Strong and electroweak interactions in nuclei

Saori Pastore
NuSTEC
FNAL - Batavia IL - November 2017

Thanks to Jorge and Luis

Topics (3 hours)

* Two- and Three-nucleon Pion Exchange Interactions
* Realistic Models of Two- and Three-Nucleon Interactions
* Realistic Models of Many-Body Nuclear Electroweak Currents
* Short-range Structure of Nuclei, Nuclear Correlations, and Quasi-Elastic Scattering

Reading Material

* On line material *

* Notes from Prof Rocco Schiavilla (for personal use only)
  https://indico.fnal.gov/event/8047/material/0/0
* Notes from Prof Luca Girlanda (for personal use only)
  http://chimera.roma1.infn.it/OMAR/ECTSTAR_DTP/girlanda/lez1.pdf
  http://chimera.roma1.infn.it/OMAR/ECTSTAR_DTP/girlanda/lez2.pdf
  http://chimera.roma1.infn.it/OMAR/ECTSTAR_DTP/girlanda/lez3.pdf
* Review Articles on *Ab initio* calculations of electromagnetic properties of light nuclei
  * Carlson & Schiavilla - Rev.Mod.Phys. 70 (1998) 743-842: http://inspirehep.net/record/40882
  * Bacca & Pastore - J.Phys. G41 (2014) no.12, 123002: http://inspirehep.net/record/1306337
  * Marcucci & F. Gross & M.T. Pena & M. Piarulli & R. Schiavilla & I. Sick & A. Stadler & J.W. Van Orden & M. Viviani - J.Phys. G43 (2016) 023002: https://inspirehep.net/record/1362209

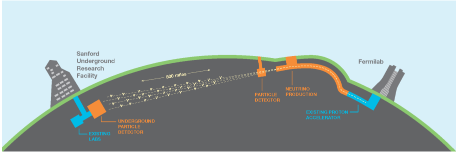
* Textbooks *

* *Pions and Nuclei* by Torleif Ericson and Wolfram Weise, Oxford University Press (October 6, 1988)
* *Theoretical Nuclear and Subnuclear Physics* by John Dirk Walecka, Oxford University Press (March 23, 1995)
* *Foundations of Nuclear and Particle Physics* by T. William Donnelly, Joseph A. Formaggio, Barry R. Holstein, Richard G. Milner, Bernd Surrow, Cambridge University Press; 1st edition (February 1, 2017) new item!
* *A Primer for Chiral Perturbation Theory* by Stefan Scherer and Matthias R. Schindler, Springer; 2012 edition (September 30, 2011) (somewhat) new item!

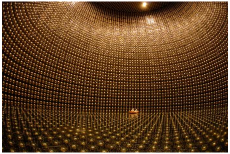
saori.pastore@gmail.com

Motivations (Why Nuclear Physics?)

Fundamental Physics Quests: Accelerator Neutrinos



LBNF



T2K

neutrinos oscillate

$\rightarrow$

they have tiny masses

=

BSM physics

Beyond the Standard Model

Simplified 2 flavors picture:

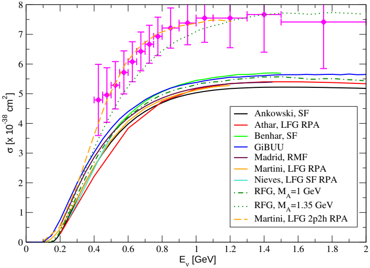
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2 L}{2E_\nu} \right)$$

* Unknown *

ν-mass hierarchy, CP-violation, accurate mixing angles

Neutrino-Nucleus scattering

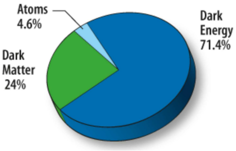
CCQE on ^{12}C

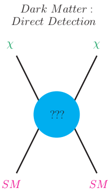


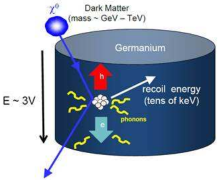
Alvarez-Ruso arXiv:1012.3871

DUNE, MiniBoone, T2K, Minerνa ... active material * ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

Fundamental Physics Quests: Dark Matter Direct Detection







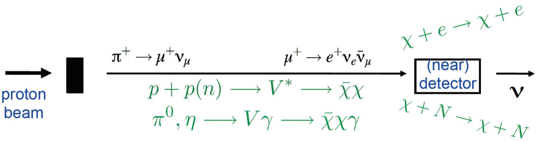
CDMS

Dark Matter Beam Production and Direct detection:

$$\chi + A \rightarrow \chi + A$$

Dark Matter is detected via scattering on nuclei in the detector

Detection of Sub-GeV Dark Matter requires knowledge of nuclear responses



A. A. Aguilar-Arevalo *et al.* arXiv:1211.2258

Fundamental Physics Quests: Double Beta Decay

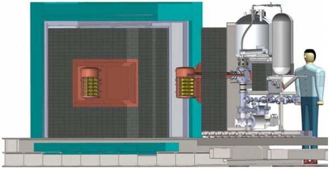
observation of $0\nu\beta\beta$-decay

$\rightarrow$

lepton # $L = l - \bar{l}$ not conserved

$\rightarrow$

implications in matter-antimatter imbalance



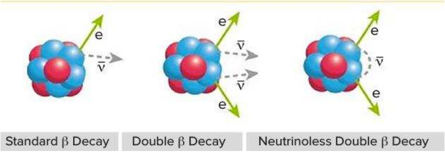
Majorana Demonstrator

* detectors' active material ^{76}Ge *

$0\nu\beta\beta$-decay $\tau_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)

1 ton of material to see (if any) $\sim$ 5 decays per year

* also, if nuclear m.e.'s are known, absolute ν-masses can be extracted *

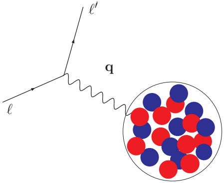


2015 Long Range Plane for Nuclear Physics

Creating a Common Language

* Interface Theory with Experiments and with Neutrino Generators and likewise *

The Basic Model
aka Microscopic or *ab initio* Description of Nuclei



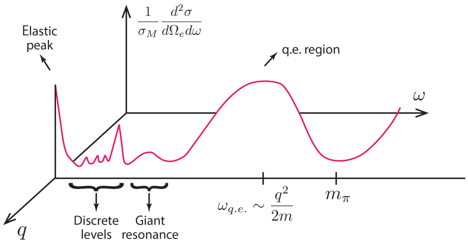
GOAL

Develop a comprehensive theory that describes quantitatively and predictably all nuclear structure and reactions

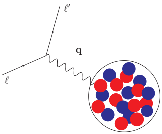
* The *ab initio* Approach*

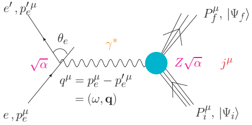
In the *ab initio* Approach one assumes that all nuclear phenomena can be explained in terms of (or emerge from) interactions between nucleons, and interactions between nucleons and external electroweak probes (electrons, photons, neutrinos, DM, . . .)

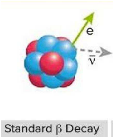
Electroweak Reactions



- $\omega \sim 10^2$ MeV: Accelerator neutrinos
- $\omega \sim 10^1$ MeV: EM decay, β-decay
- $\omega \lesssim 10^1$ MeV: Nuclear Rates for Astrophysics







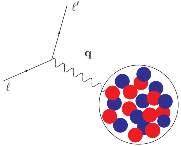
The *ab initio* Approach

The nucleus is made of A interacting nucleons and its energy is

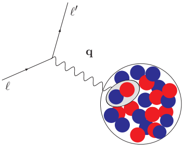
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} \upsilon_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

where υ_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD

1b



2b



$$\begin{aligned} \rho &= \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots \,, \\ \mathbf{j} &= \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots \end{aligned}$$

Two-body 2b currents essential to satisfy current conservation

$$\mathbf{q} \cdot \mathbf{j} = [\, H, \rho \,] = \left[t_i + \upsilon_{ij} + V_{ijk}, \rho \right]$$

* "Longitudinal" component fixed by current conservation

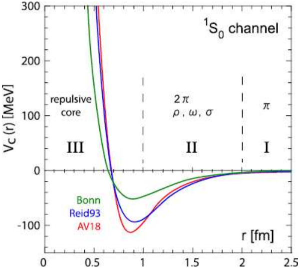
* "Transverse" component "model dependent"

The Basic Model
Requirement 1: Nuclear Interactions
DAY 1

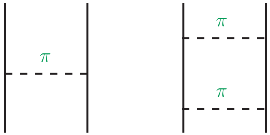
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

Step 1. Construct two- and three-body interactions

* Chiral Effective Field Theory Interactions
* "Conventional" or "Phenomenological" Interactions



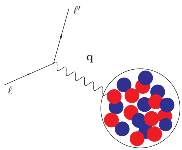
Aoki *et al.* Comput.Sci.Disc.1(2008)015009



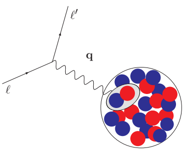
* One-pion-exchange: range$\sim \frac{1}{m_\pi} \sim 1.4$ fm
* Two-pion-exchange: range$\sim \frac{1}{2m_\pi} \sim 0.7$ fm

The Basic Model
Requirement 2: Nuclear Many-Body Currents
DAY 2 and 3

1b



2b



$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots \,,$$

$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

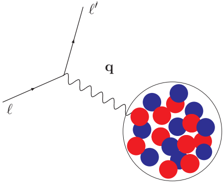
Step 2. Understand how external probes (electrons, neutrinos, DM ...) interact with nucleons, nucleon pairs, nucleon triplets...

* Chiral Effective Field Theory Electroweak Many-Body Currents
* "Conventional" or "Phenomenological" Electroweak Many-Body Currents

Step 2.a Validate and then Use the model

* Validation of the theory against Electromagnetic observables in a wide range of energies
* Neutrino-Nucleus Observables from low to high energies and momenta

The Basic Model
Requirement 3: Solve the Many-Body Nuclear Problem



Step 3. Develop Computational Methods to solve (numerically) exactly or within approximations that are under control

$$H\Psi(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A,s_1,s_2,\ldots,s_A,t_1,t_2,\ldots,t_A,)=E\Psi(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A,s_1,s_2,\ldots,s_A,t_1,t_2,\ldots,t_A,)$$

* Green's function Monte Carlo Method is a path-integral Monte Carlo Method

pro *Ab initio* Approach supported by GFMC Methods provides numerically exact results (*e.g.*, nuclear spectra, responses ...)

con The computational cost increases exponential with A, limited to $A \leq 12$

For QMC Methods see Alessandro Lovato's Lectures

History of Nuclear Force in one page

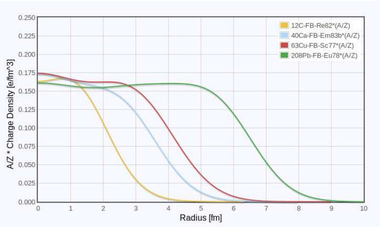


Fig. from virginia.edu

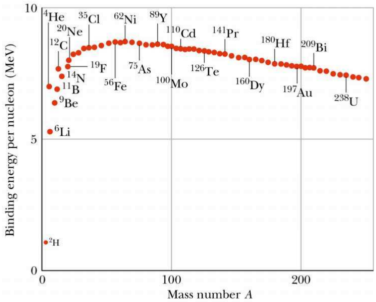


Fig. from ohio.edu

* Range $\propto \frac{1}{m}$
* 1930s Yukawa Potential

$$\upsilon_Y \sim -\frac{e^{-mr}}{r}$$

* 1960-1990 Highly sophisticated "meson exchange" potentials
* 1990s to present - do it all over again but within Chiral Effective Field Theory (plus now we have better tools and data)

The nucleus is made of A interacting nucleons and its energy is

$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} \upsilon_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

where υ_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD

Time-Ordered-Perturbation Theory

The relevant degrees of freedom of nuclear physics are bound states of QCD

* non relativistic nucleons N
* pions π as mediators of the nucleon-nucleon interaction
* non relativistic Delta's Δ with $m_\Delta \sim m_N + 2m_\pi$

Transition amplitude in time-ordered perturbation theory

$$T_{fi} = \langle N'N' \mid H_1 \sum_{n=1}^{\infty} \left(\frac{1}{E_i - H_0 + i\eta} H_1 \right)^{n-1} \mid NN \rangle^{*}$$

H_0 = free π, N, Δ Hamiltonians
H_1 = interacting π, N, Δ, and external electroweak fields Hamiltonians

$$T_{fi} = \langle N'N' \mid T \mid NN \rangle \propto \upsilon_{ij} \,, \qquad T_{fi} = \langle N'N' \mid T \mid NN;\gamma \rangle \propto (A^0 \rho_{ij}, \mathbf{A} \cdot \mathbf{j}_{ij})$$

* Note no pions in the initial or final states, *i.e.*, pion-production not accounted in the theory

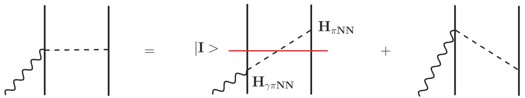
Transition amplitude in time-ordered perturbation theory

Insert complete sets of eigenstates of H_0 between successive terms of H_1

$$T_{fi} = \langle N'N' \mid H_1 \mid NN;\gamma\rangle + \sum_{|I\rangle} \langle N'N' \mid H_1 \mid I\rangle \frac{1}{E_i - E_I} \langle I \mid H_1 \mid NN;\gamma\rangle + \ldots$$

The contributions to the T_{fi} are represented by time ordered diagrams

Example: seagull pion exchange current



N number of H_1's (vertices) $\rightarrow$ N! time-ordered diagrams

Q1. How do we construct H_1 and how is it related to QCD ?

A1. Symmetries of QCD, Parity, Charge Conjugation, Isospin, ..., and Chiral

Richard Hill's lecture of this morning

Q2. How do we know which dynamical process (diagram) is more relevant?

A2. We identify a (small) expansion parameter and do perturbation theory in terms of it

Conceptual Perturbation Theory

$$\frac{1}{1-x} = \sum_{n=0} x^n = 1 + x + x^2 + x^3 \ldots$$

* x is small expansion parameter
* one only needs to evaluate few terms in the expansion (if lucky)
* the error is given by the truncation in the expansion

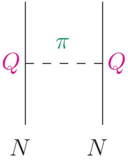
* Examples *

* Chiral Effective Field Theory: $x = Q$
* Large N_c: $x = \frac{1}{N_c}$
* $\ldots$

Nuclear Chiral Effective Field Theory (χEFT) approach

S. Weinberg, Phys. Lett. **B251**, 288 (1990); Nucl. Phys. **B363**, 3 (1991); Phys. Lett. **B295**, 114 (1992)

* χEFT is a low-energy ($Q \ll \Lambda_\chi \sim 1$ GeV) approximation of QCD
* It provides effective Lagrangians describing π's, N's, Δ's, ... interactions that are expanded in powers n of a perturbative (small) parameter Q/Λ_χ



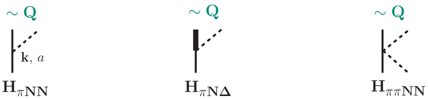
$$\mathscr{L}_{eff} = \mathscr{L}^{(0)} + \mathscr{L}^{(1)} + \mathscr{L}^{(2)} + \ldots + \mathscr{L}^{(n)} + \ldots$$

* The coefficients of the expansion, Low Energy Constants (LECs), are unknown and need to be fixed by comparison with exp data, or take them from LQCD
* The systematic expansion in Q naturally has the feature

$$\langle \mathscr{O} \rangle_{1-\text{body}} > \langle \mathscr{O} \rangle_{2-\text{body}} > \langle \mathscr{O} \rangle_{3-\text{body}}$$

* A theoretical error due to the truncation of the expansion can be assigned

π, N and Δ Strong Vertices



$$H_{\pi NN} = \frac{g_A}{F_\pi}\int d\mathbf{x}\, N^\dagger(\mathbf{x})\,[\boldsymbol{\sigma}\cdot\nabla\pi_a(\mathbf{x})]\,\tau_a N(\mathbf{x}) \quad\longrightarrow\quad V_{\pi NN} = -i\frac{g_A}{F_\pi}\frac{\boldsymbol{\sigma}\cdot\mathbf{k}}{\sqrt{2\,\omega_k}}\tau_a \sim Q^1\times Q^{-1/2}$$

$$H_{\pi N\Delta} = \frac{h_A}{F_\pi}\int d\mathbf{x}\, \Delta^\dagger(\mathbf{x})\,[\mathbf{S}\cdot\nabla\pi_a(\mathbf{x})]\,T_a N(\mathbf{x}) \quad\longrightarrow\quad V_{\pi N\Delta} = -i\frac{h_A}{F_\pi}\frac{\mathbf{S}\cdot\mathbf{k}}{\sqrt{2\,\omega_k}}T_a \sim Q^1\times Q^{-1/2}$$

$g_A \simeq 1.27$; $F_\pi \simeq 186$ MeV; $h_A \sim 2.77$ (fixed to the width of the Δ)
are 'known' LECs

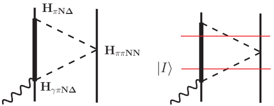
$$\pi_a(\mathbf{x}) = \sum_{\mathbf{k}} \frac{1}{\sqrt{2\,\omega_k}}\left[c_{\mathbf{k},a}\,e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}\right] ,$$

$$N(\mathbf{x}) = \sum_{\mathbf{p},\sigma\tau} b_{\mathbf{p},\sigma\tau}\,e^{i\mathbf{p}\cdot\mathbf{x}}\chi_{\sigma\tau} ,$$

(Naïve) Power Counting

Each contribution to the $T_{f\,i}$ scales as

$$\underbrace{\left(\prod_{i=1}^{N} Q^{\alpha_i-\beta_i}\right)}_{H_1\,\text{scaling}} \times \underbrace{Q^{-(N-1)}}_{\text{denominators}} \times \underbrace{Q^{3L}}_{\text{loop integration}}$$



$\alpha_i =$ # of derivatives (momenta) in H_1;
$\beta_i =$ # of π's;
$N =$ # of vertices; $N-1 =$ # of intermediate states;
$L =$ # of loops

$$H_1 \text{ scaling} \sim \underbrace{Q^1}_{H_{\pi N\Delta}} \times \underbrace{Q^1}_{H_{\pi\pi NN}} \times \underbrace{Q^0}_{H_{\pi\gamma N\Delta}} \times Q^{-2} \sim Q^0$$

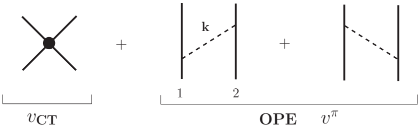
$$\text{denominators} \sim \frac{1}{E_i - H_0}|I\rangle \sim \frac{1}{2m_N - (m_\Delta + m_N + \omega_\pi)}|I\rangle = -\frac{1}{m_\Delta - m_N + \omega_\pi}|I\rangle \sim \frac{1}{Q}|I\rangle$$

$$Q^1 = Q^0 \times Q^{-2} \times Q^3$$

* This power counting also follows from considering Feynman diagrams, where loop integrations are in 4D

χEFT nucleon-nucleon potential at LO

$v_{\mathrm{NN}}^{\mathrm{LO}} =$



$\sim \mathbf{Q}^0$

$$T_{fi}^{\mathrm{LO}} = \langle N'N' \mid H_{\mathrm{CT},1} \mid NN\rangle + \sum_{|I\rangle} \langle N'N' \mid H_{\pi NN} \mid I\rangle \frac{1}{E_i - E_I} \langle I \mid H_{\pi NN} \mid NN\rangle$$

Leading order nucleon-nucleon potential in χEFT

$$v_{\mathrm{NN}}^{\mathrm{LO}} = v_{\mathrm{CT}} + v_{\pi} = C_S + C_T\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 - \frac{g_A^2}{F_\pi^2} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{k}\, \boldsymbol{\sigma}_2 \cdot \mathbf{k}}{\omega_k^2} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

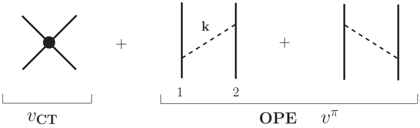
* Configuration space *

$$v_{12} = \sum_p v_{12}^p(r)\, O_{12}^p; \qquad O_{12} = 1,\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2,\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2,\, S_{12} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

$$S_{12} = 3\, \boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}}\, \boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

One Pion Exchange in Configuration Space

$v_{\mathrm{NN}}^{\mathrm{LO}} =$



$\sim \mathbf{Q}^0$

One-Pion-Exchange Potential (OPEP)

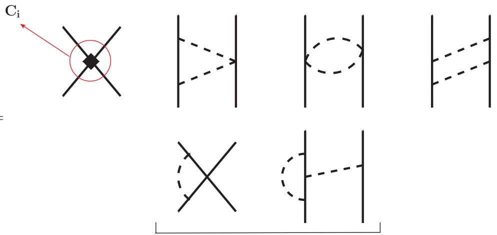
$$
\begin{aligned}
v_\pi(\mathbf{k}) &= -\frac{g_A^2}{F_\pi^2}\,\frac{\boldsymbol{\sigma}_1\cdot\mathbf{k}\,\boldsymbol{\sigma}_2\cdot\mathbf{k}}{\omega_k^2}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 \\
v_\pi(\mathbf{r}) &= \frac{f_{\pi NN}^2}{4\pi}\,\frac{m_\pi}{3}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\left[T_\pi(r)S_{12}+\left[Y_\pi(r)-\frac{4\pi}{m_\pi^3}\delta(\mathbf{r})\right]\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right]
\end{aligned}
$$

$$
\begin{aligned}
Y_\pi(r) &= \frac{e^{-m_\pi r}}{m_\pi r} \\
T_\pi(r) &= \left(1+\frac{3}{m_\pi r}+\frac{3}{m_\pi^2 r^2}\right)Y_\pi(r)
\end{aligned}
$$

$$
S_{12} = 3\,\boldsymbol{\sigma}_1\cdot\hat{\mathbf{r}}\,\boldsymbol{\sigma}_2\cdot\hat{\mathbf{r}} - \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2
$$

χEFT nucleon-nucleon potential at NLO (without Δ's)

$v_{\rm NN}^{\rm NLO} =$



$\sim \mathrm{Q}^2$

renormalize $\mathrm{C_S}$, $\mathrm{C_T}$, and $\mathrm{g_A}$

* At NLO there are 7 LEC's, C_i, fixed so as to reproduce nucleon-nucleon scattering data (order of k data)
* C_i's multiply contact terms with 2 derivatives acting on the nucleon fields (∇N)
* Loop-integrals contain ultraviolet divergences reabsorbed into g_A, C_S, C_T, and C_i's (for example, use dimensional regularization)

* Configuration space *

$$v_{12} = \sum_p v_{12}^p(r)\, O_{12}^p; \qquad O_{12} = [1,\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2,\, S_{12}, \mathbf{L} \cdot \mathbf{S}] \otimes [1,\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$$

Technicalities: The Cutoff

* χEFT operators have a power law behavior in Q

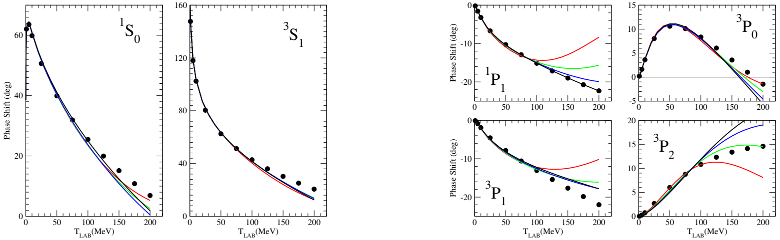
1. introduce a regulator to kill divergencies at large Q, *e.g.*, $C_\Lambda = e^{-(Q/\Lambda)^n}$
2. pick n large enough so as to not generate spurious contributions

$$C_\Lambda \sim 1 - \left(\frac{Q}{\Lambda}\right)^n + \ldots$$

3. for each cutoff Λ re-fit the LECs
4. ideally, your results should be cutoff-independent

* In r_{ij}-space this corresponds to cutting off the short-range part of the operators that make the matrix elements diverge at $r_{ij} = 0$

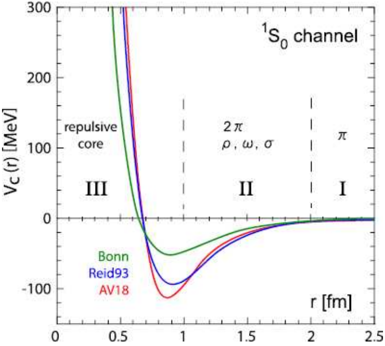
Determining LEC's: fits to *np* phases $*$ up to $T_{\rm LAB} = 100$MeV
NLO Chiral Potential



LS-equation regulator $\sim \exp(-2\,Q^4/\Lambda^4)$, (cutting off momenta $Q \gtrsim 3$–$4\; m_\pi$),
Λ=500, 600, and 700 MeV

$*$ F.Gross and A.Stadler PRC **78**, 104405 (2008)

Nucleon-nucleon potential

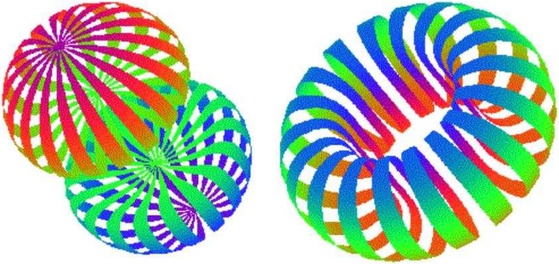


Aoki *et al.* Comput.Sci.Disc.1(2008)015009

CT = Contact Term (short-range);
OPE = One Pion Exchange (range $\sim \frac{1}{m_\pi}$);
TPE = Two Pion Exchange (range $\sim \frac{1}{2m_\pi}$)

Nucleon-Nucleon Potential and the Deuteron

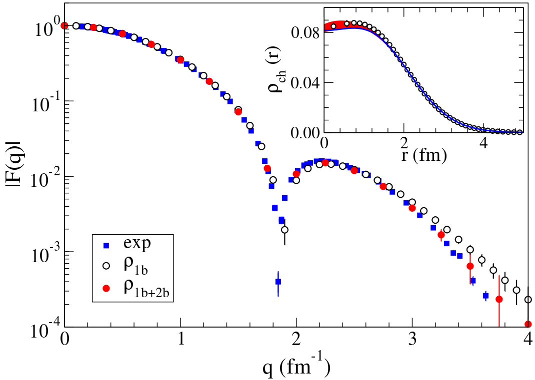
$M = \pm 1$ $\qquad$ $M = 0$



Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

Carlson and Schiavilla Rev.Mod.Phys.70(1998)743

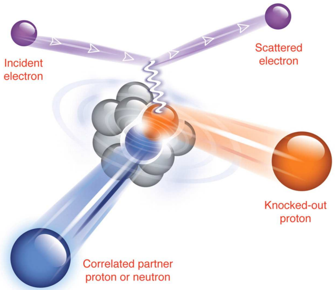
Shape of Nuclei

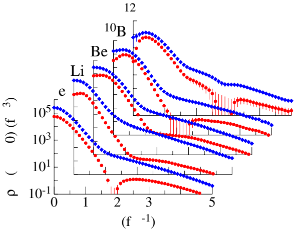


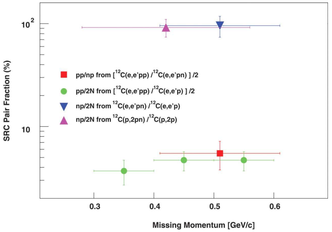
Lovato *et al.*

PRL111(2013)092501

Back-to-back *np* and *pp* Momentum Distributions





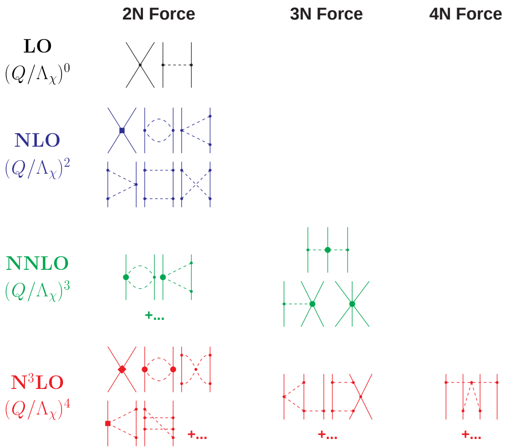


Wiringa *et al.* PRC89(2014)024305

JLab, Subedi *et al.* Science320(2008)1475

Nuclear properties are strongly affected by two-nucleon interactions!

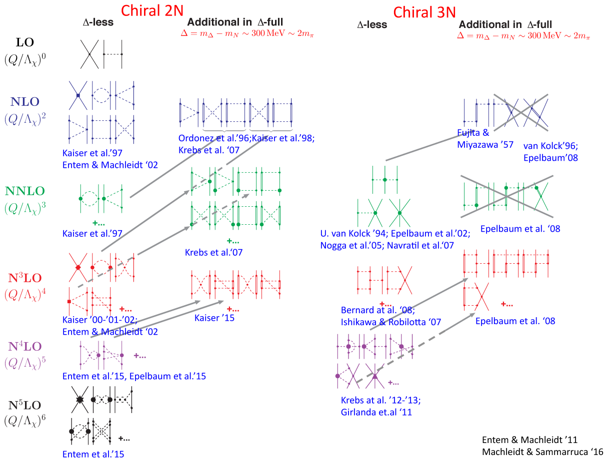
χEFT many-body potential: Hierarchy



Machleidt & Sammarruca - PhysicaScripta91(2016)083007

CT = Contact Term (short-range);
OPE = One Pion Exchange (range $\sim \frac{1}{m_\pi}$);
TPE = Two Pion Exchange (range $\sim \frac{1}{2m_\pi}$)

Nuclear Interactions and the role of the Δ



Courtesy of Maria Piarulli

* N3LO with Δ nucleon-nucleon interaction constructed by
Piarulli *et al.* in PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883 with $\Delta's$
fits ∼ 2000 (∼ 3000) data up 125 (200) MeV with χ^2/datum ∼ 1;
* N2LO with Δ 3-nucleon force fits ^{3}H binding energy and the *nd* scattering length

"Phenomenological" aka "Conventional" aka "Traditional" aka "Realistic" Two- and Three- Nucleon Potentials

L A AM LT A

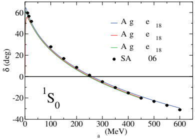
$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

K_i - e ati isti i eti e e g m_n-m_p effe ts i ded

A g e 18 $v_{ij} = v^{\gamma}_{ij} + v^{\pi}_{ij} + v^{I}_{ij} + v^{S}_{ij} = \sum v_p(r_{ij}) O^p_{ij}$

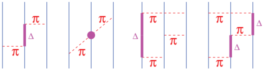
- 18 s i te s s i - it is s i et e at s
- f M a d st g a d SB te s i ded
- ed i a t a e at st t e
- ts i ege P A 3 data ith χ^2/d f 1 1

i i ga St s S hia i a P **51** (1 5)



a a i is $V_{ijk} = V^{2\pi}_{ijk} + V^{3\pi}_{ijk} + V^{R}_{ijk}$

- a a has sta da d 2π P- a e sh t- a ge e si f atte sat ati
- i is adds 2π S- a e 3π i gs t ide e t a T 3 2 i te a ti
- i is- has f a a ete s t t 23 e e s i $A \leq 10$ ei



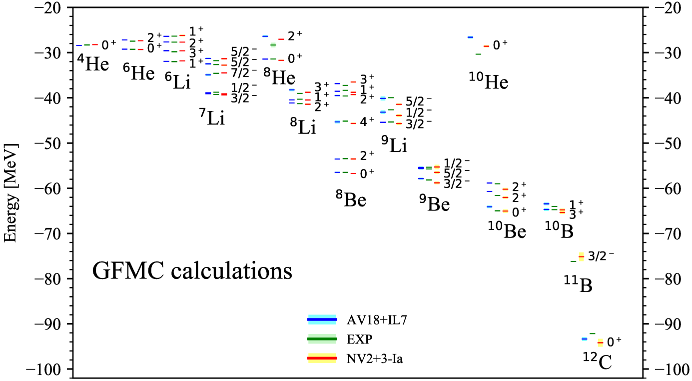
Pie e Pa dha i a de i i ga a s P **64** 014001 (2001)
Pie e A P P **1011** 143 (2008)

Courtesy of Bob Wiringa

* AV18 fitted up to 350 MeV, reproduces phase shifts up to ∼ 1 GeV *

* IL7 fitted to 23 energy levels, predicts hundreds of levels *

Spectra of Light Nuclei



M. Piarulli *et al.* - arXiv:1707.02883

* one-pion-exchange physics dominates *

* it is included in both chiral and “conventional” potentials *

Three-body forces

$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

$$V_{ijk} \sim (0.2 - 0.9)\, v_{ij} \sim (0.15 - 0.6)\, H$$

$$v_\pi \sim 0.83\, v_{ij}$$

^{10}B VMC code output

```
Ti + Vij =  -38.2131 (0.1433)          + Vijk =  -46.7975 (0.1150)

Ti   = 290.3220 (1.2932)  Vij  =-328.5351 (1.1983)  Vijk =  -8.5844 (0.0892)
```

Chiral Potentials (Incomplete List of Credits)

- $\ast$ van Kolck *et al.*; PRL72(1994)1982-PRC53(1996)2086
- $\ast$ Kaiser, Weise *et al.*; NPA625(1997)758-NPA637(1998)395
- $\ast$ Epelbaum, Glöckle, Meissner*; RevModPhys81(2009)1773 and references therein
- $\ast$ Entem and Machleidt*; PhysRept503(2011)1 and references therin

* Chiral Potentials suited for Quantum Monte Carlo calculations *

- $\ast$ Gezerlis *et al.* PRL111(2013)032501-PRC90(2014)054323;
  Lynn *et al.* PRL113(2014)192501
- $\ast$ Piarulli *et al.** PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883 (with $\Delta' s$)

* Potentials fitted and used in many-body calculations

* Observations *

- Nuclear two-body forces contain a number of parameters (up to ~ 40) fitted to a large $\sim 4k$ ($\sim 3k$) data base up to 350 (~ 200) MeV in the case of AV18 (Chiral) model
- Intermediate and long components are described in terms of one- and two-pion exchange potentials
- Short-range repulsion core described by Contact Terms in Chiral Formulations and special functions in AV18
- Chiral Formulation requires a study of variation with respect to cut off
- The AV18 has fixed cutoffs
- Due to a cancellation between kinetic and two-body contribution, three-body potentials are necessary to reach agreement with the data
- Three-body potentials Illinois fitted to 23 energy levels predicts hundreds levels
- Three-body potentials Chiral fitted to triton binding energy and *nd*-scattering length only! Strong validation of the Microscopic picture of the nucleus

Observations continuation

* Chiral Effective Field Theory *

- * Chiral Formulation of Nuclear Physics is extremely successful
- * But limited to low-energies ($\sim$ 200 MeV)
- * Inclusion of the Δ possibly allows for applications to higher energies

* "Conventional" Formulation *

- * "Conventional" Formulation of Nuclear Physics is extremely successful
- * But hard to be systematically improved
- * "Conventional" AV18 Interaction has a range of applicability as $\sim$ 1 GeV

Fundamental Physics with Electroweak Probes of Light Nuclei

June 12 - July 13, 2018

S. Bacca, R. J. Hill, S. Pastore, D. Phillips

Contacts

http://www.int.washington.edu/

saori.pastore@gmail.com

saori@lanl.gov

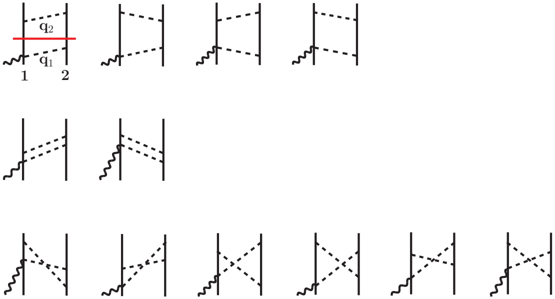
Technicalities I: Reducible Contributions

4 interaction Hamiltonians $\longrightarrow$ 4! time ordered diagrams

Reducible

Irreducible direct

Irreducible crossed



$$
\begin{aligned}
|\Psi\rangle &\simeq |\phi\rangle + \frac{1}{E_i - H_0}\upsilon^{\pi}|\phi\rangle + \dots \\
\langle \Psi_f|\mathbf{j}|\Psi_i\rangle &\simeq \langle\phi_f|\mathbf{j}|\phi_i\rangle + \langle\phi_f|\upsilon^{\pi}\frac{1}{E_i - H_0}\mathbf{j} + \text{h.c.}|\phi_i\rangle + \dots
\end{aligned}
$$

* Need to carefully subtract contributions generated by the iterated solution of the Schrödinger equation