CNS Summer School, Univ. of Tokyo,
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Nuclear Forces

- Lecture 1 -

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Nuclear Forces
- Overview of all lectures -

- Lecture 1: History, facts, and phenomenology
- Lecture 2: The meson theory of nuclear forces
- Lecture 3: Low-energy QCD and the nuclear force
- Lecture 4: Effective field theory and nuclear forces

Lecture 1: History, facts, and phenomenology

- Historical review
- Properties of the nuclear force
- Phenomenological descriptions

History of Nuclear Forces

1930's

Chadwick (1932): Neutron

Heisenberg (1932): First Phenomenology (Isospin)

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, cont'd

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))

History, cont'd

1980's

Nuclear physicists dicover QCD:

Quark cluster models.

1990

- 2005

Nuclear physicists discover Effective Field Theory (EFT)

Weinberg (1990)

Ordonez, Ray, van Kolck (1994/96)

… many others …

Properties of the nuclear force

- Finite range
- Intermediate-range attraction
- Short-range repulsion (“hard core”)
- Spin-dependent non-central forces:
  - Tensor force
  - Spin-orbit force
- Charge independence

Finite range

- Comparison of the binding energies of
  ^{2}H (deuteron), ^{3}H (triton), ^{4}He (alpha - particle)
  show that the nuclear force is of finite range (1-2 fm) and very strong within that range (Wigner, 1933).

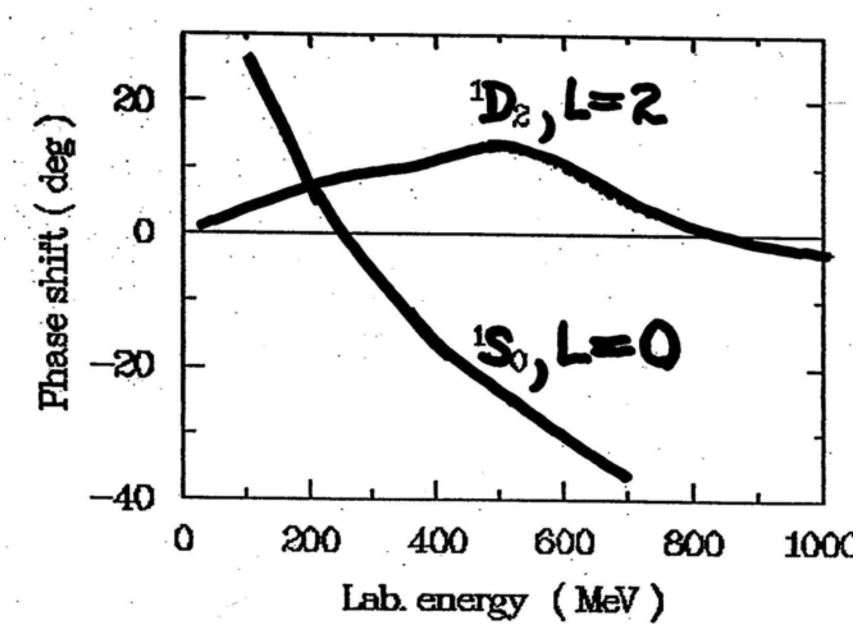
- "Saturation". Nuclei with A>4 show saturation: Volume and binding energies of nuclei are proportional to the mass number A.

Intermediate-range attraction

Nuclei are bound. The average distance between nucleons in nuclei is about 2 fm which must roughly correspond to the range of the attractive force.

Short-range repulsion ("hard core")

Analyze 1S0 phase shifts and compare to 1D2 phase shifts.



$L_{max} \approx R\, p_{cm}$

$L_{max} \lesssim 1 \implies R \lesssim \frac{1}{p_{cm}} \approx 0.6\text{ fm}$

for $E_{lab} = 250$ MeV $\quad \approx$ hard-core radius

$E_{lab} = \frac{2 p_{cm}^2}{M}$

Tensor Force: First evidence from the deuteron

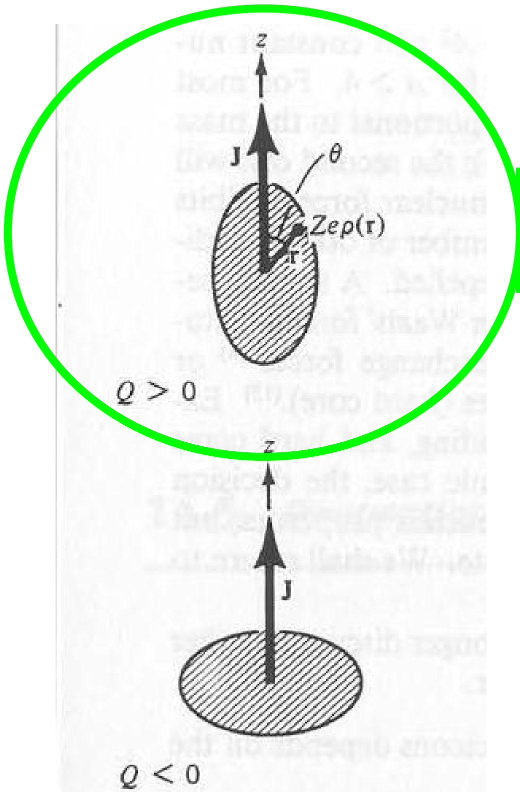


Fig. 14.10. Oblate and prolate nuclei, with spins pointing in the z direction. The nuclei are assumed to be axially symmetric; z is the symmetry axis.

Deuteron

Tensor force, cont'd

$$(-S_{12}) = -3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) + \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

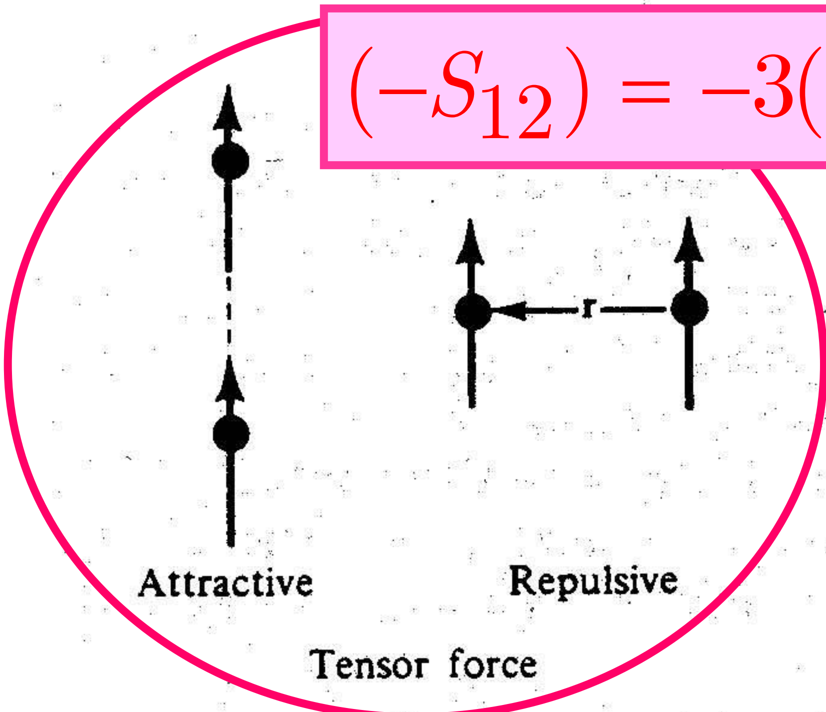
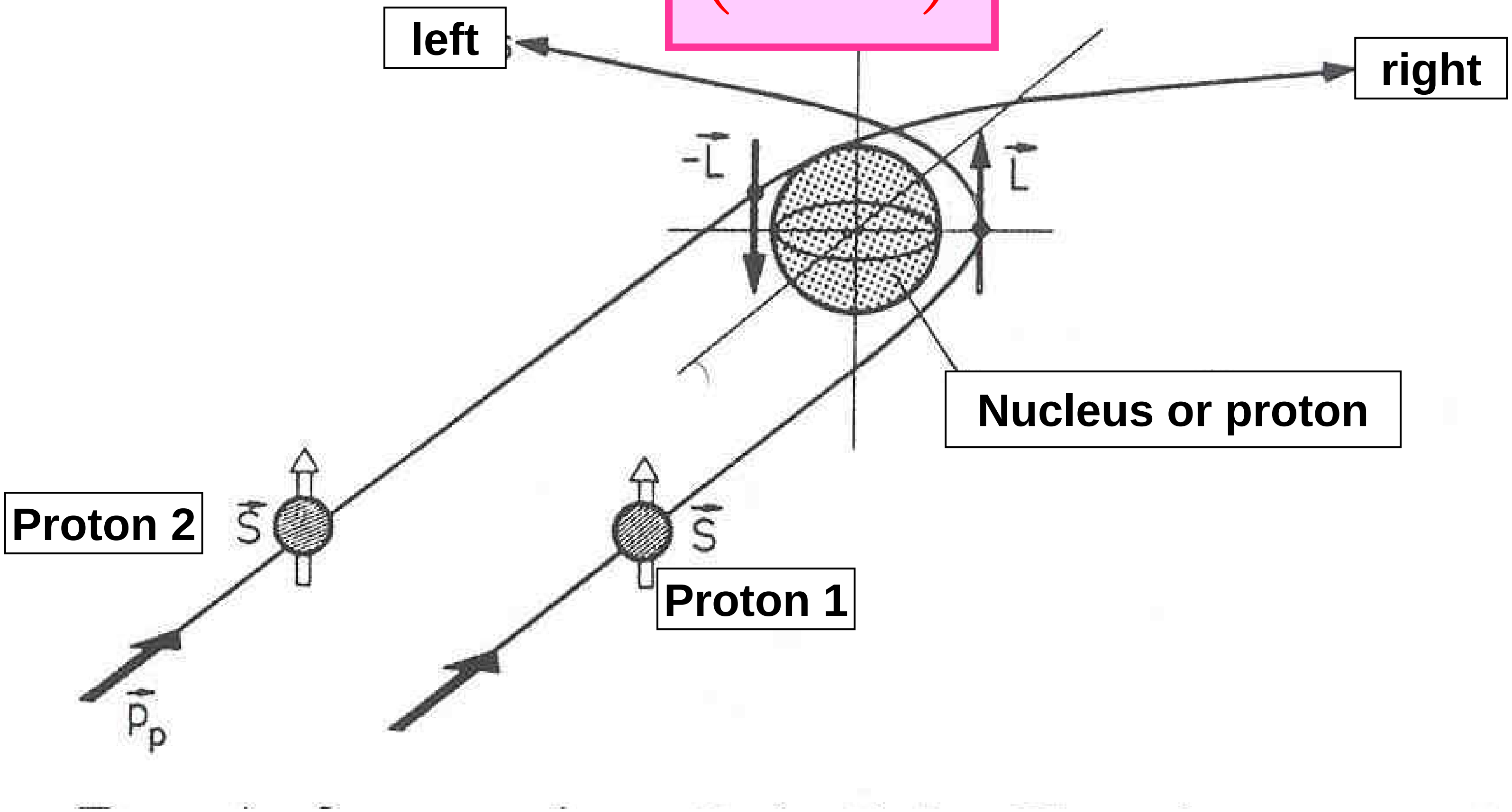


Fig. 14.11. The tensor force in the deuteron is attractive in the cigar-shaped configuration and repulsive in the disk-shaped one. Two bar magnets provide a classical example of a tensor force.

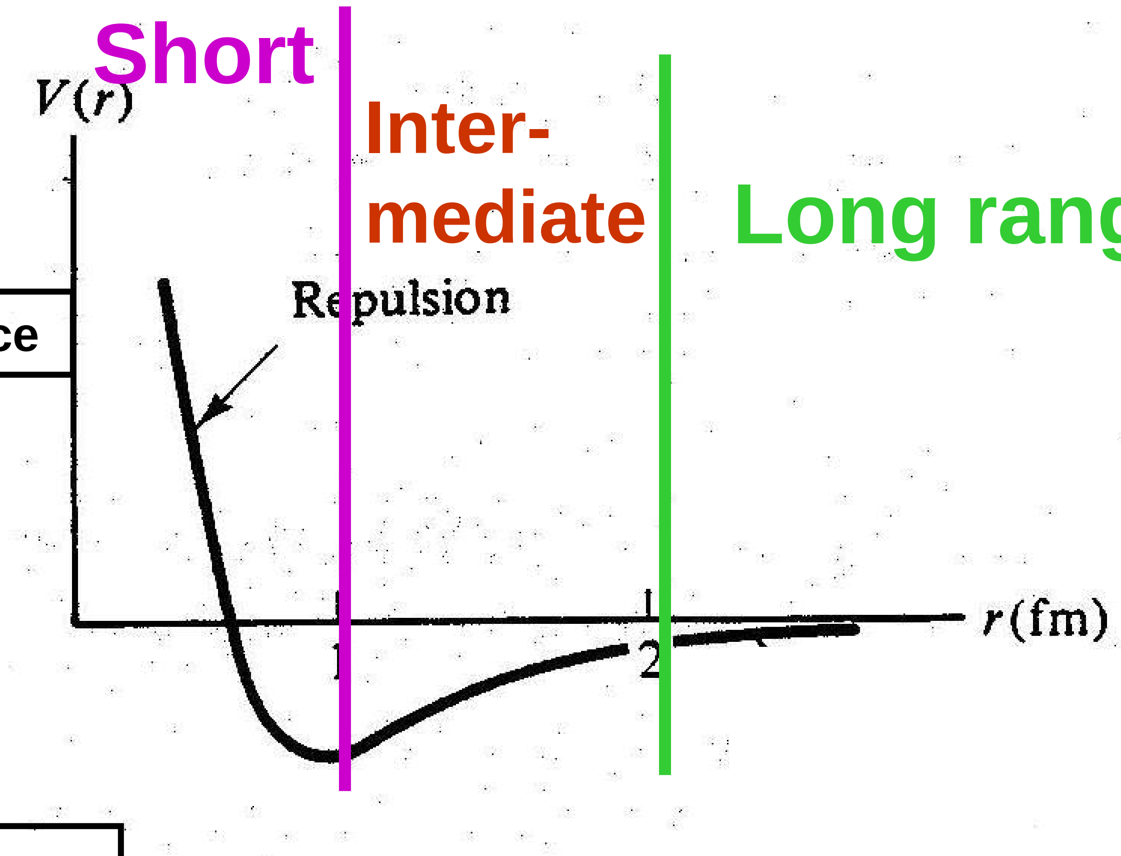
Non-central forces

Spin-Orbit Force

$$(\vec{L} \bullet \vec{S})$$



Summary:
Most important parts of the nuclear force



Central force

Tensor force

Spin-orbit force

Charge-independence

- After correcting for the electromagnetic interaction, the forces between nucleons (pp, nn, or np) in the same state are almost the same.
- "Almost the same":

  Charge-independence is slightly broken.
- Notation:

  Equality between the pp and nn forces:

  Charge symmetry.

  Equality between pp/nn force and np force:

  Charge independence.
- **Better notation: Isospin symmetry;**

  invariance under rotations in isospin space.

Charge-independence: Evidence

Since the scattering length is a magnifying glass on the interaction, charge-independence breaking (CIB) is seen most clearly in the different scattering lengths of pp, nn, and np low-energy scattering.

Charge-symmetry breaking (CSB) - after electromagnetic effects have been removed:

$$a^N{}_{pp} = -17.3 \pm 0.4 \text{ fm}$$

$$a^N{}_{nn} = -18.9 \pm 0.4 \text{ fm}$$

Charge-independence breaking (CIB):

$$a_{np} = -23.74 \pm 0.02 \text{ fm}$$

Phenomenological descriptions

- Symmetries and the general expression for the NN potential

- Historically important examples of phenomenological NN potentials

The symmetries

- Translation invariance
- Galilean invariance
- Rotation invariance
- Space reflection invariance
- Time reversal invariance
- Invariance under the interchange of particle 1 and 2
- Isospin symmetry
- Hermiticity

Most general two-body potential under those symmetries (Okubo and Marshak, *Ann. Phys.* **4**, 166 (1958))

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

$$+ V_{LS}(r)\boldsymbol{L}\cdot\boldsymbol{S} + V_{LS\tau}(r)(\boldsymbol{L}\cdot\boldsymbol{S})(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$$ **spin-orbit**

$$+ V_T(r)S_{12} + V_{T\tau}(r)S_{12}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$ **tensor**

$$+ V_Q(r)Q_{12} + V_{Q\tau}(r)Q_{12}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$ **quadratic spin-orbit**

$$+ V_{PP}(r)(\boldsymbol{\sigma}_1\cdot\boldsymbol{p})(\boldsymbol{\sigma}_2\cdot\boldsymbol{p}) + V_{PP\tau}(r)(\boldsymbol{\sigma}_1\cdot\boldsymbol{p})(\boldsymbol{\sigma}_2\cdot\boldsymbol{p})(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$$ **another tensor**

with $Q_{12} \equiv \frac{1}{2}\{(\boldsymbol{\sigma}_1\cdot\boldsymbol{L})(\boldsymbol{\sigma}_2\cdot\boldsymbol{L}) + (\boldsymbol{\sigma}_2\cdot\boldsymbol{L})(\boldsymbol{\sigma}_1\cdot\boldsymbol{L})\}$

Potentials which are based upon the operator structure shown on the previous slide (but may not include all operators shown or may include additional operators) are called “Phenomenological Potentials”. Some historically important examples are given below.

- Gammel-Thaler potential (Phys. Rev. **107**, 291, 1339 (1957)), hard-core.
- Hamada-Johnston potential (Nucl. Phys. **34**, 382 (1962)), hard core.
- Reid potential (Ann. Phys. *(N.Y.)* **50**, 411 (1968)), soft core.
- Argonne **V14** potential (Wiringa e*t al.,* Phys. Rev. C **29**, 1207 (1984)), uses 14 operators.
- Argonne **V18** potential (Wiringa e*t al.,* Phys. Rev. C **51**, 38 (1995)), uses 18 operators.