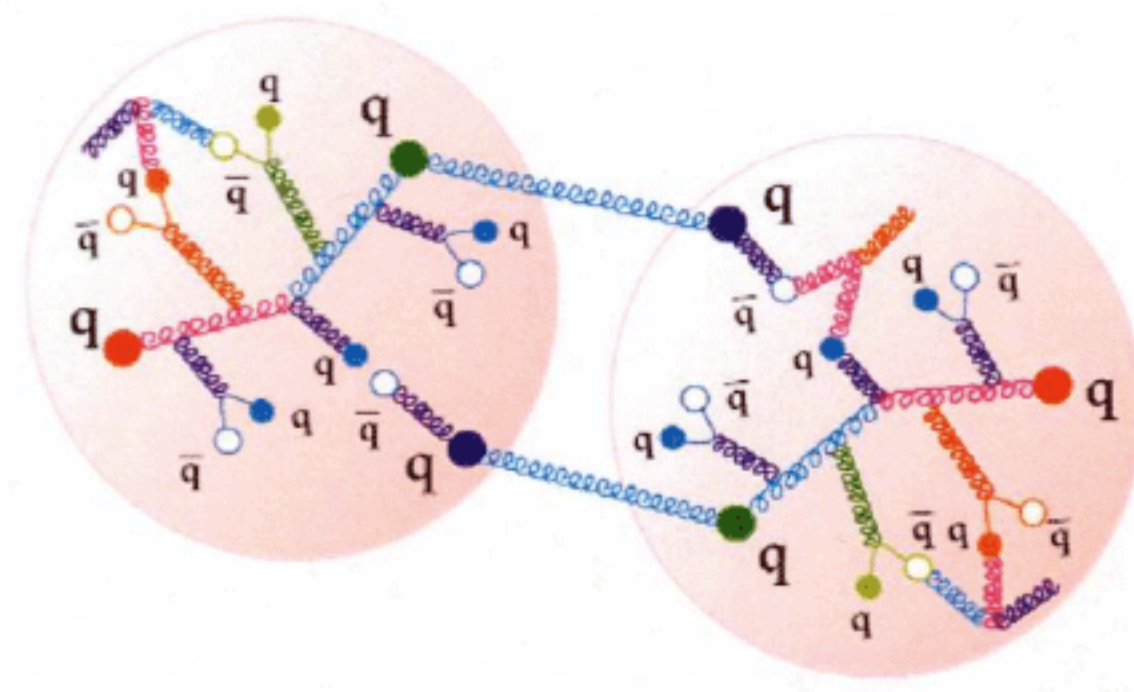
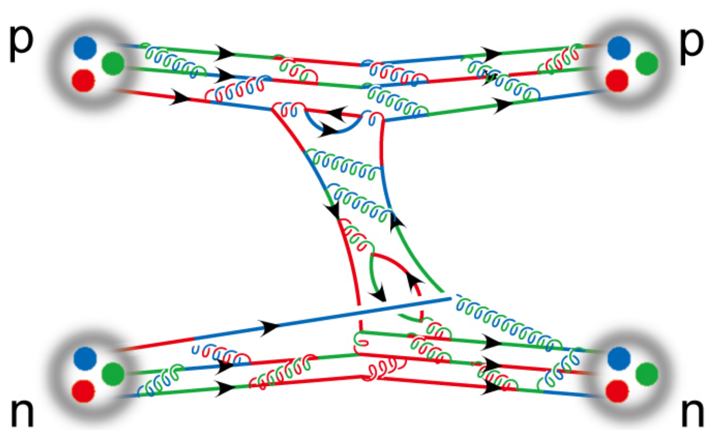
May the Strong Force be with you

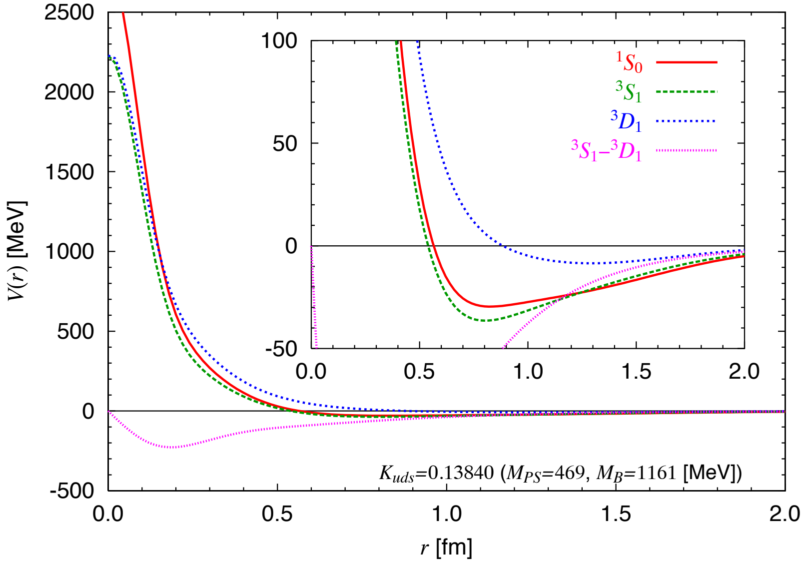
Origin of the nucleon-nucleon force



The simplest contributions to the force between nucleons, as viewed from QCD. Here, the exchange of two colored gluons causes two quarks in each nucleon to change their colors (blue changes to green and vice versa in the case illustrated). This process produces a force without violating the overall color neutrality of the nucleons. The strength of the force depends on the separation of the different quark colors within each nucleon. On the other hand, low-energy nuclear physics measurements show clearly that the longest-range part of the force arises from the exchange of a single pi meson between two nucleons, as in In this low-energy view, the internal structure of each nucleon is generally attributed to three pseudo-quarks, which somehow combine the properties of the valence quarks, sea quarks, and gluons predicted by QCD.

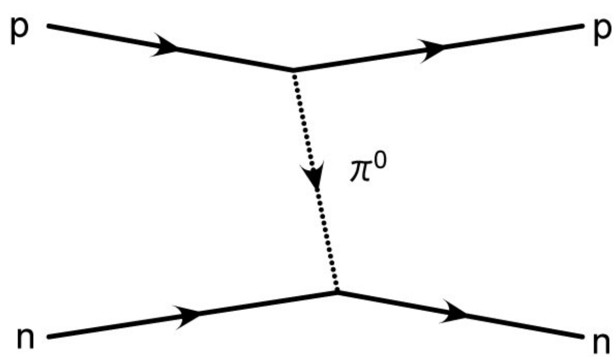
The challenge and the prospect: physics of nuclei directly from QCD





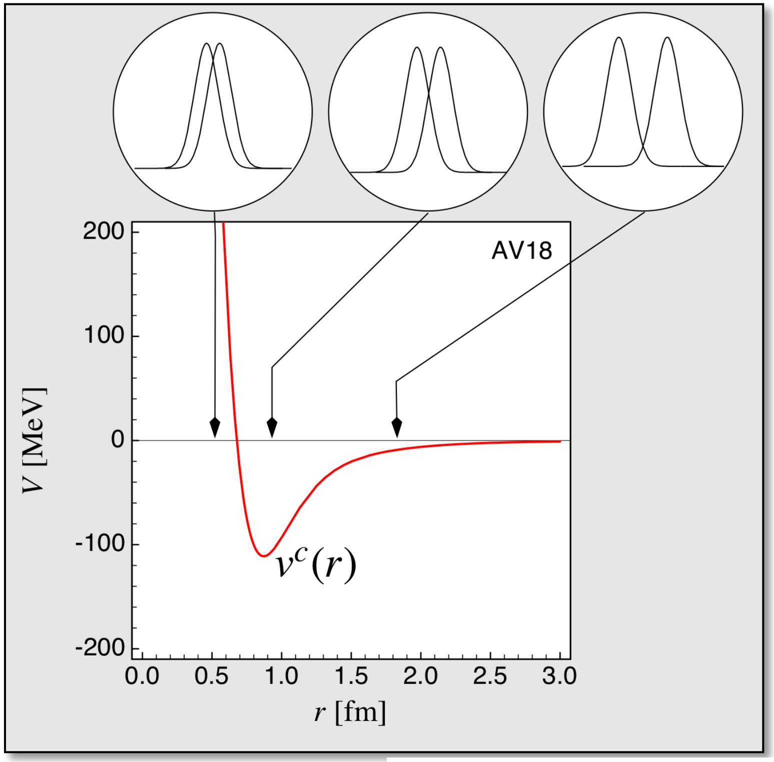
Nuclear Force from Lattice QCD

Inoue et al. PRL 111, 112503 (2013); HALQCD/HPCI



The interaction between two nucleons is effected by the exchange of a particle. However, because the nucleon interactions appear to be short-ranged, the particle must have a finite mass. In fact, one can correlate the range and mass roughly by the quantum uncertainty principle, *$r \sim 1/m$*, therefore, the mass of the quanta exchanged is about 1/fm which is about 200 MeV.

Nuclear force



A realistic nuclear force force: schematic view

- Nucleon r.m.s. radius ~0.86 fm
- Comparable with interaction range
- Half-density overlap at max. attarction
- V_{NN} not fundamental (more like inter-molecular van der Waals interaction)
- Since nucleons are composite objects, three-and higher-body forces are expected.

$$v_\pi(\mathbf{r}) = \frac{f^2_{\pi NN}}{4\pi}\frac{m_\pi}{3}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\left[T_\pi(r)S_{12} + [Y_\pi(r) - \frac{4\pi}{m^3_\pi}\delta(\mathbf{r})]\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right] ,$$

where $Y_\pi(r)$ and $T_\pi(r)$ are dimensionless functions of $m_\pi r$ defined as

OPEP: One-pion-exchange potential (at large distances)

$$Y_\pi(r) = \frac{e^{-m_\pi r}}{m_\pi r} ,$$

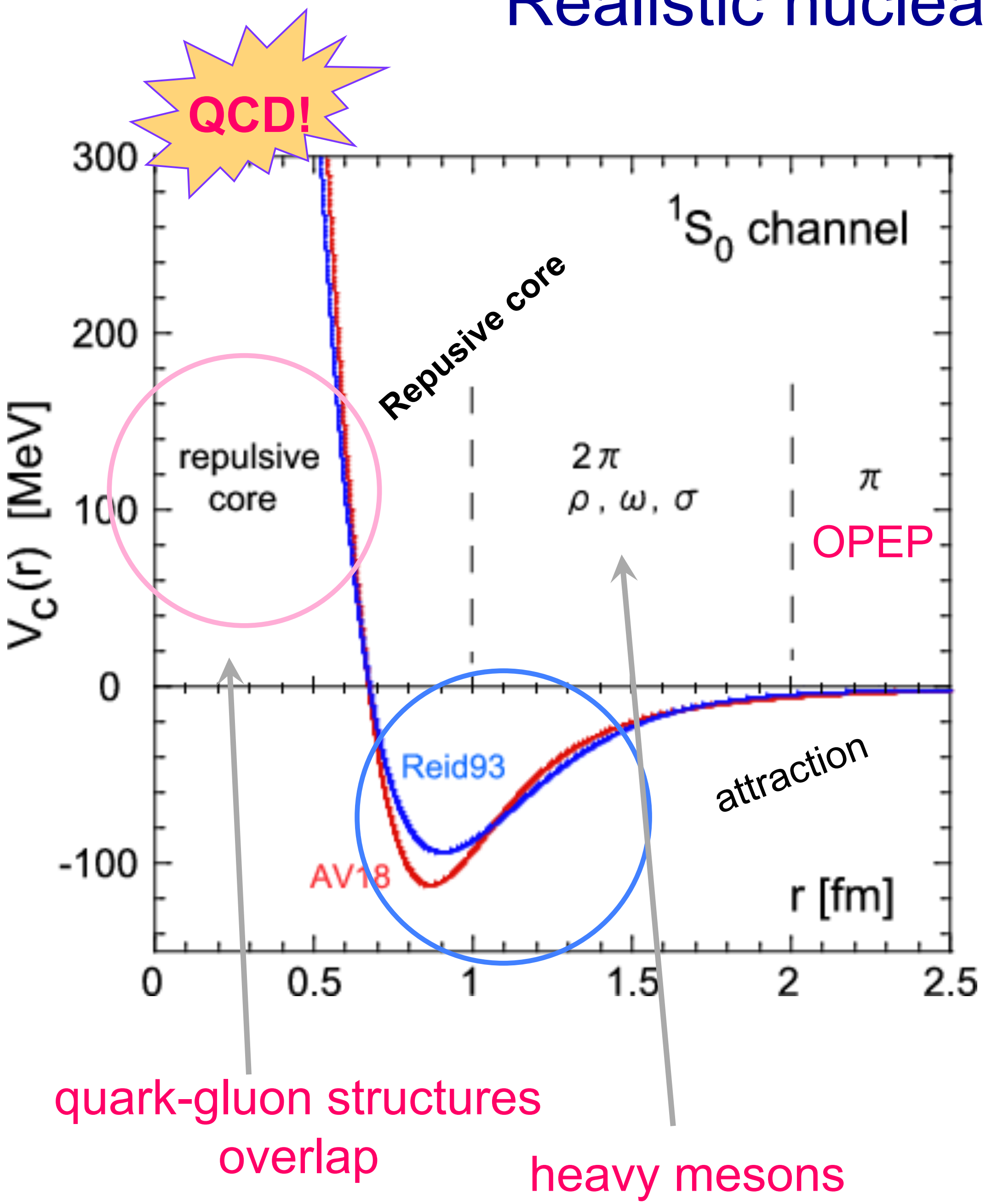
Yukawa force

$$T_\pi(r) = \left(1 + \frac{3}{m_\pi r} + \frac{3}{m^2_\pi r^2}\right) Y_\pi(r) ,$$

and S_{12} is the tensor operator,

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

Realistic nuclear force



There are infinitely many equivalent nuclear potentials!

$$\hat{H}\Psi = E\Psi$$

$$(\hat{U}\hat{H}\hat{U}^{-1})\hat{U}\Psi = E\hat{U}\Psi$$

Reid93 is from
V.G.J.Stoks et al., PRC**49**, 2950 (1994).

AV16 is from
R.B.Wiringa et al., PRC**51**, 38 (1995).

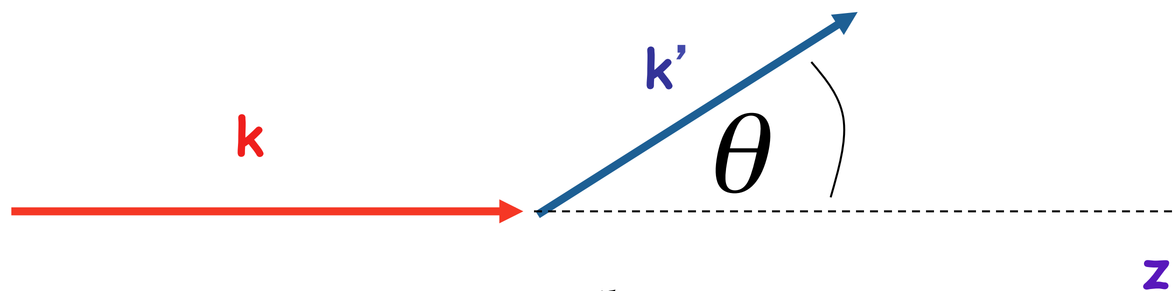
Nucleon-nucleon scattering

pp, np, nn scattering in T=0, 1 channels

- pp scattering easy
- neutron beams (np,nn) and neutron targets (pn,nn) difficult

^{7}Li(p,n), reactors

short neutron lifetime (~10min); deuteron - a substitute (pp and 3N effects have to be subtracted)



$$\psi(r,\theta) \xrightarrow[r\to\infty]{} e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

$$\frac{d\sigma}{d\Omega} = \left|f(\theta,\varphi)\right|^2 \qquad k = \frac{1}{\lambda\!\!\!^{-}} = \frac{|\vec{p}|}{\hbar} = \frac{\sqrt{2\mu E}}{\hbar}$$

Elastic scattering (the same value of k) valid for short-ranged potentials (V=0 at large r); Coulomb contribution must be removed