boson-Exchange Model

Phase



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$\sigma(600)$, $\rho(770)$, $\omega(782)$ ...

One-Boson-Exchange Model

Phase II: The meson period

1960's

Many pions = multi-pion resonances:

$\sigma(600), \rho(770), \omega(782) \ldots$

One-Boson-Exchange Model

1970's

Refined Meson Theories

Sophisticated models for two-pion exchange:

Paris Potential (Lacombe *et al.,* PRC **21**, 861 (1980))

Bonn potential (Machleidt *et al.,* Phys. Rep. **149**, 1 (1987))

The exponential tail of phase II

(or the epigone period of meson theory)

1980's **Nijmegen: We need more precision!!!**

"A χ^2/dat of ≈ 2 is not good enough, it has to be 1.0"

1990's

1993: The high-precision Nijmegen phase shift analysis

1994-2001: High-precision NN potentials:

- **Nijmegen I, II, '93, Reid93 (Stoks et al. 1994)**
- **Argonne V18 (Wiringa et al, 1995)**
- **CD-Bonn (Machleidt et al. 1996, 2001)**

1960's

Gell-Mann and Zweig (1963): 3 quarks!

Phase III: The QCD/EFT period

1980's	**Nuclear physicists discover QCD:** **Quark cluster models.**
1990 – today	**Nuclear physicists discover Effective Field Theory (EFT):** **Weinberg (1990); Ordonez, Ray, van Kolck (1994/96).** **Another "pion theory"; but now right: constrained by chiral symmetry**

Phase III: The QCD/EFT period

1980's	**Nuclear physicists discover QCD:** **Quark cluster models.**
1990 - today	**Nuclear physicists discover Effective Field Theory (EFT):** **Weinberg (199...); Ordóñez, Ray, van Kolck (199...-...6)** **Another "pion theory"; but now right: constrained by chiral symmetry**

The second pion period:

No disaster!

Summary

Table 1. Eight Decades of Struggle: The Theory of Nuclear Forces

1935	**Yukawa: Meson Theory**
1950's	*The "Pion Theories"* One-Pion Exchange: o.k. Multi-Pion Exchange: disaster
1960's	Many pions ≡ multi-pion resonances: σ, ρ, ω, ... The One-Boson-Exchange Model
1970's	Refine meson theory: More sophisticated meson-exchange models (Stony Brook, Paris, Bonn)
1980's	Nuclear physicists discover **QCD** Quark Cluster Models
1990's and beyond	Nuclear physicists discover **EFT** Weinberg, van Kolck **Back to Yukawa's Meson Theory!** *But, with Chiral Symmetry*

Table 1. Eight Decades of Struggle: The Theory of Nuclear Forces

1935	
1950's	
	T
a	n Theory!
	Symmetry

The circle of history is closing.

End Lecture 1