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

Nuclear Forces
- Lecture 2 -

Properties and Phenomenology

R. Machleidt
University of Idaho

<u>Lecture 2:</u> Properties and Phenomenology

- ⦿Properties of the nuclear force
- ⦿Phenomenological descriptions

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

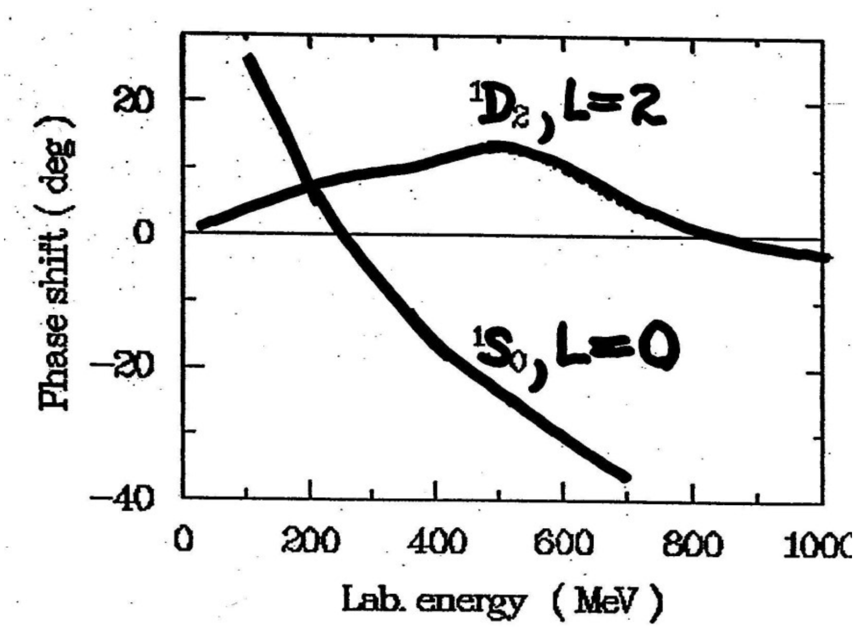
- "Saturation". Nuclei with A>4 show saturation: Volume and binding energies of nuclei are proportional to the mass number A.

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.



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

$L_{max} \lesssim 1 \Longrightarrow R \lesssim \frac{1}{p_{cm}} \approx$ **0.6 fm** $\approx$ hard-core radius

for $E_{lab} = 250$ MeV

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

Non-central forces

Tensor Force: First evidence from the deuteron

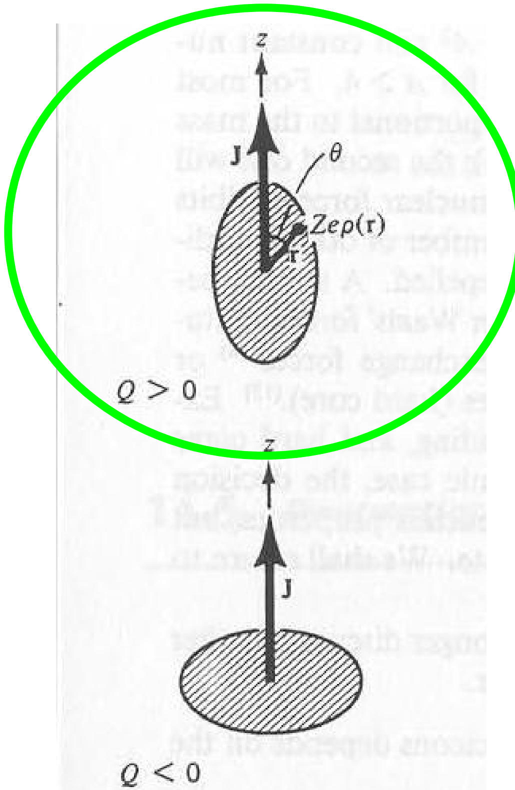


Fig. 14.10. Oblate and prolate nuclei, with spins pointing in the z direction. The nuclei are assumed to be axially symmetric; z is the symmetry axis.

Deuteron

Tensor force, cont'd

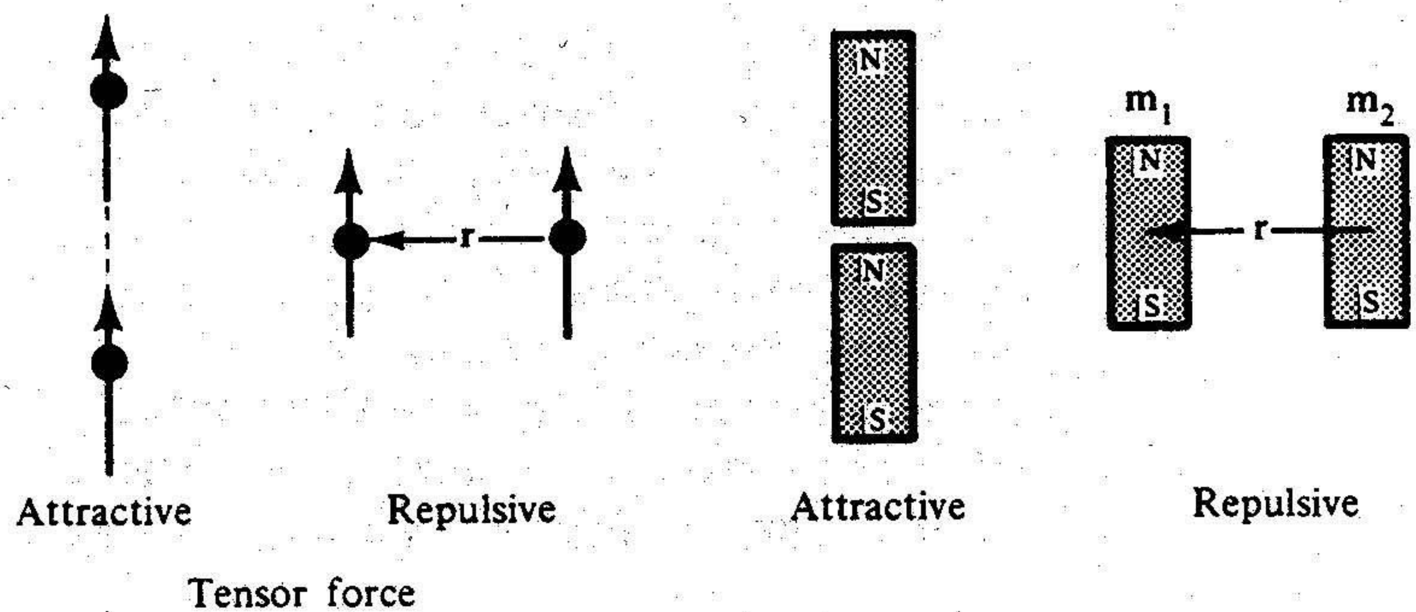


Fig. 14.11. The tensor force in the deuteron is attractive in the cigar-shaped configuration and repulsive in the disk-shaped one. Two bar magnets provide a classical example of a tensor force.

R.

Tensor force, cont'd

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

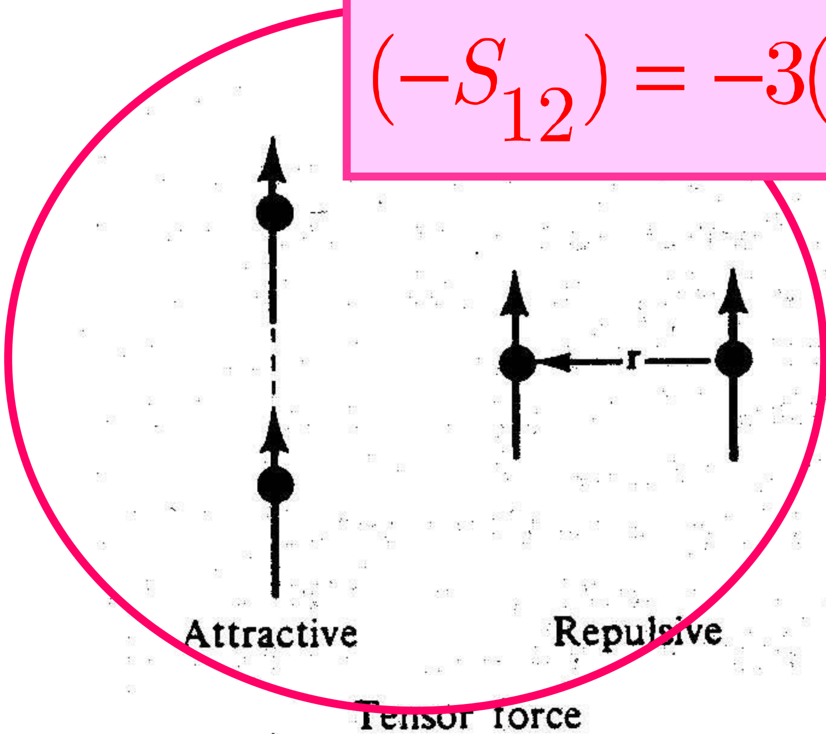


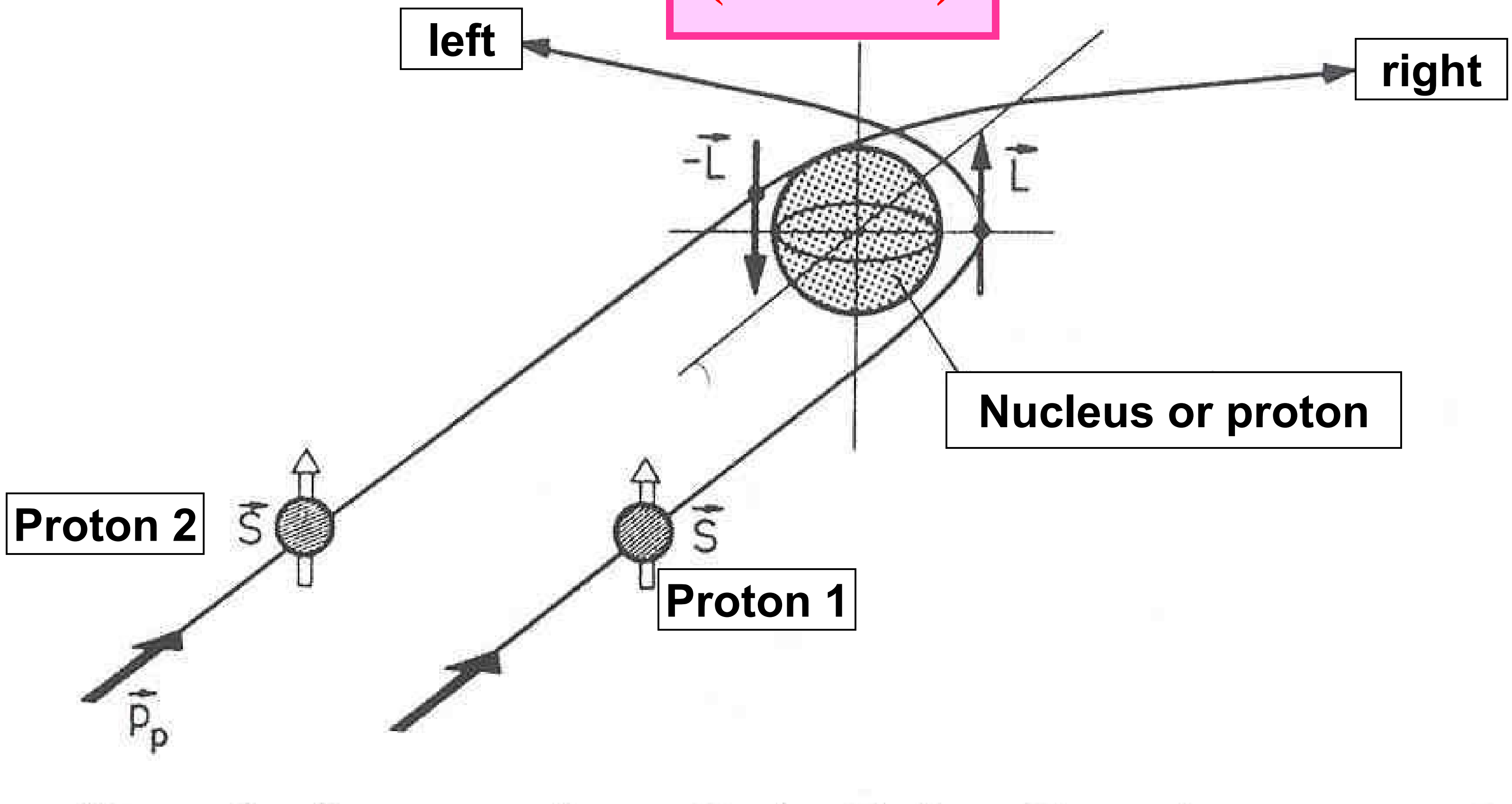
Fig. 14.11. The tensor force in the deuteron is attractive in the cigar-shaped configuration and repulsive in the disk-shaped one. Two bar magnets provide a classical example of a tensor force.

R.

Non-central forces

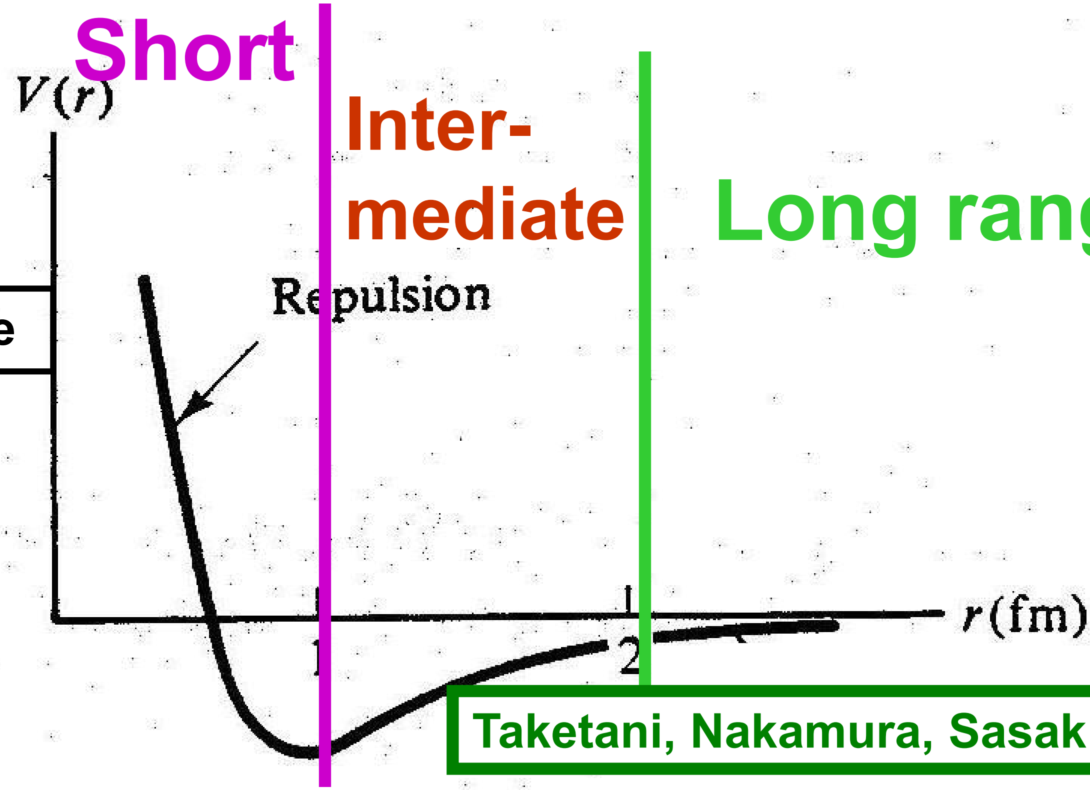
Spin-Orbit Force

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



Summary:
Most important parts of the nuclear force

Central force



Taketani, Nakamura, Sasaki (1951): 3 ranges

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 breaking: 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:

$$a^N_{pp} = -17.3 \pm 0.4 \text{ fm (model dependent)}$$

$$a^N_{nn} = -18.8 \pm 0.5 \text{ fm}$$

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.

End Lecture 2