What is Nuclear Physics?

“Nuclear Physics is the field of physics that studies the building blocks and interactions in atomic nuclei”
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“Nuclear Physics is the field of physics that studies the building blocks and interactions in atomic nuclei”

- It is a science build on a strong connection between theory and experiment

- It has also many interesting applications that influence and improve our daily life:
  - nuclear medicine (radiopharmaceuticals)
  - hadron therapy (cure of cancer)
  - engineering materials (ion implantation)
  - archaeology (carbon dating)
  - ...
What is Nuclear Theory?

Google

nuclear theory

Advising Programs - Business Solutions - About Google

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What is Nuclear Theory?

Google

nuclear theory

link to publication archive

lanl.arXiv.org
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It is the theory that tries to understand and predict nuclear properties, by studying the way protons and neutrons interact to form nuclei.
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What are the interesting questions we try to answer?
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★ What is the interaction that binds nucleons together?
What is its relation to Quantum Chromo Dynamics?
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What is Nuclear Theory?

It is the theory that tries to understand and predict nuclear properties, by studying the way protons and neutrons interact to form nuclei.

What are the interesting questions we try to answer?

- How did the nucleosynthesis of elements occur?
  Big Bang Nucleosynthesis
  r-process...

- How happens that protons and neutrons are bound into stable and rare isotopes?
  What are the limits of their existence?
What is Nuclear Theory?

It is the theory that tries to understand and predict nuclear properties, by studying the way protons and neutrons interact to form nuclei.

What are the interesting questions we try to answer?

★ What is the nature of neutron stars?

★ What are the nuclear reactions that drive supernovae explosions?
Frontiers in Nuclear Theory

- **Interaction challenges**
  How can we connect nuclear forces to QCD?

- **Few and many-body challenges**
  How can we accurately solve the Schroedinger equation?

- **Astrophysical challenges**
  Can nuclear physics provide an answer to astrophysical questions?
Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales

\[ \frac{1}{\lambda} = Q \ll A_B = \frac{1}{R} \]

\[ \lambda \gg R \]

\[ \vec{R} \]
Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales

\[ \frac{1}{\lambda} = Q \ll A_b = \frac{1}{R} \]
Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales

\[ \frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R} \]

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Interaction challenges

The Chiral Effective Field Theory Approach

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\[ \frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R} \]

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Limited resolution at low energy
expand in powers
\[ \frac{Q}{\Lambda_b} \]
Interaction challenges

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Limited resolution at low energy
expand in powers

\[ \frac{Q}{\Lambda_b} \]

\[ \begin{array}{ccc}
\text{LO} & \mathcal{O}\left(\frac{Q^0}{\Lambda_b}\right) & - & - \\
\text{NLO} & \mathcal{O}\left(\frac{Q^2}{\Lambda_b^2}\right) & - & - \\
\end{array} \]
Interaction challenges

The Chiral Effective Field Theory Approach

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\[ \frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R} \]

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Limited resolution at low energy

Expand in powers

\[ \frac{Q}{\Lambda_b} \]

<table>
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<tr>
<td>LO</td>
<td>( \mathcal{O}\left(\frac{Q^0}{\Lambda_b^0}\right) )</td>
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Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales

\[ \frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R} \]

\[ \lambda >> R \]

Limited resolution at low energy

expand in powers

\[ \frac{Q}{\Lambda_b} \]

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Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales

$$\frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R}$$

Limited resolution at low energy
expand in powers

$$\frac{Q}{\Lambda_b}$$

Systematic and can provide error estimates

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Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales
\[ \frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R} \]

\[ \lambda >> R \]

Limited resolution at low energy
expand in powers
\[ \frac{Q}{\Lambda_b} \]

Systematic and can provide error estimates

Details of short distance physics not resolved, but captured in short range couplings
fit to experiment

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Interaction challenges

The Chiral Effective Field Theory Approach
- NN Sector -

LO $O \left( \frac{q^0}{M} \right)$

NLO $O \left( \frac{q^2}{M^2} \right)$

$N^2$LO $O \left( \frac{q^3}{M^3} \right)$

$N^3$LO $O \left( \frac{q^4}{M^4} \right)$

coupling constants fitted to NN scattering phase-shifts

Phase Shift [deg]

Lab. Energy [MeV]

$^1S_0$
Interaction challenges

The Chiral Effective Field Theory Approach

- NN Sector -

LO $O\left(\frac{\Lambda^0}{\Lambda}\right)$

NLO $O\left(\frac{\Lambda^2}{\Lambda^2}\right)$

N$^2$LO $O\left(\frac{\Lambda^3}{\Lambda^2}\right)$

N$^3$LO $O\left(\frac{\Lambda^4}{\Lambda^3}\right)$

coupling constants fitted to NN scattering phase-shifts

We have a resolution dependence!
Coupling constants run with the resolution scale $\Lambda$
Interaction challenges

The Chiral Effective Field Theory Approach
- NN Sector -

We have a resolution dependence!
Coupling constants run with the resolution scale $\Lambda$

The dependence on the cutoff leads to different potentials, but observables should be cutoff independent.
Interaction challenges

The Chiral Effective Field Theory Approach

- 3N Sector -

N^2LO
Interaction challenges

The Chiral Effective Field Theory Approach

- 3N Sector -

What is its origin? Nucleons are effective degrees of freedom
Interaction challenges

The Chiral Effective Field Theory Approach
- 3N Sector -

What is its origin? Nucleons are effective degrees of freedom

“The three-body force is a force that does not exist in a two-nucleon system, but appears in a system with three objects or more” $A \geq 3$
Interaction challenges

The Chiral Effective Field Theory Approach

- 3N Sector -

What is its origin? Nucleons are effective degrees of freedom

“The three-body force is a force that does not exist in a two-nucleon system, but appears in a system with three objects or more” $A \geq 3$

As an analogy, if we identify objects with human beings and forces with emotions, then jealousy is a good example of a three-body force: it is not felt as long as two-person are acting, but it shows up as soon as a third person enters the scene.

From N. Kalantar, FM50
Interaction challenges

The Chiral Effective Field Theory Approach
- 3N Sector -

N\textsuperscript{2}LO

- What is its origin? Nucleons are effective degrees of freedom

- How to realize if they are important? By comparing theoretical calculations with two-nucleon forces only with experimental data

A \geq 3
Interaction challenges

The Chiral Effective Field Theory Approach
- 3N Sector -

What is its origin? Nucleons are effective degrees of freedom

How to realize if they are important? By comparing theoretical calculations with two-nucleon forces only with experimental data

How to constrain it? By fitting the coupling constants to data for an observable which is sensitive to 3NF

\[ A \geq 3 \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c} 
E(\text{H}) [\text{MeV}] & 7.6 & 7.8 & 8.0 & 8.2 & 8.4 & 8.6 & 8.8 \\
E(\text{He}) [\text{MeV}] & 24 & 25 & 26 & 27 & 28 & 29 & 30 & 31 \\
\hline
\end{array} \]

NN only

Exp.
Interaction challenges

The Chiral Effective Field Theory Approach
- 3N Sector -

- What is its origin? Nucleons are effective degrees of freedom

- How to realize if they are important? By comparing theoretical calculations with two-nucleon forces only with experimental data

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Interaction challenges

The Chiral Effective Field Theory Approach
- 3N Sector -

N\textsuperscript{2}LO \quad A \geq 3

• What is its origin? Nucleons are effective degrees of freedom

• How to realize if they are important? By comparing theoretical calculations with two-nucleon forces only with experimental data

• How to constrain it?
  By fitting the coupling constants to data for an observable which is sensitive to 3NF

• Predict new observables!

Sonia Bacca
APSNW Meeting, May 15 2009
Few- and many-body challenges

In the sector of few-body nuclei (A<5) we have reached an incredible level of accuracy.

Challenge: develop new many-body methods that can extend the frontiers to heavier nuclei

Coupled Cluster Theory

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<thead>
<tr>
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<tr>
<td>⁴He</td>
<td>-5.99</td>
<td>-22.75</td>
<td>1.08</td>
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<tr>
<td>¹⁶O</td>
<td>-6.72</td>
<td>-30.69</td>
<td>1.25</td>
</tr>
<tr>
<td>⁴⁰Ca</td>
<td>-7.72</td>
<td>-36.40</td>
<td>0.84</td>
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<td>-37.97</td>
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Hagen et al., PRL 101 (2008)
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<td>-6.72</td>
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Hagen et al., PRL 101 (2008)

**Future:** advance ab-initio methods to heavier and neutron rich nuclei
The physics of Halo Systems

Moon Halo
The physics of Halo Systems

Nuclear Halo
Halo nuclei

- One neutron halo
- Two neutron halo
- Four neutron halo
- One proton halo
- Two proton halo

Element
- $^{11}\text{Li}$
- $^{208}\text{Pb}$

Distance: 12 fm
The helium isotope chain

Shows many interesting features:

\(^3\text{He}\) \(^4\text{He}\)

bound bound
The helium isotope chain

Shows many interesting features:

$^3\text{He}$  $^4\text{He}$  $^5\text{He}$

bound  bound  unbound
The helium isotope chain

Shows many interesting features:

\[ ^3\text{He} \quad ^4\text{He} \quad ^5\text{He} \quad ^6\text{He} \]

bound  bound  unbound  bound

halo
The helium isotope chain

Shows many interesting features:

$^3\text{He}$ bound

$^4\text{He}$ bound

$^5\text{He}$ unbound

$^6\text{He}$ bound
  halo

Borromean system
The helium isotope chain

Shows many interesting features:

$^3\text{He}$ bound

$^4\text{He}$ bound

$^5\text{He}$ unbound

$^6\text{He}$ bound halo

$^7\text{He}$ unbound

Borromean system
The helium isotope chain

Shows many interesting features:

$^3\text{He}$ $^4\text{He}$ $^5\text{He}$ $^6\text{He}$ $^7\text{He}$ $^8\text{He}$

bound bound unbound bound halo unbound bound halo

Borromean system
The helium isotope chain

Shows many interesting features:

\[ ^3\text{He} \quad ^4\text{He} \quad ^5\text{He} \quad ^6\text{He} \quad ^7\text{He} \quad ^8\text{He} \]

bound \quad bound \quad unbound \quad bound \quad unbound \quad bound

halo \quad halo

Borromean system

Most exotic nucleus “on earth”

\[ \frac{N}{Z} = 3 \]
The helium isotope chain

Shows many interesting features:

\begin{align*}
\text{\textsuperscript{3}He} & \quad \text{bound} \\
\text{\textsuperscript{4}He} & \quad \text{bound} \\
\text{\textsuperscript{5}He} & \quad \text{unbound} \\
\text{\textsuperscript{6}He} & \quad \text{bound} \quad \text{halo} \\
\text{\textsuperscript{7}He} & \quad \text{unbound} \\
\text{\textsuperscript{8}He} & \quad \text{bound} \quad \text{halo} \\
\end{align*}

Borromean system

Most exotic nucleus “on earth”

\[ \frac{N}{Z} = 3 \]

\text{lives 806 ms}
\text{lives 108 ms}
The helium isotope chain

Shows many interesting features:

\[ \begin{align*}
  ^3\text{He} & \quad \text{bound} \\
  ^4\text{He} & \quad \text{bound} \\
  ^5\text{He} & \quad \text{unbound} \\
  ^6\text{He} & \quad \text{bound} \quad \text{halo} \\
  ^7\text{He} & \quad \text{unbound} \\
  ^8\text{He} & \quad \text{bound} \quad \text{halo} \\
  \text{...} &
\end{align*} \]

Borromean system

Most exotic nucleus "on earth"

\[ \frac{N}{Z} = 3 \]

Synthesized in the laboratory
The helium isotope chain

Shows many interesting features:

$^3\text{He}$ bound

$^4\text{He}$ bound

$^5\text{He}$ unbound

$^6\text{He}$ bound halo

$^7\text{He}$ unbound

$^8\text{He}$ bound halo

Borromean system

Most exotic nucleus “on earth”

$^N_Z = 3$

lives 806 ms

lives 108 ms

Synthesized in the laboratory
Production of rare isotopes at TRIUMF

ISAC I & II

- Cyclotron
- Beam
- Target
- Mass separator
Ab initio calculations for halo nuclei

Our calculations:
low-momentum EFT NN force

- $\Lambda = 1.8$ fm$^{-1}$
- $\Lambda = 2.0$ fm$^{-1}$
- $\Lambda = 2.4$ fm$^{-1}$

Experimental data

Previous calculations:
- NCSM: NN only
- GFMC: NN+3NF

Sonia Bacca

APSNW Meeting, May 15 2009
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S.Bacca et al., arXiv:0902.1696
Ab initio calculations for halo nuclei

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- low-momentum EFT NN force
  - $\Lambda = 1.8 \text{ fm}^{-1}$
  - $\Lambda = 2.0 \text{ fm}^{-1}$
  - $\Lambda = 2.4 \text{ fm}^{-1}$

Estimates error in neglected

Future:
- Include 3NF
- Apply to other isotope chains with halo features
Nuclear Reactions: photo-absorption

Semi-realistic NN force

S.B. et al., PRL 89 ('02), PLB 603 and PRC 69 ('04)
Nuclear Reactions: photo-absorption

Semi-realistic NN force

Giant Dipole Resonance

\[ \sigma_\gamma \text{ [mb]} \]

\[
\begin{align*}
\omega & \text{ [MeV]} \\
0 & 20 40 60 80 100
\end{align*}
\]

\[ {^6}\text{Li} \]

\[ {^6}\text{He} \]

S.B. et al., PRL 89 ('02), PLB 603 and PRC 69 ('04)
Nuclear Reactions: photo-absorption

Semi-realistic NN force

$^6$Li

Giant Dipole Resonance

protons $\rightarrow$ neutrons

$^6$He

Signatures of the halo

Soft-dipole Mode

neutron halo $\rightarrow$ $\alpha$-core

Giant Dipole Mode

neutrons $\rightarrow$ protons

S.B. et al., PRL 89 ('02), PLB 603 and PRC 69 ('04)
Nuclear Reactions: photo-absorption

Semi-realistic NN force

\[ \sigma_\gamma \text{ [mb]} \]

\[ \omega \text{ [MeV]} \]

\( ^6\text{He} \)

GSI ('99)

NSCL ('02)
Nuclear Reactions: photo-absorption

Semi-realistic NN force

Photo-absorption can be also related to neutron capture reactions for astrophysics
Astrophysics: Neutrino Reactions in Supernovae

- Core collapse supernovae are gigantic explosions of massive stars
- 99% of the released energy is carried by neutrinos in all flavors, therefore neutrino interactions with matter are crucial

- In the iron core the burning process stops and it becomes gravitationally unstable → the core collapses
- Nuclear forces halt the collapse, and drive an outgoing shock, which loses energy due to dissociation, neutrino radiation.
- The shock stalls ... possibly revived by neutrino heating
Neutrino bremsstrahlung affects the time scale of the delayed explosion

but standard neutrino rates are based on one-pion-exchange for NN

A. Mezzacappa (ORNL), JUSTIPEN Workshop (2008)
Neutrino bremsstrahlung from EFT

Pure neutron matter \( NN \to NN\bar{\nu}\bar{\nu} \)

Chiral expansion

- LO (=one-pion exchange)
- NLO
- \( N^2 \)LO
- \( N^3 \)LO

S.B. et al. arXiv:0812.0102

\( q \approx 0 \)
Neutrino bremsstrahlung from EFT

Pure neutron matter $NN \rightarrow NN\nu\bar{\nu}$

Modern Hamiltonians give a very different result!

S.B. et al. [arXiv:0812.0102]
Neutrino bremsstrahlung from EFT

Pure neutron matter $NN \rightarrow NN\nu\bar{\nu}$

Visible effect of 3NF at higher density
Neutrino bremsstrahlung from EFT

Pure neutron matter $NN \rightarrow NN\nu\bar{\nu}$

Visible effect of 3NF at higher density

**Aim:** the new standard rates in SN simulation!
Summary

Exciting era in nuclear physics with advances on many fronts!

Nuclear physics is build upon a strong connection theory-experiment: fundamental for testing our knowledge of nuclear forces

• Enormous progress done in ab-initio approaches to nuclear structure
  ★ Description of helium halo isotopes from evolved Effective Field Theory forces

• Advances in the accurate calculation of nuclear reactions
  ★ Different dipole strength distribution in stable-unstable light nuclei

• Nuclear physics provides fundamental microscopic input for astrophysics
  ★ First neutrino rates based on Effective Field Theory

Future: the study of the role of 3NF is key in all areas from light nuclei to astrophysics
Thanks to my collaborators:

Nir Barnea
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Oak Ridge National Laboratory

Katy Hally
 Acadia University

Kai Hebeler, Achim Schwenk
Triumf

Winfried Leidemann, Giuseppina Orlandini

Chris Pethick
Nordita

I acknowledge useful discussions with the group members
Thank you!

Merci!