Nuclear forces and their impact on structure, reactions and astrophysics

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Lectures for Week 1

M. QCD 1 (as); Scattering theory 1 (rjf)

T. Nuclear forces 1 (rjf); Scattering theory 2 (as)

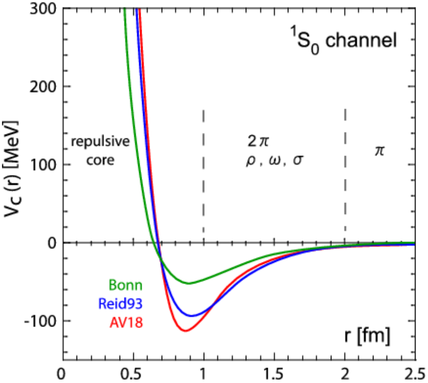
W. Nuclear forces 2 (rjf); Renormalization and Universality (as)

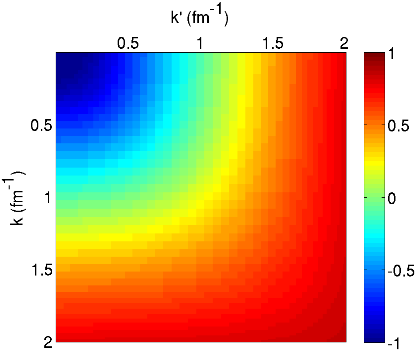
Th. Cold atoms and neutrons, QMC (ag);
Tensor/spin-orbit forces, deuteron properties (rjf)

F. QMC and chiral EFT interactions (ag);
Three-body forces and halo nuclei (as)

Outline

AV18


300
200
100
0
-100
Vc (r) [MeV]
$^1S_0$ channel
repulsive core
2 π
ρ, ω, σ
π
Bonn
Reid93
AV18
r [fm]
0
0.5
1
1.5
2
2.5


k' (fm^{-1})
0.5
1
1.5
2
k (fm^{-1})
0.5
1
1.5
2
1
0.5
0
-0.5
-1

Example: coordinate basis for *local* one-body potential

- Discretize $0 \leq r \leq R_{\rm max}$ with $r_i = i \times h$, where $h = R_{\rm max}/N$
- We can approximate the Schrödinger equation at point r_k as

$$-\frac{\hbar^2}{2M}\frac{u(r_k+h) - 2u(r_k) + u(r_k-h)}{h^2} + V(r_k)u(r_k) = Eu(r_k) \; .$$

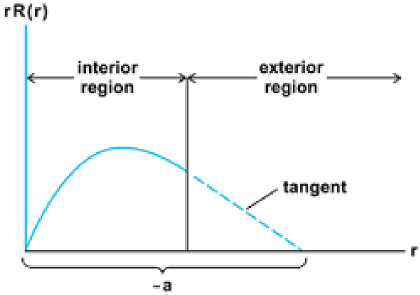
$$\text{or} \qquad -\frac{u_{k+1} - 2u_k + u_{k-1}}{h^2} + V_k u_k = Eu_k \; .$$

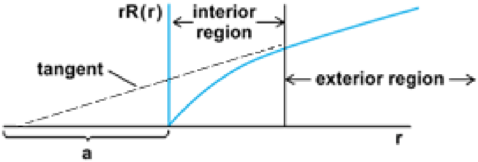
- In matrix form with $u_0 = 0$, $u_N \approx 0$, this is tri-diagonal $(\hbar = 2M = 1)$:

$$\begin{pmatrix} \frac{2}{h^2} + V_1 & -\frac{1}{h^2} & 0 & \cdots & 0 \\ -\frac{1}{h^2} & \frac{2}{h^2} + V_2 & -\frac{1}{h^2} & & \vdots \\ 0 & -\frac{1}{h^2} & \ddots & & \vdots \\ \vdots & & & \ddots & -\frac{1}{h^2} \\ 0 & \cdots & \cdots & -\frac{1}{h^2} & \frac{2}{h^2} + V_{N-1} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ \vdots \\ u_{N-1} \end{pmatrix} = E \begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ \vdots \\ u_{N-1} \end{pmatrix}$$

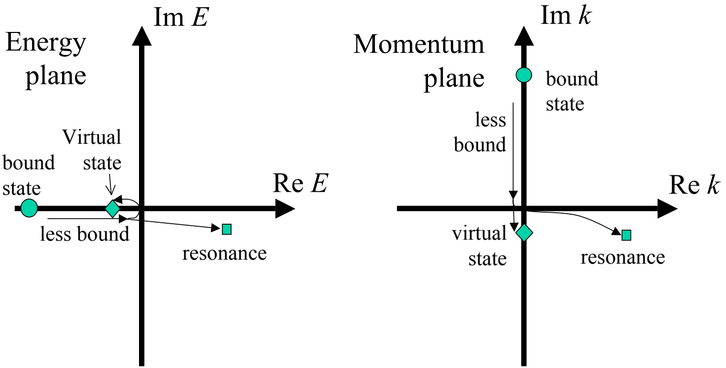
- If V is *non-local*, it has off-diagonal matrix elements in this basis

Identifying the S-wave scattering length a_0





From Filomena Nunes notes

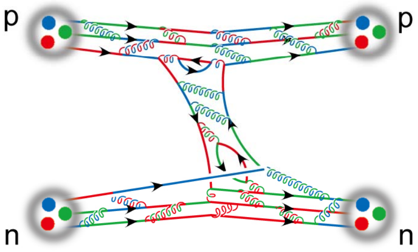


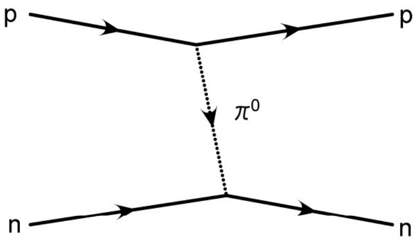
Outline

Scattering theory 1

Nuclear forces 1

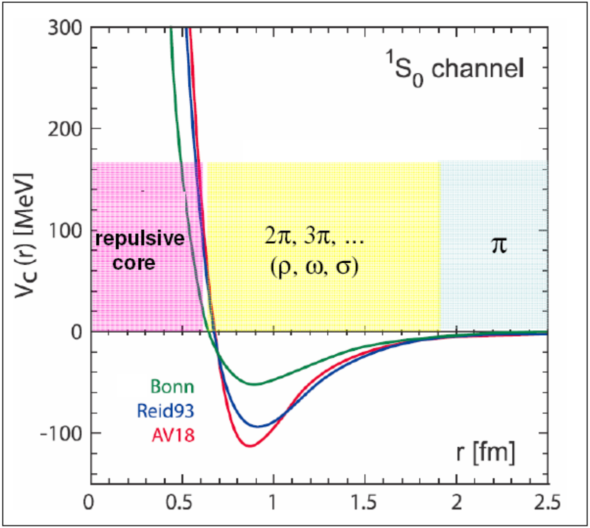
Quark (QCD) vs. hadronic NN interaction





- Old goal: replace hadronic descriptions at ordinary nuclear densities with quark description (since QCD is *the* theory)
- New goal: use hadronic dof's *systematically* at low E
  - Seek model independence and theory error estimates
  - Future: Use lattice QCD to match via "low-energy constants"

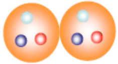
“Traditional” nucleon-nucleon interaction (from T. Papenbrock)



From T. Hatsuda (Oslo 2008)

One-pion exchange by Yukawa (1935)

Multi-pions by Taketani (1951)



Repulsive core by Jastrow (1951)

Effective theories [H. Georgi, Ann. Rev. Nucl. Part. Sci. 43, 209 (1993)]

- *One of the most astonishing things about the world in which we live is that there seems to be interesting physics at all scales.*
- *To do physics amid this remarkable richness, it is convenient to be able to isolate a set of phenomena from all the rest, so that we can describe it without having to understand everything. Fortunately, this is often possible. We can divide up the parameter space of the world into different regions, in each of which there is a different appropriate description of the important physics. Such an appropriate description of the important physics is an "effective theory."*
- *The common idea is that if there are parameters that are very large or very small compared to the physical quantities (with the same dimension) that we are interested in, we may get a simpler approximate description of the physics by setting the small parameters to zero and the large parameters to infinity. Then the finite effects of the parameters can be included as small perturbations about this simple approximate starting point.*
- E.g., non-relativistic QM: $c \to \infty$
- E.g., chiral effective *field* theory (EFT): $m_\pi \to 0$, $M_N \to \infty$
- Features: model independence (completeness) and error estimates