PIONS and NUCLEI
- In Honour of the PIONeers -
Foundations of Pion-Nuclear Physics

- Pion-nucleus optical potential
- Pionic atoms
- Pion propagation in a nuclear medium
- Ericson-Ericson-Lorentz-Lorenz effect
- Pion absorption

Optical Properties of Low-Energy Pions in Nuclei

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A simple nonlocal potential for low-energy pions in finite nuclei is calculated from the amplitudes for \( \pi N \) scattering and for \( \pi \) production in \( NN \) collisions. The potential includes absorption and has no free parameters. The appropriate multiple scattering equations are derived in the coordinate representation with nuclear pair correlations included. Owing to the large mass of the scatterers the pion field behaves nearly classically. It is shown that short-range pair correlations are important in the multiple scattering owing to the dominant dipole component in the \( \pi N \) scattering. To a good approximation this produces a Lorentz-Lorenz effect analogous to the one occurring in the scattering of electromagnetic waves in dense media. The contributions of Fermi motion to the potential are shown to be small. The isospin part of the potential is derived and is shown to have a tensor component in addition to the ordinary vector one. The former gives rise to direct double charge exchange of pions; its strength becomes important for high momentum pions. The potential is further found to have a term which gives a small but possibly observable hyperfine coupling.

A comparison is made between predictions of the potential and experimental data on level shifts and widths for \( \pi \) mesic atoms. Satisfactory agreement is found within experimental uncertainties which is quantitative evidence for nuclear pair-absorption of pions. There is also some indication of short range anticorrelations between nucleons.
Pion-Nuclear Many-Body Problems

- **Nuclear PCAC**
- **Spin-isospin (axial)** polarizability
- **Delta-isobar in nuclei**
- **Renormalization of the axial vector coupling in nuclei**
Prominent role of PION-EXCHANGE TENSOR FORCE in nuclear physics

deuteron density contours

- deuteron properties largely determined by one-pion exchange

T. E.O. Ericson, M. Rosa-Clot (1985)
NUCLEAR MATTER and QCD PHASES

nuclei

Scales in nuclear matter:

- momentum scale: **Fermi momentum**
- NN distance:
- energy per nucleon:
- compression modulus:

\[
k_F \simeq 1.4 \text{ fm}^{-1} \simeq 2m_\pi
\]

\[
d_{NN} \simeq 1.8 \text{ fm} \simeq 1.3 \text{ m}_\pi^{-1}
\]

\[
E/A \simeq -16 \text{ MeV}
\]

\[
K = (260 \pm 30) \text{ MeV} \simeq 2m_\pi
\]
PIONS and NUCLEI in the context of LOW-ENERGY QCD

- **CONFINEMENT** of quarks and gluons in hadrons
- Spontaneously broken **CHIRAL SYMMETRY**

**LOW-ENERGY QCD:**

**Effective Field Theory** of weakly interacting

Nambu-Goldstone Bosons (PIONS)

representing QCD at (energy and momentum) scales

\[ Q << 4\pi f_\pi \sim 1 \text{ GeV} \]

Weinberg  
Gasser & Leutwyler
CHIRAL EFFECTIVE FIELD THEORY

- Systematic framework at interface of QCD and Nuclear Physics

- Interacting systems of **PIONS** (light / fast) and **NUCLEONS** (heavy / slow):

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_\pi(U, \partial U) + \mathcal{L}_N(\Psi_N, U, \ldots)
\]

\[
U(x) = \exp\left[ i\tau_a \pi_a(x)/f_\pi \right]
\]

- Construction of Effective Lagrangian: **Symmetries**

  short distance dynamics:

contact terms
Nuclear Forces
- recent developments -

Early history: M. Taketani et al. (1951)

contemporary approach:

Chiral Effective Field Theory + Lattice QCD


Hierarchy of SCALES

repulsive core
contact terms
explicit treatment of two-pion exchange
Important pieces of the CHIRAL NUCLEON-NUCLEON INTERACTION

**ISOVECTOR TENSOR FORCE**

- \( \Delta(1232) \)
- \( S_1 \rightarrow V_T \rightarrow S_2 \)
- \( \text{note: no } \rho \text{ meson} \)

**CENTRAL ATTRACTION from TWO-PION EXCHANGE**

- \( \Delta(1232) \)
- \( \text{note: no } \sigma \text{ boson} \)

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Isovector Tensor Potential

\( V_T(r) \propto - \frac{\exp[-2m_\pi r]}{r^6} P(m_\pi r) \)

... at intermediate and long distance

Van der WAALS - like force:

**CHIRAL DYNAMICS and the NUCLEAR MANY-BODY PROBLEM**


- **Small scales:** \[ k_F \sim 2m_\pi \sim M_\Delta - M_N < < 4\pi f_\pi \]

- **PIONS (and DELTA isobars) as explicit degrees of freedom**

**IN-MEDIUM CHIRAL PERTURBATION THEORY**

- Pion exchange processes in presence of filled Fermi sea

- **2nd order TENSOR force** + nucleon’s SPIN-ISOSPIN polarizability

- Short-distance dynamics: \[ N \times N \] contact interactions

- **Ericsonian concepts** at work, now implemented in ChPT
Explicit \( \Delta(1230) \) DEGREES of FREEDOM

- **Large spin-isospin polarizability** of the Nucleon

  - example: polarized Compton scattering

  \[
  \beta_\Delta = \frac{g_A^2}{f_\pi^2 (M_\Delta - M_N)} \sim 5 \text{ fm}^3 \\
  M_\Delta - M_N \simeq 2 \text{ m}_\pi << 4\pi f_\pi \\
  \text{(small scale)}
  \]

- **Pionic Van der Waals** - type intermediate range central potential

  \[
  V_c(r) = -\frac{9 g_A^2}{32\pi^2 f_\pi^2} \beta_\Delta \frac{e^{-2m_\pi r}}{r^6} P(m_\pi r)
  \]

J. Fujita, H. Miyazawa (1957)
Pieper, Pandharipande, Wiringa, Carlson (2001)
N. Kaiser, S. Fritsch, W.W., NPA750 (2005) 259

Technische Universität München
**IN-MEDIUM CHIRAL PERTURBATION THEORY**

- **Loop expansion** in Chiral Perturbation Theory ↔
  Systematic expansion of **ENERGY DENSITY** \( \mathcal{E}(k_F) \) in
  **powers** of Fermi momentum [modulo functions \( f_n(k_F/m_\pi) \)]

- **Finite nuclei** ↔ **energy density functional**
  many quantitatively successful applications throughout the nuclear chart

- **Nuclear thermodynamics**: compute **free energy density**

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**in-medium**

nucleon propagators incl. Pauli blocking

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(3-loop order)

**In-medium ChPT**
3-loop \((\pi, N, \Delta)\)

- **Input** parameter:
  - single contact term

- basically:
  - analytic calculation

- **Output:**

  - Binding & saturation
    \[ E_0/A = -16 \text{ MeV} \ , \ \rho_0 = 0.16 \text{ fm}^{-3} \ , \ K = 290 \text{ MeV} \]

  - Realistic (complex, momentum dependent) single-particle potential
    ... satisfying Hugenholtz - van Hove and Luttinger theorems (!)

  - Asymmetry energy \( A(k_F^0) = 34 \text{ MeV} \)

  - Landau parameters
NUCLEAR THERMODYNAMICS

NUCLEAR CHIRAL (PION) DYNAMICS

BINDING & SATURATION:

Van der Waals + Pauli

\[ N, \Delta \]

+ 3-body forces

contact terms

3-loop in-medium ChEFT

Liquid - Gas Transition at Critical Temperature \( T_c = 15 \text{ MeV} \)

(empirical: \( T_c = 16 - 18 \text{ MeV} \))

**PHASE DIAGRAM of NUCLEAR MATTER**

- **Critical point**
- **In-medium chiral effective field theory** (3-loop in the free energy density)

- Pion-nucleon dynamics incl. delta isobars
- Short-distance NN contact terms
- Three-body forces

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**Diagram Details**

- **Temperature** $T$ [MeV]
- **Baryon chemical potential** $\mu_B$ [MeV]
- **Phase Regions**
  - Gas
  - Liquid
  - Gas-Liquid
- **Critical Point** $N = Z$
- **Nuclear Matter**
PHASE DIAGRAM of NUCLEAR MATTER

Trajectory of CRITICAL POINT for asymmetric matter
as function of proton fraction Z/A

...determined almost entirely by isospin dependent pion exchange dynamics

New constraints from EFT and neutron star observables

kaon condensate

quark matter

realistic “nuclear” EoS (Illinois)


CHIRAL CONDENSATE at finite BARYON DENSITY

- Chiral (quark) condensate $\langle \bar{q}q \rangle$:
  Order parameter of spontaneously broken chiral symmetry in QCD

- Hellmann - Feynman theorem: $\langle \Psi | \bar{q}q | \Psi \rangle = \langle \Psi | \frac{\partial H_{QCD}}{\partial m_q} | \Psi \rangle = \frac{\partial \mathcal{E}(m_q; \rho)}{\partial m_q}$

\[
\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} = 1 - \frac{\rho}{f_\pi^2} \left[ \frac{\sigma_N}{m_{\pi}^2} \left(1 - \frac{3 p_F^2}{10 M_N^2} + \ldots \right) + \frac{\partial}{\partial m_{\pi}^2} \left( \frac{E_{int}(p_F)}{A} \right) \right]
\]

sigma term
\[m_q \frac{\partial M_N}{\partial m_q}\]

in-medium chiral effective field theory

(free) Fermi gas of nucleons

nuclear interactions (dependence on pion mass)
Chiral Condensate: Density Dependence

- In-medium Chiral Effective Field Theory (NLO 3-loop)
  - Constrained by realistic nuclear equation of state

- Substantial change of symmetry breaking scenario between chiral limit $m_q = 0$ and physical quark mass $m_q \sim 5\text{ MeV}$

- Nuclear Physics would be very different in the chiral limit!
a long road together

...thank you, Magda & Torleif
Supplementary Materials
NN Scattering Phase Shifts
from CHIRAL EFFECTIVE FIELD THEORY


quantitatively accurate at same level of precision
as best phenomenological potentials
CHIRAL EFFECTIVE FIELD THEORY
at work in nuclear few-body systems

element: elastic nd scattering

differential cross sections
[mb/sr]

vector analyzing powers

tensor analyzing powers

... constrained by (chiral) **symmetry breaking pattern** of Low-Energy QCD

\[
E[\rho] = E_{\text{kin}} + \int d^3x \left[ \mathcal{E}^{(0)}(\rho) + \mathcal{E}_{\text{exc}}(\rho) \right] + E_{\text{coul}} \\
\rho \rightarrow \rho(x) \quad \rightarrow \quad \text{Kohn - Sham equations}
\]

\[ \mathcal{E}_{\text{exc}}(\rho) : \] from in-medium **Chiral Perturbation Theory** (**"Pionic fluctuations"**) 

\[ \mathcal{E}^{(0)}(\rho) : \] Hartree mean field(s) from **contact terms**

(equiv. to) \[ \leftrightarrow \] strong **SCALAR** and **VECTOR** mean fields

\[ \leftrightarrow \] leading order **IN-MEDIUM** changes of **QCD CONDENSATES**
Strategy:

- Calculate physics at **long** and **intermediate** distances using nuclear **chiral effective field theory**
- Fix **short** distance constants (contact interactions) e.g. in Pb region
- Predict **systematics** for all other nuclei

deviations (in %) between calculated and measured **binding energies** per nucleon ...

... and **charge radii**

Examples (part II)

charge density of $^{48}$Ca

**Examples (part III):**

**DEFORMED NUCLEI**

deviations (in %) between calculated and measured binding energies

Ground state deformations

Systematics through **isotopic chains**
governed by **isospin** dependent forces
from **chiral pion dynamics**

Gamow-Teller beta decays

interesting case: $^{14}\text{C} \xrightarrow{\beta^-} ^{14}\text{N}$

anomalously long lifetime (5739 y)

enables radiocarbon dating

Theoretically not understood on the basis of two-nucleon interactions only

Solution: chiral effective interaction including three-body force


Spin-orbit interactions

Role of 2nd order tensor force from pion exchange and three-body interactions


In-medium Chiral SU(3) dynamics and hypernuclei

Weak $\Lambda$-nuclear spin-orbit coupling

Anomalously long beta decay lifetime of $^{14}\text{C}$

- **Early history:** B. Janovici, I. Talmi : Phys. Rev. 95 (1954) 289 (Role of tensor force)

$^{14}\text{C} \xrightarrow{\beta^-} ^{14}\text{N}$

- Known lifetime of 5730 years enables radiocarbon dating
- But theoretical description using realistic nucleon-nucleon interactions overestimates the GT strength

**Idea:** Derive a density-dependent two-nucleon force from the leading-order chiral three-nucleon force

$$T_{1/2} = \frac{1}{f(Z, E_0)} \frac{2\pi^3 \hbar^7 \ln 2}{m_e^5 c^4 G_V^2} \frac{1}{g_A^2 |M_{GT}|^2}$$

Expt : $B(\text{GT}) \sim |M_{GT}|^2 \sim 10^{-6}$

Large suppression of GT strength at $\rho_0$ due to chiral 3NF!