Complexity out of simplicity in atomic nuclei





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Atomic Nucleus - what is it?

We need models to imagine atoms & nuclei:

Atomic nuclei are bound systems of protons and neutrons (nucleons) - but are there protons & neutrons in nuclei? EMC effect, Δ , mesons, α -clustering ..

Structure of An Atom



Nuclear Chart

Physics of atomic nucleus: about 2500 known isotopes, 263 stable isotopes estimate 4000 unobserved yet



Nuclear Chart

Online database www.nndc.bnl.gov/chart/



Database Manager and Web Programming: Alejandro Sonzogni, NNDC, Brookhaven National Laboratory, sonzogni@bnl.gov Data Source: National Nuclear Data Center, Brookhaven National Laboratory, based on ENSDF and the Nuclear Wallet Cards

Energy spectra

Online database www.nndc.bnl.gov/chart/

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"Simplicity"

Atomic **nucleus** formed by **Z**-protons and **N**-neutrons bound together. Nucleons interact via **strong interaction**.

$${\cal L}_{
m QCD} = ar{\psi}_i \, (i (\gamma^\mu D_\mu)_{ij} - m \, \delta_{ij}) \, \psi_j - rac{1}{4} G^a_{\mu
u} G^{\mu
u}_a$$



My expectation of understanding of nuclear physics when I was student...

In the popular books about science and physics the things often described as "everything solved with the exception of few remaining problems regarding fundamental particles and initial moments of Big Bang.."



angular momentum

Deformations: expansion into multipoles

Vibrational states:

Description analogous to the excitations of Harmonic Oscillator (in collective degrees of freedom)



"particle-hole" excitations of "mean-field"



Excitations due to collectivity:

 $\gamma + (A, Z) \rightarrow (A, Z)^*$

- excitations of 1 particle-hole type
- collective excitations (coherent superpositions of big amount of "particle-hole" excitations)



Many "particle-hole" excitations simultaneously More configurations → richer excitation spectra





Giant dipole resonance (E1) collective state – vibration of protons in opposite phase to neutrons

Example of excitation spectrum - ²⁰⁸Pb





Atomic nucleus - how to describe it

Implicit paradigm of theoretical nuclear physics:

Nucleus is **bound state of nucleons**. We describe nucleus by methods of **quantum mechanics** (QM) from **interactions** among **nucleons**.

This paradigm itself is not most **fundamental approach** – we should describe nuclei from **QCD**. Except of first pioneering attempts [**Phys. Rev. Lett.** 113, 252001 (2014)] **impossible**!!

Instead we employ the strategy: build **potential** among **nucleons** (NN, NNN, etc.) → solve QMB problem with given nucleon potential (i.e. Hamiltonian)

Building potentials itself is complicated task – **nucleons** as particles with the **inner structure**. Even the potentials cannot be build directly from **QCD**.

Models to describe nucleon potentials. For potentials suitable for nuclear calculations we need to solve many-body nuclear problem. Solution of the nuclear many-body

problem strongly depend on the

employed nucleon potential.

Atomic nucleus - how to describe it

Different scales - they are not separated of each other.



What we see depends on resolution:

< 0.0001 fm: quarks</p>

 0.1-1 fm : baryons, mesons

I fm: nucleons

10 fm : collective modes

Atomic nucleus – how to describe it Possible approach to derive NN interactions

4N Force

$$\mathcal{L}_{\pi N} = \hat{\mathcal{L}}_{\pi N}^{(1)} + \hat{\mathcal{L}}_{\pi N}^{(2)} + \hat{\mathcal{L}}_{\pi N}^{(3)} + \dots$$

$$\hat{\mathcal{L}}_{\pi N}^{(1)} = \bar{N} \left[i \partial_0 - \frac{1}{4F_{\pi}^2} \vec{\tau} \cdot (\vec{\pi} \times \partial_0 \vec{\pi}) - \frac{g_A}{2F_{\pi}} \vec{\tau} \cdot (\vec{\sigma} \cdot \vec{\nabla}) \vec{\pi} \right] N + \dots$$

3N Force 2N Force \mathbf{LO} X ----- $(Q/\Lambda_{\chi})^0$ -Xok NLO $(Q/\Lambda_{\chi})^2$ NNLO $(Q/\Lambda_{\chi})^3$ N³LO $(Q/\Lambda_{\chi})^4$



Effective field theory – instead of QCD field theory with elem. degrees of freedom (quarks, gluons) we build field theory with nucleons and pions. Must obey the same symmetries as QCD -> Chiral Perturbation Theory (ChPT)

> Only mesons here are pions. But pion exchanges 2π , 3π , ... till any order. Multi-pion exchanges replace presence of other types of mesons.

Diagrams of NN scatering can be divided to orders - perturbative theory (?)

Atomic nucleus - how to describe it

Existence of more-body interactions between nucleons As consequence of inner structure of nucleons







In nucleus - there is lot of degrees of freedom quark, gluons, mesons, baryons

Summary

- Atomic nuclei as bound microscopic many-body systems with very rich structure
- Huge complexity of different states and also different isotopes must arise from simplicity relatively simple laws and the fact that we bind A nucleons
- Single-particle as well as collective modes in nuclei
- Clustering, deformations, vibrations, rotations,
- There is no any "Standard Model" for atomic nuclei theoretical description is very demanding
- We need new bright ideas only young clever scientists can bring new solutions!!!

Thank you for attention!