Introduction to Radiochemistry

Lecture 6

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The Nuclear Force

Introduction

- Nuclear Models: Collective and Microscopic

- Examples of the two classes:
  - Liquid Drop Model
  - Nuclear Shell Model

- Many models existing and applicable in different regions of the nuclear chart.

- A fundamental element is still missing:
  - **The Nuclear Force**

- Is it possible to derive it? Which are its properties?

Basic Observations

- Protons and neutrons are bound states of quarks and gluons. When we put more of them together they interact due to the strong force.

- If we are interested in the low energy region, where nucleons do not get internally excited, we can treat the nucleons as inert (no internal structure).

- If the nucleons are non relativistic then we can introduce the concept of a potential V,
  Hamiltonian H=T+V with T kinetic energy

- If we knew V, we could then solve the Schroedinger equation to calculate properties of nuclei (deuteron, light nuclei, heavy nuclei) from first principle

- We do not know V, we can only construct (many) models for nuclear forces

- Since protons and neutrons interact strongly, V should come from QCD, but this is very hard. For now we take a semi-phenomenological approach and then come back to QCD later

Empirical Observations

- What do we know about the nuclear forces from experimental observations?
  - ★ Short range (from the saturation property of the BE)
  - ★ Attractive at long range (must be for having bound states: nuclei)
  - ★ Repulsive at short range (evidence from NN scattering)
  - ★ Spin dependent (evidence from NN scattering)
  - ★ Charge independent (Charge is only involved in EM interactions)
  - ★ Spin-orbit force (remember the Shell Model)
  - ★ Tensor force (eg from Deuteron ground state)
  - ★ Conserve parity

We can learn this looking at properties and reactions of nuclei (NN phase-shifts, spectra, etc..)

The NN potential has a dominant strong and electromagnetic and a weak component. The EM part is well known and the weak component is extremely small. When we talk about NN potentials, we refer to the strong interaction part.

A Form for the Nuclear Force

In a simplified view (neglecting isospin and other quantum mechanics details), we can write phenomenologically the nuclear force as:

In spin-coordinate space

$$V_{\rm NN} = V_0(r) +$$ purely central

$$+ V_s(r)\ \vec{\sigma}_1 \cdot \vec{\sigma}_2$$ spin-dependent

$$+ V_{\ell s}(r)\ \vec{\ell} \cdot \vec{S}$$ spin-orbit

$$+ V_T(r)\ S_{12}$$ tensor

Actually it is found out that to better describe NN scattering phase shifts, one can add:

$$+V_{\ell^2}\ \vec{\ell}^2$$

$$+V_{\ell^2 s}\ \vec{\ell}^2\ \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

$$+V_{\ell^2 s^2}\ (\vec{\ell} \cdot \vec{S})^2$$

Including "charge symmetry breaking" terms, these are the ingredients of the phenomenological **AV18 potential** (1995).

A Nuclear Force from First Principles?

- The AV18 is a successful description of the nuclear force at low energies.

- Still, it is not easy to do microscopic calculations with such a complex potential

- It is constructed in a phenomenological way, so:

    - Is it possible to construct a potential from first principles or at least from some more fundamental principles?

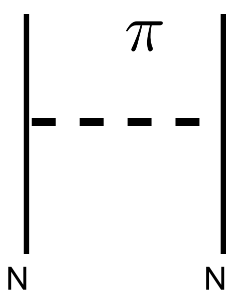
- The first step: **Yukawa's one-pion exchange potential.**

A Nuclear Force from First Principles?

Yukawa postulated the existence of a massive particle m~130 MeV to be responsible of the interaction between nucleons. This idea came from the analogy with the one photon exchange in electromagnetism.
Originally, Yukawa assumed that the particle exchanged was a scalar: $J^\pi = 0^+$

Hideki Yukawa
Nobel prize in 1949

Today, we know that the pion is a pseudo scalar particle with: $J^\pi = 0^-$
It is possible to describe the potential between two nucleons with the exchange of a pion:

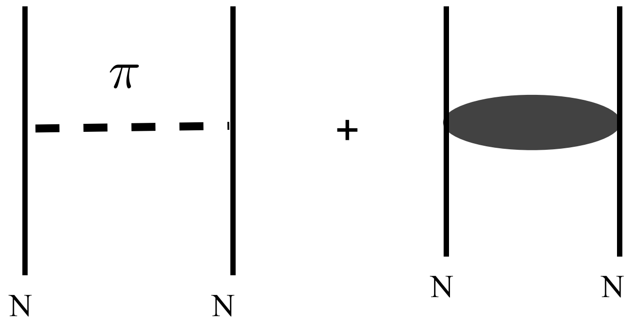


The derived potential describes part of the central force and explains the presence of the tensor force.

One-Boson Exchange Potential

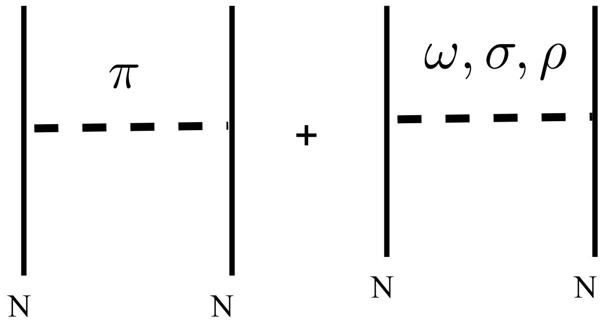
The OPEP is at the basis of most NN potentials!

For example the AV18 potential is **(Phys.Rev.C 51 (1995) 38)**



phenomenological ansatz for the short range part

Alternatively you can extend the OPEP to the one boson exchange potential (OBEP)



Exchange of heavier mesons for the short range part. (So called CD-Bonn Potential).

These are named realistic NN potentials: fit NN scattering data with $\chi^2 \approx 1$

Even though this is not pure phenomenology and there is a lot of theory in these potentials, the connection to the underlying QCD theory (acting inside the nucleons) is weak.

Modern Frontier: **EFFECTIVE FIELD THEORY** approach.

Summary

- The nuclear force is a "shadow" force originating from QCD
  In some sense, it is analogous to the van der Waals force which originates from electromagnetism.

- Possible ways to construct the NN force:

    - Phenomenology (AV18, CD-Bonn, ...)
    - Effective Field Theory (starting from QCD principles)
    - Future: brute-force MC simulation?

- Something is still missing! There is evidence that the NN force is not enough: need for 3-body forces (NNN)! Such forces arise naturally in the effective theories context.