Overview of low energy NN and few nucleon systems

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- Lecture I
  - General structure of the NN potential
  - Historical development
- Lecture II
  - Basics on chiral EFT
  - $\not\pi$ EFT

References

- R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989),
- R. Machleidt and I. Slaus, J. Phys. **G27**, R69 (2001), arXiv: nucl-th/0101056,
- S. Scherer, Adv. Nucl. Phys. **27** (2003), arXiv: hep-ph/0210398,
- V. Bernard, N. Kaiser, Ulf-G. Meißner, Int.J.Mod.Phys. **E4**, 193 (1995), arXiv: hep-ph/9501384,
- José Goity's lectures on χPT, HUGS 2004

  http://www.jlab.org/hugs/archive/Schedule2004/background.html,
- QFT: Craig Roberts' lectures

Structure of the NN potential

- nucleon: spin 1/2, isospin 1/2

$$
\begin{aligned}
|1/2\rangle \otimes |1/2\rangle \quad = \quad & \sqrt{1/2}\,[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle]\,, \qquad \text{(singlet)} & (1) \\
& |\uparrow\uparrow\rangle\,, \\
& \sqrt{1/2}\,[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]\,, \qquad \text{(triplet)} & (2) \\
& |\downarrow\downarrow\rangle\,.
\end{aligned}
$$

$$
P^1 = \frac{1}{4}\Big[1 - \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)}\Big]\,, \qquad P^3 = \frac{1}{4}\Big[3 + \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)}\Big]\,. \qquad (3)
$$

- Exercise: show that the above formulas work.

$$V_{NN} = \sum_{\alpha,\beta} V^{\alpha\beta} P_\sigma^\alpha P_\tau^\beta = V_{NN}^+ + \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \, V_{NN}^- \tag{4}$$

$$V_{NN}^\pm = V_C^\pm \, \Omega_C + V_{LS}^\pm \, \Omega_{LS} + V_T^\pm \, \Omega_T + V_{SS}^\pm \, \Omega_{SS} + V_Q^\pm \, \Omega_Q \tag{5}$$

$$(\boldsymbol{q} = \boldsymbol{p}' - \boldsymbol{p} \,, \quad \boldsymbol{z} = \boldsymbol{p}' + \boldsymbol{p})$$

$$\begin{aligned}
\Omega_C &= \mathbf{1} \\
\Omega_{LS} &= \frac{i}{4}(\boldsymbol{\sigma}^{(1)} + \boldsymbol{\sigma}^{(2)}) \cdot \boldsymbol{q} \times \boldsymbol{z} \\
\Omega_T &= \boldsymbol{q}^2 \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - 3\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{q} \boldsymbol{\sigma}^{(2)} \cdot \boldsymbol{q} \\
\Omega_{SS} &= \boldsymbol{q}^2 \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} \\
\Omega_Q &= \boldsymbol{\sigma}^{(1)} \cdot (\boldsymbol{q} \times \boldsymbol{z}) \boldsymbol{\sigma}^{(2)} \cdot (\boldsymbol{q} \times \boldsymbol{z})
\end{aligned} \tag{6}$$

- $J = L \oplus S$
- NN states labeled by $|j\,(j_3), l, s\rangle$
- eigenstates of the operators shown before, except Ω_T!
- for a given j: $|j, l = j, s\rangle$, $|j, l = j-1, s=1\rangle$, $|j, l = j+1, s=1\rangle$.

Back in history...

- 35: OPE $\longrightarrow$ Yukawa
- 37: Anderson and Nedemeyer - discovery of the "meson μ" ($\sim$ 107MeV)
- 40s: Yukawa, Schwinger, Bethe, Breit, Rosenfeld

  $\Rightarrow$ theoretical aspects of πN coupling, speculation about other particles

$$\mathcal{L}_{\pi N}^{PS} = -g\bar{N}\left(\sqrt{f_\pi^2 - \boldsymbol{\pi}^2} + i\boldsymbol{\tau}\cdot\boldsymbol{\pi}\gamma_5\right)N\,, \tag{7}$$

$$\mathcal{L}_{\pi N}^{PV} = -\frac{1}{4f_\pi^2}\bar{N}\gamma^\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N + \frac{g_A}{2f_\pi}\bar{N}\gamma^\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N\,. \tag{8}$$

- Exercise: show that both interactions lead to the same OPE amplitude.

- 47: Pancini and Piccioni - μ interacts weakly!

  Lattes and Occhialini - π meson ($\sim$ 140MeV)

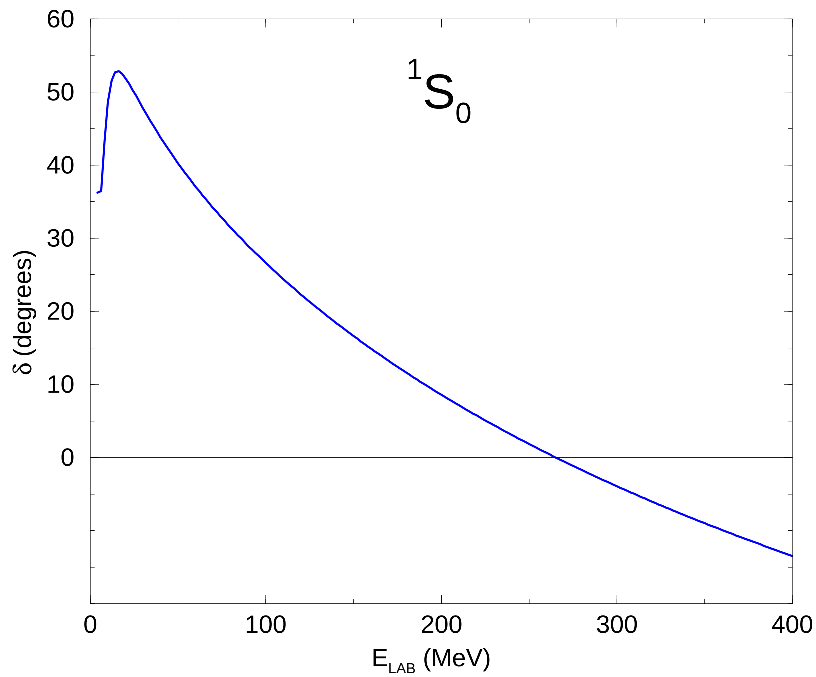
- 48: Confirmed @ Berkeley (Gardner and Lattes, Science)

- in the following 10 years it became more and more evident the necessity of the OPE to describe the long range NN interaction

- 51: Taketani, Nakamura, and Sasaki - NN interaction divided in layers:

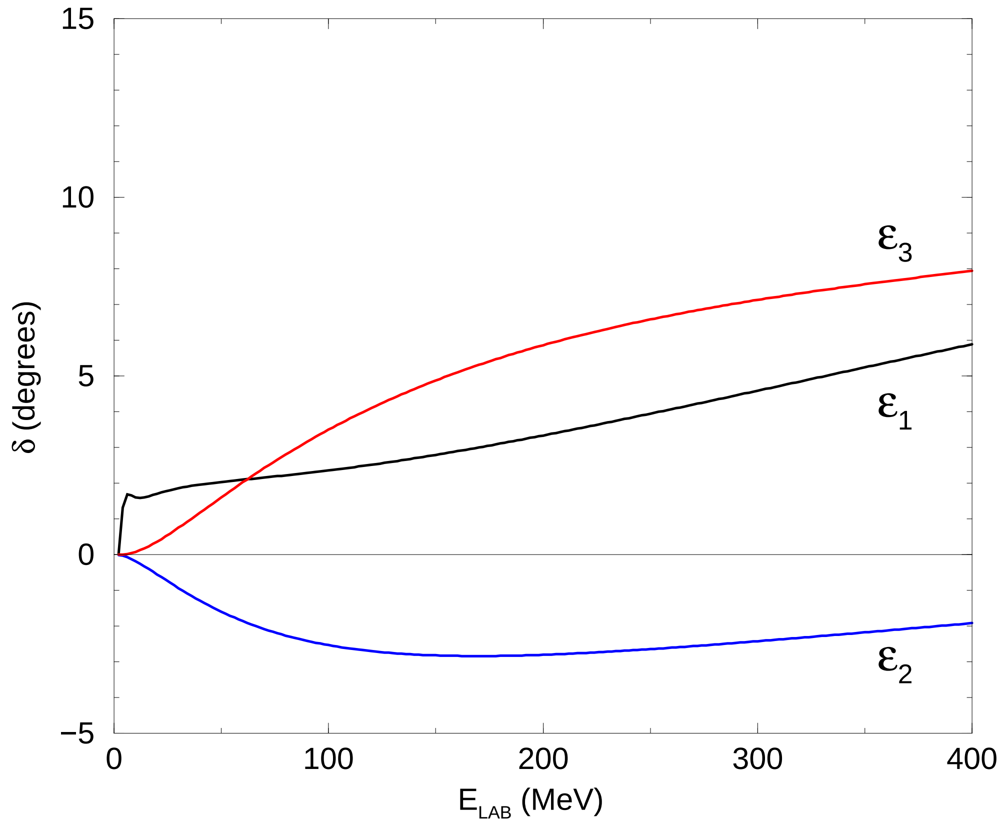
  ⋆ long range $\Rightarrow$ OPE ($r > 2$fm),
  ⋆ "dynamical" region (1fm$< r < 2$fm),
  ⋆ "phenomenological" region ($r < 1$fm).

  Dissolve



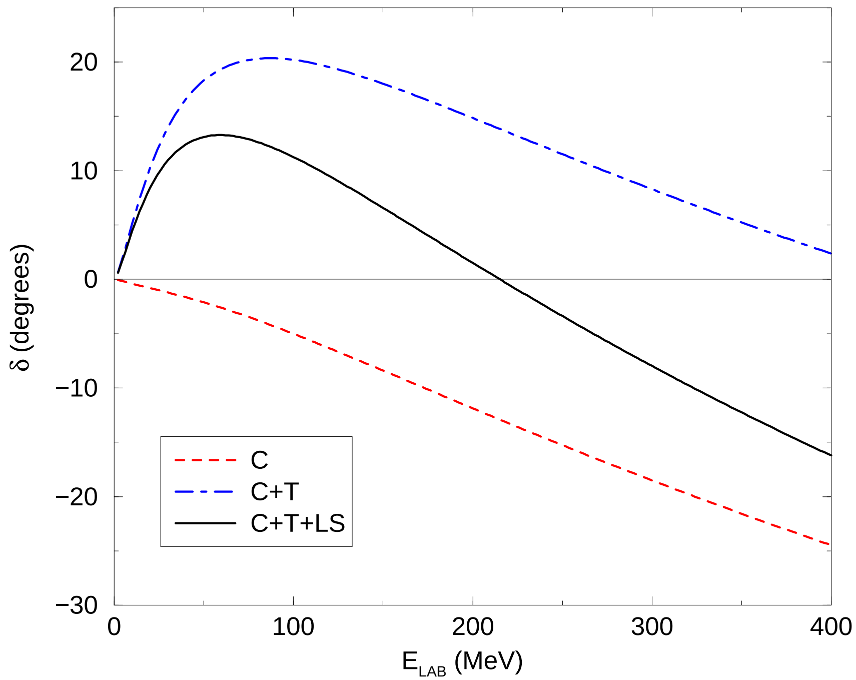
- Iwadare *et.al.* (56), Wong (59): quadrupole moment and η (asymptotic ratio D/S wave function) of the deuteron as strong evidences for OPE

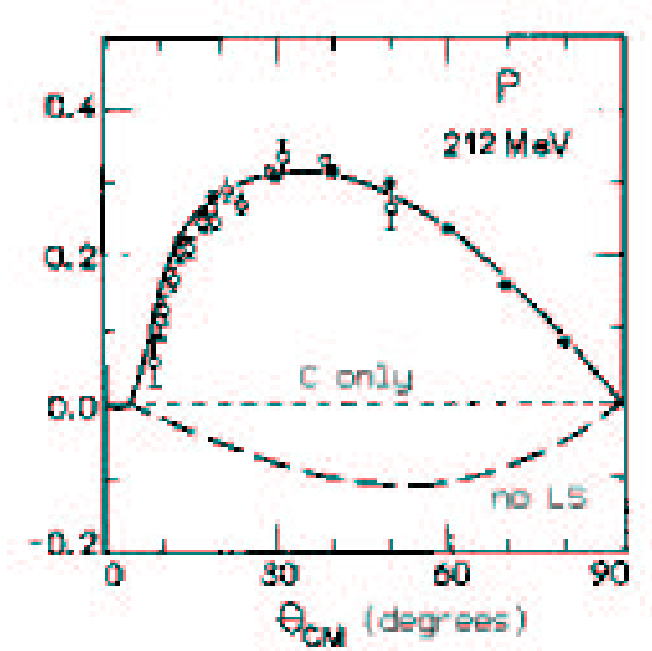
- Evidence of tensor forces: mixing parameter ϵ in PWA Dissolve



- Gammel and Thaler (57) - first phenomenological NN potential

  $\Rightarrow$ need for a spin-orbit term





- Mayer and Jensen (49, 55) - spin-orbit plays a major role in the nuclear shell model

- Hamada and Johnston (62), Yale (62), Reid (68) - OPE $+$ phenomenology (30-50 parameters)

- TPE: bad start

  ⋆ Taketani, Machida, and Onuma (50) vs. Brueckner and Watson (51) - complete disagreement

- OBE saves the program (Breit, Nambu, Sakurai, Frazer and Fulco):

  exchanges of bosons - ρ, ω, σ, ϵ

  ⋆ very good description of NN data (mid 70s)
  ⋆ few parameters ($\sim$ 10)
  ⋆ downside: does it correspond to nature?

- non-relativistic: Nijmegen group

- relativistic: Thompson, Bonn group, Tjon, Gross, van Orden

- Dispersion Relations
  - ⋆ Chemtob, Durso, and Riska (72), Stony Brook group (75)
    10 years of work, semi-quantitative results
  - ⋆ Lacombe *et.al.* (75), Vinh Mau (79) - significant improvement
  - ⋆ not only DRs, a lot of phenomenology

- Field Theory
  - ⋆ Partovi and Lomon (70): 3D reduction of the Bethe-Salpeter equation (Blankenbecler and Sugar prescription)
  - ⋆ Bonn potential (87): OPE + TPE (uncorrelated, correlated, plus delta) + $\sim 3\pi$ $(\pi\rho)$ + $\sim 4\pi$ $(\pi\omega)$, a dozen of parameters, and a good fit to data.

- Phenomenological potentials
  - ⋆ Lagaris and Pandharipande (81), de Tourreil and Sprung (73), Wiringa *et.al.* (84).

- 80s: derive the NN interaction from quark degrees of freedom
- QCD-inspired, soliton models (Skirmions)
- quark models
  - ⋆ MIT bag (Chodos *et.al.*) , chiral bag (Brown and Rho) , cloudy bag (Thomas and Miller) , qq potentials (Isgur and Karl, Glozman *et.al.*, Faessler *et.al.*).
- these models reached the 90s with only a very few quantitative features of nuclear forces
- 00s: more sofisticated methods (will they describe NN interactions?)
  - ⋆ Spectator approach (Gross, Agbakpe)
  - ⋆ Dyson-Schwinger Equations (Roberts, Maris, Tandy)

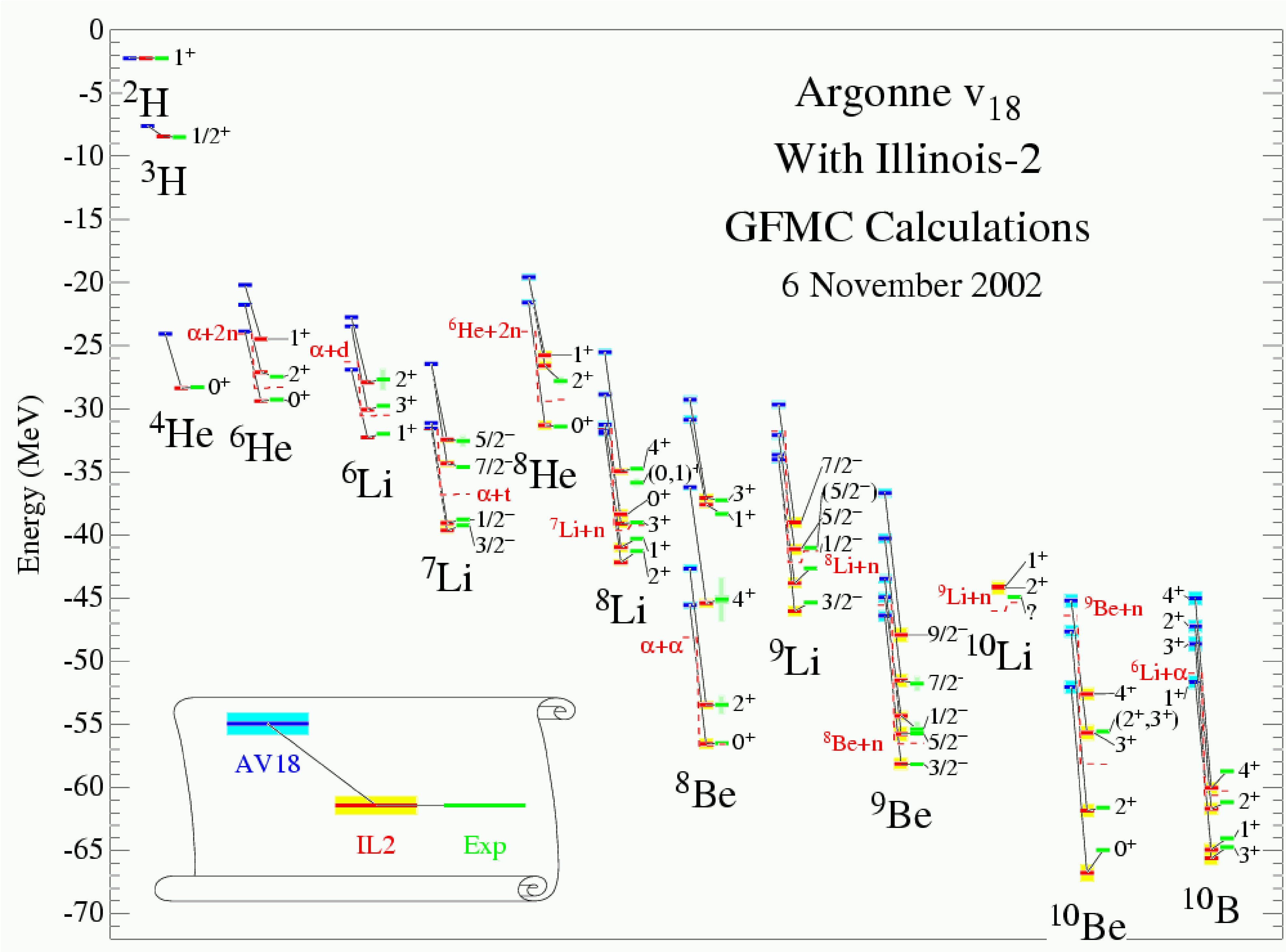
- 90s: high-precision NN potentials
  - ⋆ coulomb and magnetic moment interactions
  - ⋆ proton-neutron mass difference
  - ⋆ $\pi^{\pm}$ - π^{0} mass difference

- more accurate NN scattering data

- Reid93, Nijmegen I and II , Argonne v18 , CD-Bonn , Chiral NN potentials

- χ^2/datum $\sim$1 , looking at small details
  - ⋆ a_{nn} - a_{pp} difference (CSB)
  - ⋆ (a_{nn}, a_{pp}) - a_{np} difference (CIB)
  - ⋆ charge dependence of $g_{\pi N}$?

- Three nucleon forces: Fujita and Miyazawa (57) , Tucson-Melbourne (Coon *et.al.*, 79) , Brazilian (Coelho, Das, Robilotta, 83) , Texas (Friar, Hüber, van Kolck, 99) , Illinois (Pieper, Pandharipande, Wiringa, Carlson, 97 - 01)



Argonne v18
With Illinois-2
GFMC Calculations
6 November 2002
Energy (MeV)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
2H
3H
4He
6He
6Li
7Li
8He
8Li
8Be
9Li
9Be
10Li
10Be
10B
α+2n
α+d
α+t
6He+2n
7Li+n
α+α
8Li+n
8Be+n
9Li+n
9Be+n
6Li+α
AV18
IL2
Exp