Strong Interactions and Nuclear Forces

Advanced Subatomic Physics (FUF025)

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Outline

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Introduction

- One of the basic problems in nuclear physics is determining the nature of the interactions between the nucleons, which is crucial for understanding the properties of nuclei.
- According to our present understanding, the nuclear force is due to residual strong interactions between the color-charge neutral hadrons. A direct derivation of the nuclear force from QCD, the underlying theory of strong interactions, is not yet possible due to its non-perturbative nature at low energy.
- The standard way to describe the nuclear force is based on the meson-exchange picture, which goes back to the seminal work by Yukawa.
- His idea as well as experimental discovery of π- and heavier mesons $(\rho, \omega, \ldots)$ stimulated the development of boson-exchange models of the nuclear force, which still provide a basis for many modern, highly sophisticated phenomenological nucleon-nucleon (NN) potentials.

The standard model

Electroweak theory

Gauge invariance (see Chapter 12) of non-Abelian (non-commuting) vector fields, and Spontaneous Symmetry breaking leads to the unification of the electromagnetic and weak interactions into the electroweak theory (see Chapter 13).

Quantum chromodynamics

At high energies (momentum transfer) the theory of strong interactions can be described in a similar fashion. This theory is known as Quantum Chromodynamics (QCD).

QCD versus QED

	QED	QCD
Fundamental particles	Leptons	Quarks
Gauge quanta	Photon	Gluons
Interaction source	Electric charge	Color charge
Coupling constant	$\alpha = \frac{e^2}{\hbar c}$	α_S

- Asymptotic freedom (perturbative) at large momenta [small distances]
- Quark confinement ("infrared slavery") at small momenta [large distances]

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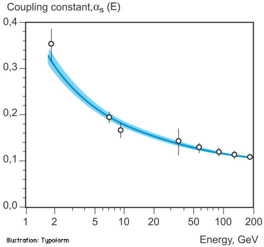


Illustration: Typoform

Outline

Effective degrees of freedom

The nucleon-nucleon (NN) force

QCD is commonly accepted as the theory of the strong interaction. Therefore, the NN interaction should be completely determined by the underlying quark-quark dynamics.

Non-perturbative

Since the quarks are bound inside the nucleons, the NN force is an effective interaction. However, due to the non-perturbative character of low-energy QCD, one is still far from a quantitative understanding of this effective NN interaction.

General properties

Attraction

Nuclei are self-bound. The force is predominantly attractive.

Range and Strength

E.g., comparison of the binding energies of ^{2}H, ^{3}H, and ^{4}He indicates that the range is of the order of 1 fm.

Saturation

For nuclei with $A > 4$ the binding energy saturates at around 8 MeV$/A$. The average distance between nucleons is ~ 2 fm which should roughly correspond to the range of the attractive part. Both the binding energy and the volume $\propto A$. Saturation can be explained by repulsive forces at short distances (hard core) and/or by exchange forces.

Properties derived from studies of the deuteron

Spin dependence: V_σ

- The deuteron spin is $\mathbf{J} = \mathbf{s}_p + \mathbf{s}_n + \mathbf{L}$. The value of the ground-state magnetic moment implies that $L = 0$.
- The ground state is 1^+, but there is no 0^+ bound state. So the ${}^3S_1$ partial wave must be more attractive than the ${}^1S_0$.
- This implies that the NN interaction includes a spin-dependent part

$$V_\sigma \sigma_\mathbf{1} \cdot \sigma_\mathbf{2}$$

Properties derived from studies of the deuteron

Tensor interaction (noncentral forces): S_{12}

- The deuteron magnetic moment does not correspond exactly to the expected *s*-state value.
- In addition, the deuteron has a small quadrupole deformation. Since $Q \propto Y_{20}$, a non-zero value of $< Q >$ implies $L > 1/2$ (*s*-states are sperically symmetric).
- So, in the deuteron case, the dominantly $L = 0$ ground state must contain an admixture of $L = 2$.
- This implies broken rotational symmetry and can be achieved through adding a tensor component to the NN interaction

$$V_T S_{12}, \text{ where } S_{12} = 3(\boldsymbol{\sigma_1} \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma_2} \cdot \hat{\mathbf{r}}) - \boldsymbol{\sigma_1} \cdot \boldsymbol{\sigma_2}$$

Properties derived from scattering experiments

np scattering

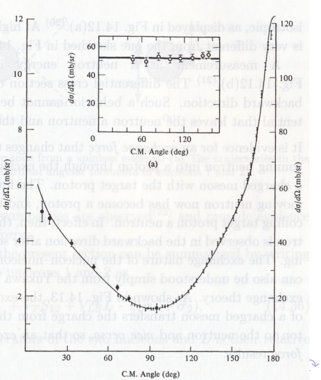
momentum transfer: $\mathbf{q} = \mathbf{p}_i - \mathbf{p}_f$
elastic scattering $(p_i = p_f = p)$: $q = 2p \sin \frac{\theta}{2}$

Angular distribution

$$\frac{d\sigma}{d\theta} = |f(\mathbf{q})|^2, \text{where in Born approx.}$$

$$f(\mathbf{q}) = -\frac{m}{2\pi\hbar^2} \int V(\mathbf{r}) \exp\left(\frac{i\mathbf{q}\cdot\mathbf{r}}{\hbar}\right) d\mathbf{r}.$$

Backscattering implies exchange force



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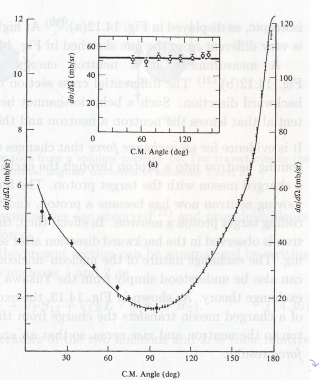

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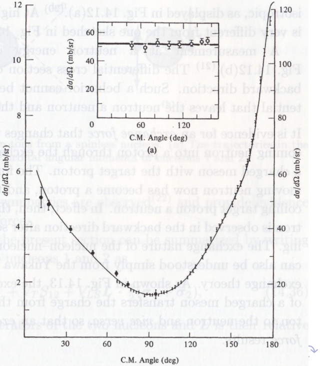
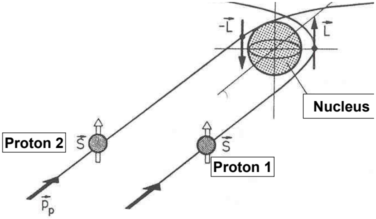


Spin-orbit force

Consider scattering of polarized nucleons off a spin-zero target.



The observation of a "left-right" asymmetry can be explained by adding a spin-orbit interaction

$$V_{LS}\mathbf{L}\cdot\mathbf{S},$$

since it will have opposite signs for nucleons 1 and 2.

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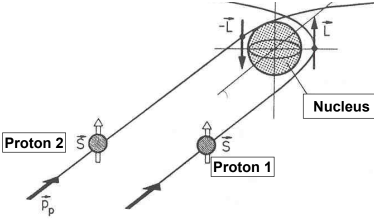

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Charge independence. . .

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

- Equality between pp and nn forces is called Charge symmetry
- Equality between (pp,nn) and np forces is called Charge independence

Isospin symmetry

Introduce isospin: $T = 1/2$ for nucleons; $T_z = +1/2$ (proton), $-1/2$ (neutron).
Isospin symmetry is an invariance under rotations in isospin, i.e. isospin dependence is either 1 or $\tau_1 \cdot \tau_2$

. . . to charge dependence

Studies of charge dependence in scattering experiments. Reults for the $^1S_0$ scattering length (See Sakurai Ch. 7).

Charge-symmetry breaking (CSB)

- After correcting for the electromagnetic interaction
- $a_{pp} = -17.3(4)$ fm
- $a_{nn} = -18.8(5)$ fm

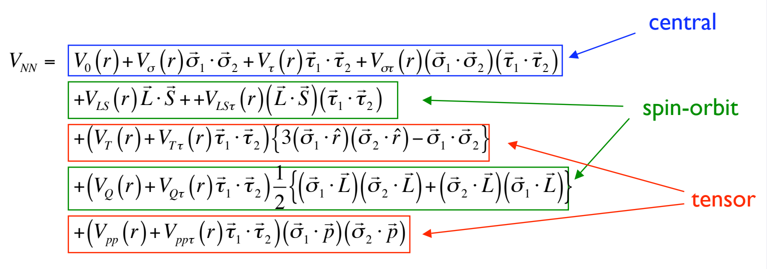
Charge-independence breaking (CIB)

- $a_{pn} = -23.74(2)$ fm

Symmetries of the nucleon-nucleon force

Okubo and Marshak, Ann. Phys. **4(1958)166**

The most general (non-relativistic) form of the nucleon-nucleon potential constrained by symmetry arguments



$$\begin{aligned} V_{NN} = {} & \boxed{V_0(r)+V_\sigma(r)\vec{\sigma}_1\cdot\vec{\sigma}_2+V_\tau(r)\vec{\tau}_1\cdot\vec{\tau}_2+V_{\sigma\tau}(r)(\vec{\sigma}_1\cdot\vec{\sigma}_2)(\vec{\tau}_1\cdot\vec{\tau}_2)} \\ & \boxed{+V_{LS}(r)\vec{L}\cdot\vec{S}++V_{LS\tau}(r)(\vec{L}\cdot\vec{S})(\vec{\tau}_1\cdot\vec{\tau}_2)} \\ & \boxed{+\left(V_T(r)+V_{T\tau}(r)\vec{\tau}_1\cdot\vec{\tau}_2\right)\left\{3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r})-\vec{\sigma}_1\cdot\vec{\sigma}_2\right\}} \\ & \boxed{+\left(V_Q(r)+V_{Q\tau}(r)\vec{\tau}_1\cdot\vec{\tau}_2\right)\frac{1}{2}\left\{(\vec{\sigma}_1\cdot\vec{L})(\vec{\sigma}_2\cdot\vec{L})+(\vec{\sigma}_2\cdot\vec{L})(\vec{\sigma}_1\cdot\vec{L})\right\}} \\ & \boxed{+\left(V_{pp}(r)+V_{pp\tau}(r)\vec{\tau}_1\cdot\vec{\tau}_2\right)(\vec{\sigma}_1\cdot\vec{p})(\vec{\sigma}_2\cdot\vec{p})} \end{aligned}$$

Breaking of charge independence

Charge (isospin) symmetry can be broken by introducing isospin direction-dependent operators of the type

$$T_{12} = 3(\tau_{\mathbf{1}} \cdot \hat{\mathbf{r}})(\tau_{\mathbf{2}} \cdot \hat{\mathbf{r}}) - \tau_{\mathbf{1}} \cdot \tau_{\mathbf{2}}$$

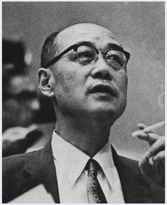
Note the analogy with the tensor operator S_{12}.

Outline

Almost a century of nuclear forces - I. The first pion period

1930s

- Chadwick (1932): Neutron
- Heisenberg (1932): First phenomenology (isospin)
- Yukawa (1934): Meson hypothesis



1940s

- Discovery of the pion in cosmic rays (1947);
- . . . and in the Berkeley Cyclotron Lab (1948).
- Nobel prize awarded to Yukawa (1949)

The Yukawa theory of nuclear forces

Electromagnetic interaction

The scalar potential A_0 produced by a *time-indep.* charge distribution $q\rho(\mathbf{x})$ is given by the (Poisson) wave equation

$$\nabla^2 A_0(\mathbf{x}) = -4\pi q\rho(\mathbf{x}),$$

with solution

$$A_0(\mathbf{x}) = \int d\mathbf{x}' \frac{q\rho(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}.$$

For a point charge $q\delta(\mathbf{x}')$ we get the familiar $A_0(r) = \frac{q}{r}$.

Yukawa (1934) - nuclear force

Klein-Gordon eq. with source

$$\left(\nabla^2 - k^2\right)\phi(\mathbf{x}) = 4\pi \frac{g\rho(\mathbf{x})}{\sqrt{\hbar c}},$$

where ϕ is a field and $g\rho(\mathbf{x})$ the (positive) strong source. For a point source the solution becomes the Yukawa potential

$$\phi(r) = -\frac{g}{\sqrt{\hbar c}}\frac{\exp(-kr)}{r}.$$

$(k \sim 1\ \mathrm{fm}^{-1} \Leftrightarrow m \sim 200\ \mathrm{MeV})$

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Almost a century of nuclear forces - I. The first pion period

1950s - 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).

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

Almost a century of nuclear forces - II. The meson period

1960s - One-boson exchange model

- Many pions = Multi-pion resonances:
  $\sigma(600)$, $\rho(770)$, $\omega(772)$.

1970s - Refined meson theories

- Sophisticated models for two-pion exchange:
  Paris potential, Lacombe et al., Phys. Rev. C **21**(1980)861
  Bonn potential, Machleidt et al., Phys. Rep. **149**(1987)1.

The cast

Baryons	Mass [MeV]	Mesons	Mass [MeV]
p, n	938.926	π	138.03
Λ	1116.0	η	548.8
Σ	1197.3	σ	$\sim$600
Δ	1232.0	ρ	770
		ω	782.6
		δ	983.0
		K	495.8
		$K^\star$	895.0

Particles with $s = c = b = 0$

Particles with strangeness $s \neq 0$

Almost a century of nuclear forces - III. The end of the boson-exchange models

1980s - the discovery of QCD

Historically, the experimental discovery of heavy mesons in the early 1960s gave momentum to the one-boson-exchange (OBE) model. Prior to that it was pion physics which dominated the picture. The weak point of this model, however, is the scalar-isoscalar "sigma" or "epsilon" boson, for which the empirical evidence remains controversial. Since this boson is associated with the correlated (or resonant) exchange of two pions, a vast theoretical effort that occupied more than a decade (1970-1980) was launched to derive the 2π-exchange contribution of the nuclear force, which creates the intermediate range attraction.

The nuclear force problem appeared to be solved; however, with the discovery of quantum chromo-dynamics (QCD), all "meson theories" had to be relegated to models and the attempts to derive the nuclear force started all over again.

Almost a century of nuclear forces - IV. The rise and fall of quark models

The problem with a derivation from QCD is that this theory is non-perturbative in the low-energy regime characteristic of nuclear physics, which make direct solutions impossible.

Therefore, during the first round of new attempts, QCD-inspired quark models became popular. These models were able to reproduce qualitatively some of the gross features of the nuclear force. But were useless for nuclear structure.

Also, on a critical note, it has been pointed out that these quark-based approaches were nothing but another set of models and, thus, did not represent any fundamental progress. Equally well, one may then stay with the simpler and much more quantitative meson models.

Almost a century of nuclear forces - V. The rebirth of the boson exchange models

1990s - High-precision NN potentials

- Nijmegen phase shift analysis – NN scattering data 0-350 MeV
- 1993-2001: Nijmegen I, II, 93, Reid93, Argonne V18 (Wiringa et al, 1995), CD-Bonn (Machleidt et al. 1996 and 2001.)
- Advances in effective field theory: Weinberg (1990); Ordonez, Ray, van Kolck and many more.

Almost a century of nuclear forces - VI. From Yukawa to Lattice QCD and χPT

2000s - the missing link to QCD

- Another pion theory; but now right: constrained by chiral symmetry.
  Three-body and higher-body forces appear naturally at a given order of the chiral expansion.
- Good review: Epelbaum, Prog. Part. Nucl. Phys. **57**(2006)654

2006 - lattice QCD for NN interaction

- Nucleon-nucleon interaction from Lattice QCD, final confirmation of meson hypothesis of Yukawa?

Outline

Quantum Chromodynamics

Two worlds:

- At high energies: weak, asymptotic freedom; perturbative QCD.
- At low energies (= nuclear physics): strong QCD, non-perturbative; a totally different world.

The fact that the scenario at low energy is so different from high-energy suggests that the effective description of the low-energy scenario should also be very different from high.

Chiral perturbation theory

Brief description

A major breakthrough occurred when the concept of an effective field theory (EFT) was introduced and applied to low-energy QCD. As outlined by Weinberg in 1979 one has to write down the most general Lagrangian consistent with the assumed symmetry principles, particularly the (broken) chiral symmetry of QCD. At low energy, the effective degrees of freedom are pions and nucleons rather than quarks and gluons; heavy mesons and nucleon resonances are "integrated out". So, in a certain sense we are back to the 1950s, except that we are smarter by 40 years of experience: broken chiral symmetry is a crucial constraint that generates and controls the dynamics and establishes a clear connection with the underlying theory, QCD.

Lattice QCD

Brief description

Analytic or perturbative solutions in QCD are hard or impossible due to the highly nonlinear nature of the strong force. The formulation of QCD on a discrete rather than continuous space-time naturally introduces a momentum cut off at the order $1/a$, which regularizes the theory. As a result lattice QCD is mathematically well-defined. Most importantly, lattice QCD provides the framework for investigation of non-perturbative phenomena such as confinement and quark-gluon plasma formation, which are intractable by means of analytic field theories.