Role of high momentum transfer in low-energy nuclear physics

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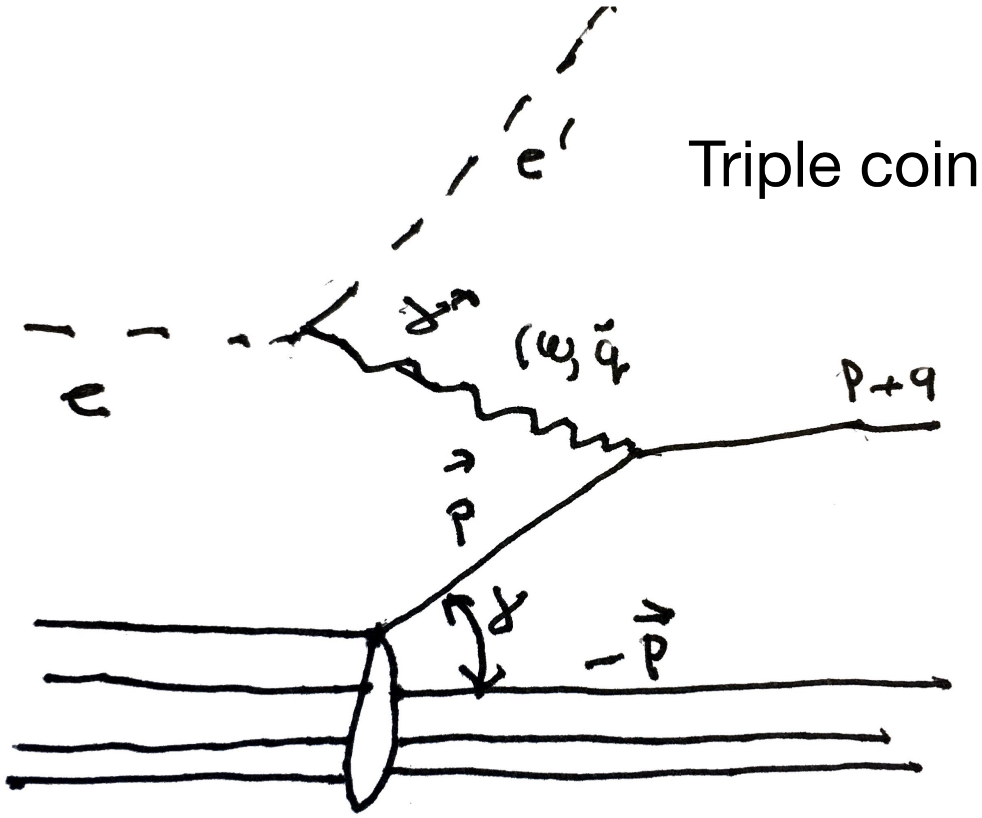
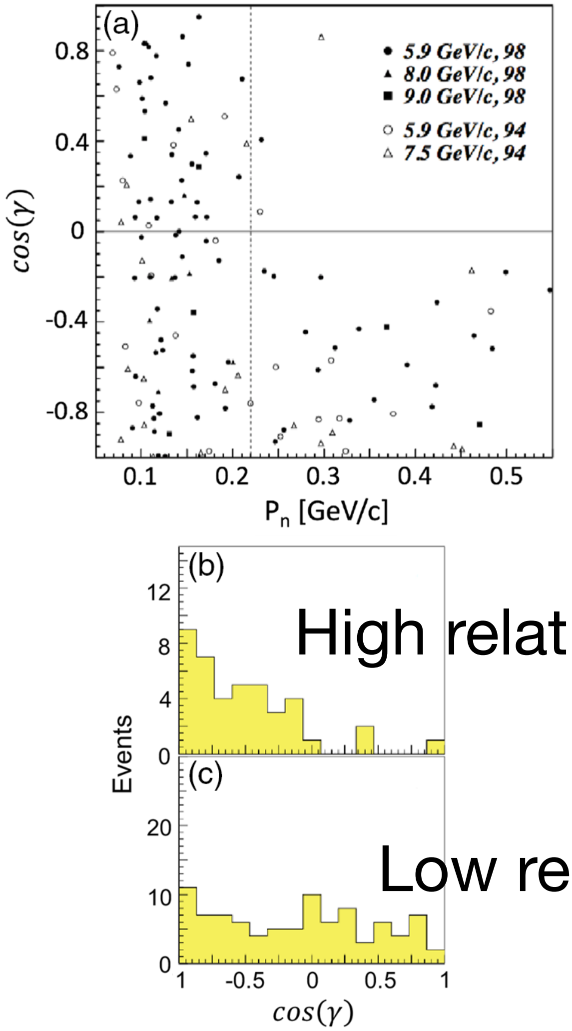
Experiments measure configurations in which two bound nucleons have high relative momenta

(p,ppn)



Triple coincidence



High relative momenta

Low relative momenta

(e,e'p,n) Associate high relative momenta with short relative distances

15-20 % of nucleon in a short-ranged correlated pair

Small relative distances- short ranged correlations

SRC- can be measured? Why & when important?

- Why ask? Wave functions can't be measured, src are part of wave function

- Furnstahl & Schwenk J. Phys. G37,064004(2010) -"systematic framework needed to address questions such as whether short-range correlations are important for nuclear structure"

- Examples: momentum-space wave functions are closely connected to cross sections: photoabsoprtion cross section on hydrogen proportional to square of wave function -Sakurai QM text. Modern version: Angle resolved photoemission spectroscopy, gives electron wave functions in solids RMP75,473.

Wave functions **can** be determined.

Perhaps the only difference between atomic physics and nuclear physics is that the interaction is known in the former case.

My opinion- SRC can be measured
+ they are important in certain processes

Why?-remainder of this talk

G A Miller, PRC 102,055206 (2020)
2008.06524 [nucl-th]

Modern EFT vs nuclear physics

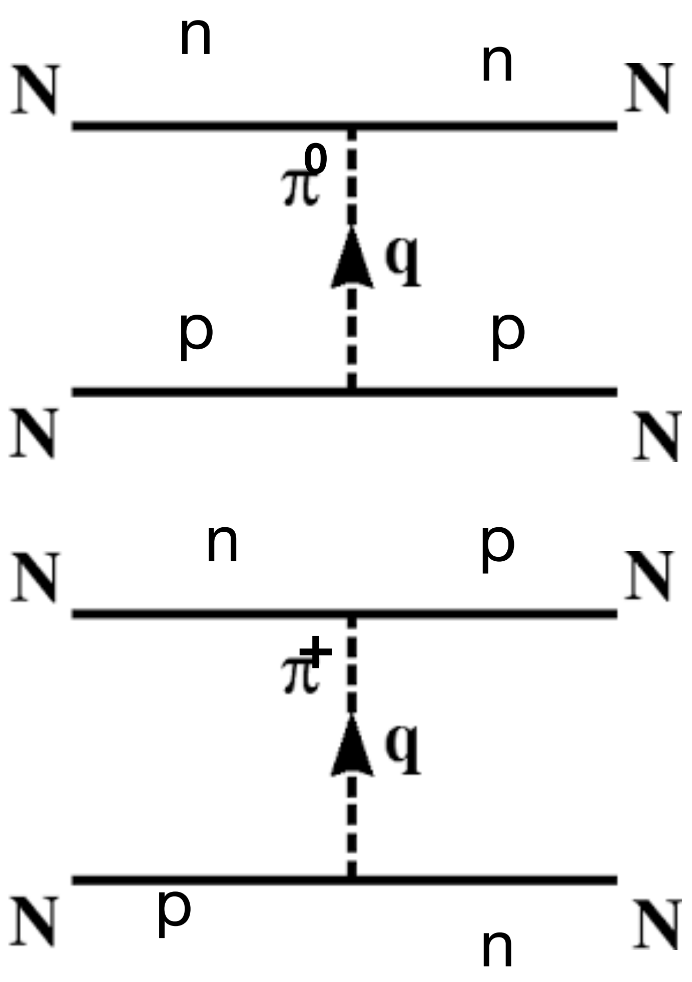
- If there are parameters that are very large or very small, get simpler approximate description by setting large parameters to ∞ and small parameter to 0
- Finite effects of large parameters included in pert. Theory. Example: low-energy weak interaction: W&Z exchange is contact interaction
- EFT uses scale separation- must be large for EFT to work
- Nuclear physics scales: nuclear radius $R_A \sim 5\,\mathrm{fm}$, average separation distance between nucleons $d \approx 1.7\,\mathrm{fm} \sim 1/\mathrm{m}_\pi \approx 1.4\,\mathrm{fm}$,$r_N$ $\mathrm{nucleon\ radius} = 0.84\mathrm{fm}$
- Nuclear scales are about the same-no scale separation
- **We must treat all scales**

Next step - quick review of nucleon-nucleon scattering
Basic features hit you in the face

One pion exchange (OPE)

np scattering

Symmetry about 90



Forward scattering looks like backward scattering

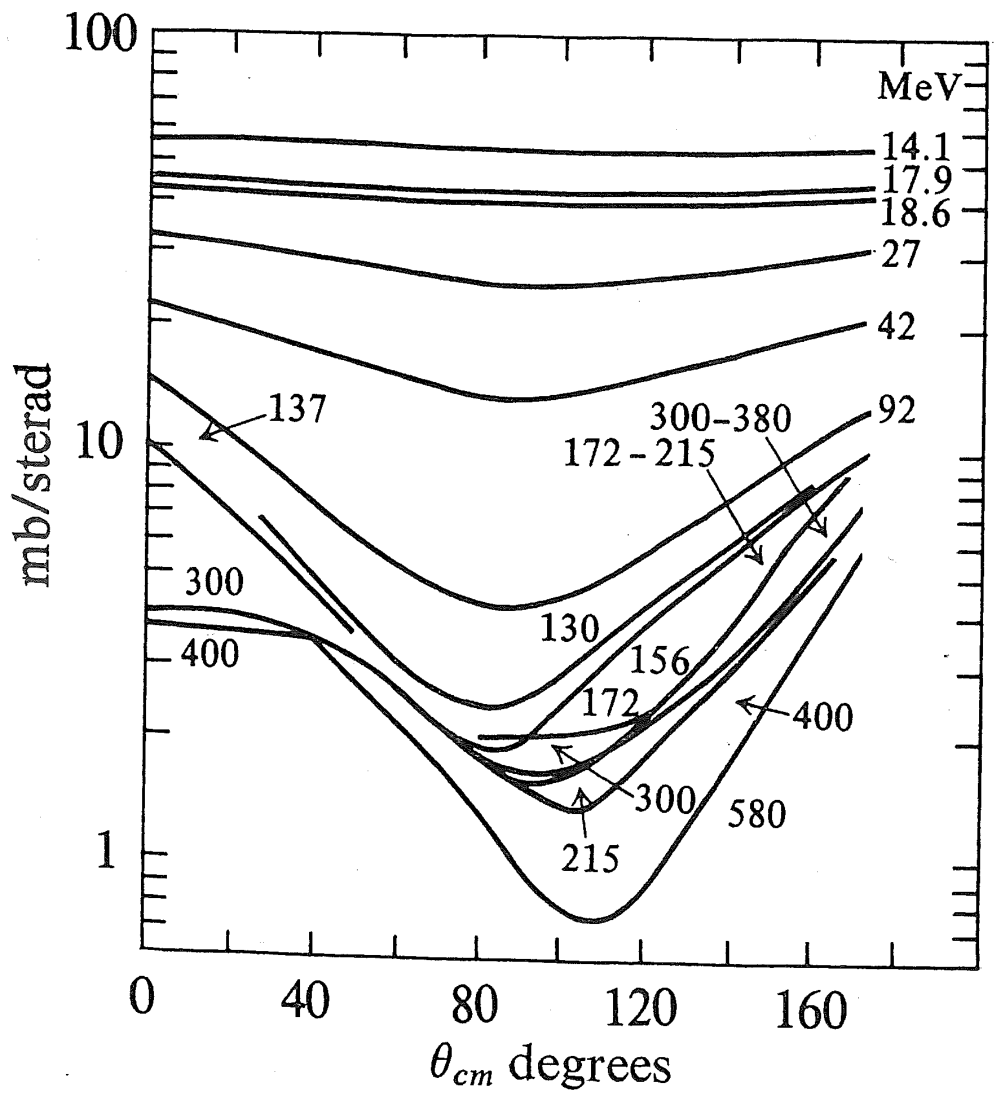


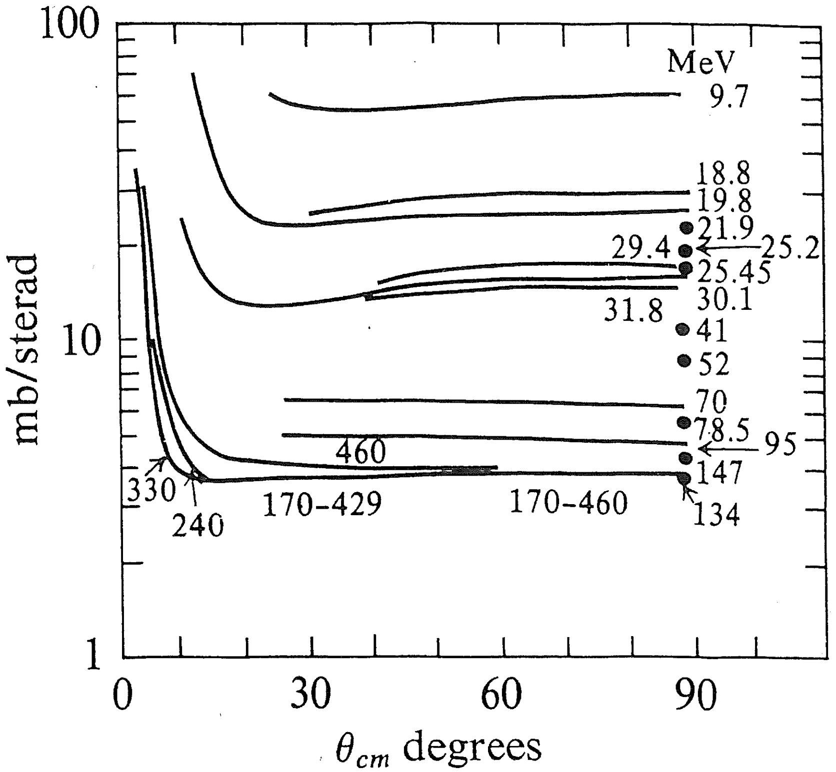
Fig. 38.1 Experimental *n-p* differential cross section in the center-of-momentum system at various laboratory energies (in MeV). (From

OPE has short-distance effects

pp scattering at high energy- strong repulsive core

Symmetric about 90 deg-(identity of particles) &
flat except for forward peak due to Coulomb

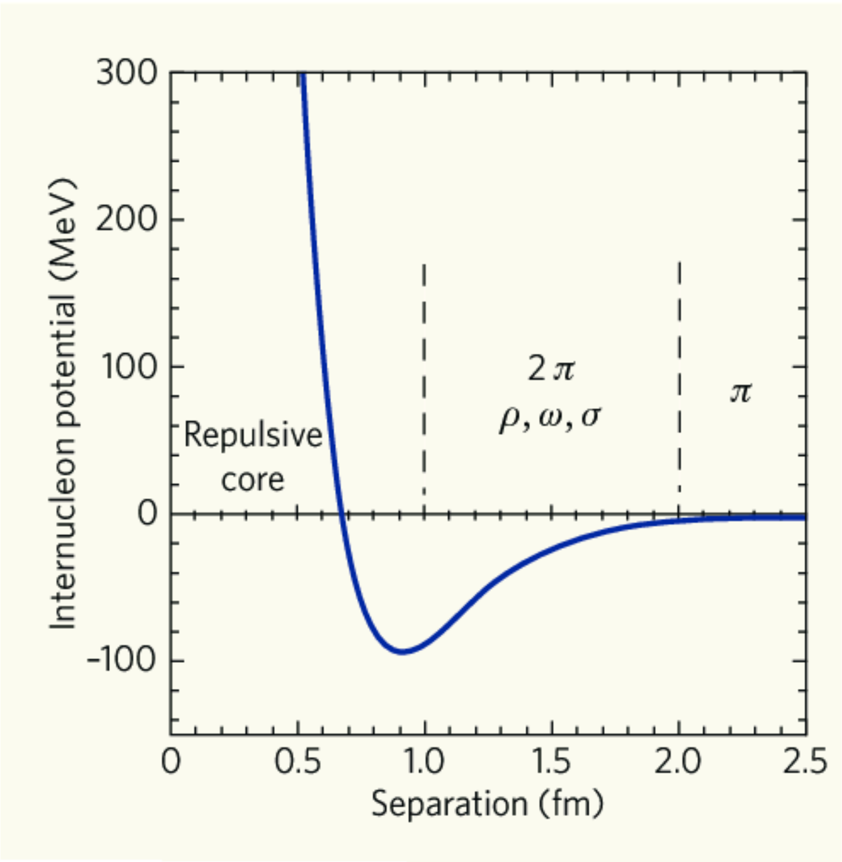
Jastrow PR 81, 165(1951)

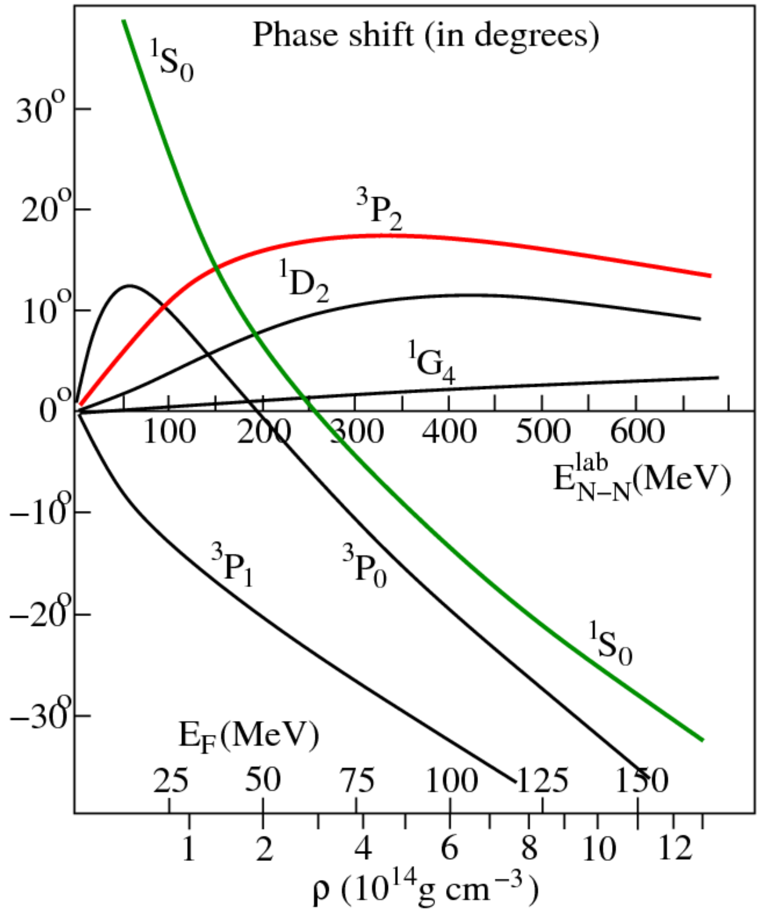


Very different than np

Fig. 38.2 Experimental *p-p* differential cross section in the center-of-momentum system at various laboratory energies (in MeV). The forward peak is due to coulomb scattering.

Isotropy due to only s-wave scattering ruled out, high energy
Interference between S&D +D^2 gives flatness IF
Potential is hard repulsive core at short distance &
long range attraction. As energy increases
sign of s-wave changes from + to -.





Isospin invariance of potential is maintained

Nucleus has high momentum neutrons

Brueckner, Eden, & Francis, (PhysRev.98.1445) argued that nuclear wave function contains nucleons with a significant probability to have high momentum: The (p, d) pick up reaction with 95 MeV protons. The neutron in the nucleus must have high momentum comparable to that of the proton, about 420 MeV/c, so that combination with the incident proton allows the deuteron to emerge from the nucleus. The only way a bound neutron could acquire such momentum is via interactions with another nearby nucleon.

If p has high momentum, n in nucleus must have high momentum to make high-momentum deuteron

Summary of NN scattering

- OPE Tensor force very important for deuteron and np scattering
- pp scattering can be described by semi-hard core plus longer-ranged attractive force
- Implication- pair-wise forces bind nuclei - must be nucleon-nucleon correlations- nucleons do not move independently in the nucleus

Scale 2 range of NN force

Lippmann-Schwinger eq. S-wave scattering at 0 energy

$$\tilde{\psi}(k) = -\frac{M}{k^3}\int dr\,\sin(kr)V(r)u(r)$$

Asymptotic series : $\sin(kr) = -\frac{1}{k}\frac{d}{dr}\cos(kr)$. Integrate by parts again and again

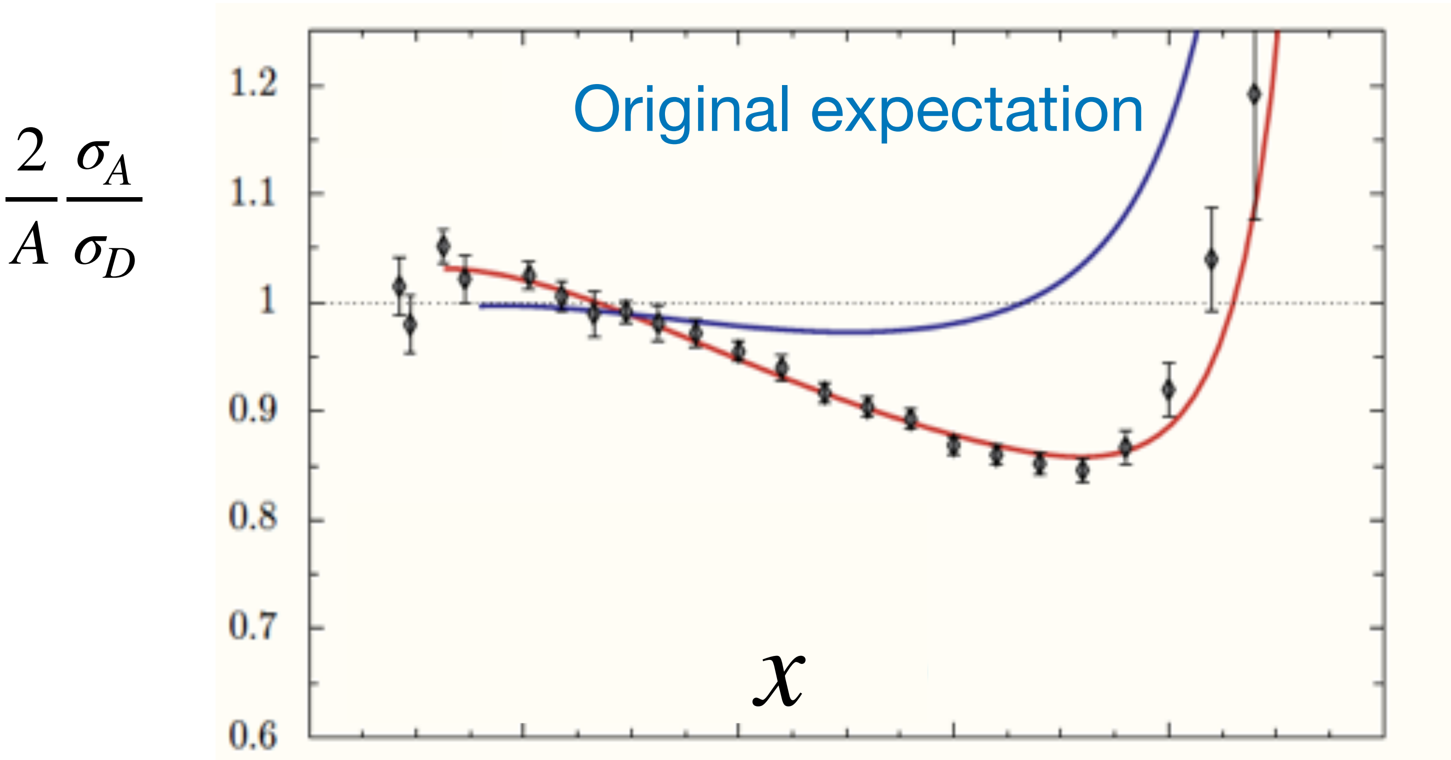
$$\tilde{\psi}(k) = \frac{M}{k^4}V(0)u(0) + \frac{M}{k^6}(Vu)''(0) + \frac{M}{k^8}(Vu)''''(0) + \cdots$$

Short range forces yield power-law falloff (slow fall) in momentum space
Must have significant high momentum content

Next- three examples of short distance physics

EMC effect -deep inelastic scattering from nuclei

Quark structure of nucleon is modified in nucleus



Quarks have a presence in nuclei
Quarks in protons influenced by
Interactions with surrounding nucleons

Effect is small, for x between 0.3 and 0.7 linear decrease with x

The EMC effect is 10 % on a small probability part of the wave function, but it IS there

Can long-range nuclear properties Be influenced by short range interactions? A chiral dynamics estimate

Physics Letters B 793 (2019) 360–364

G.A. Miller [a,*], A. Beck [b,1], S. May-Tal Beck [b,1], L.B. Weinstein [c], E. Piasetzky [d], O. Hen [b]

Data show that about 20% of nucleons are part of short-range correlated pair

These correlations influence calculations of nuclear charge radii

Chiral dynamics -one pion exchange potential via work of Weise et al

$$\langle GS|R^2|GS\rangle = \langle P|R^2|P\rangle + (\langle Q|R^2|Q\rangle - \langle P|R^2|P\rangle)\mathcal{P}_Q$$

P projects in Fermi sea, Q projects above Fermi Sea- caused by OPEP & iterations

Estimates change mean square radii of $f-p$ shell orbitals by about 1 fm^2

Important for precision measurements

Nucleon-Nucleon Short-Ranged Correlations, β Decay and the Unitarity of the CKM Matrix

Based on Miller & Schwenk (MS) PRC 78,035501 (08), PRC 80,064319 (09)
Condren & Miller 2201.10651 PHYSICAL REVIEW C **106**, L062501 (2022)

$V_{ud} = 0.97373 \pm 0.00031$ Hardy & Towner PRC 2020 $|V_{ud}| = 0.97370 \pm 0.00014$ PDG 2020

Much from superallowed β decay, many many transitions

$$\boxed{|V_{ud}|^2 = \frac{2984.43\ s}{\mathcal{F}t\,(1+\Delta_R^V)}.}$$

Single-nucleon RC
(WP2)

$$\mathcal{F}t = ft\,(1+\delta_R')\,(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}})$$

Nucleus-dependent
“outer corrections”
(under control)

Nuclear structure effects in inner RC

Isospin-breaking corrections

Corrected ft-value: nucleus-independent

$$\frac{\Delta(V_{ud}^2)}{V_{ud}^2} \approx \Delta\delta_C$$

Example $\delta_C = 0.960(63)\,\%$ in $^{42}\mathrm{Ti}$, orbital $0f_{7/2}$, 20 \% change = 0.2%, $\Delta V_{ud} = 0.001$
3.5 times ± 0.00031 or 8 times 0.00014!

δ_C matters

What is δ_C?

$0^+ \rightarrow 0^+$ nuclear β decays generated by isospin operator

If nuclei are pure isospin states, matrix element is known, but they are not so correction needed

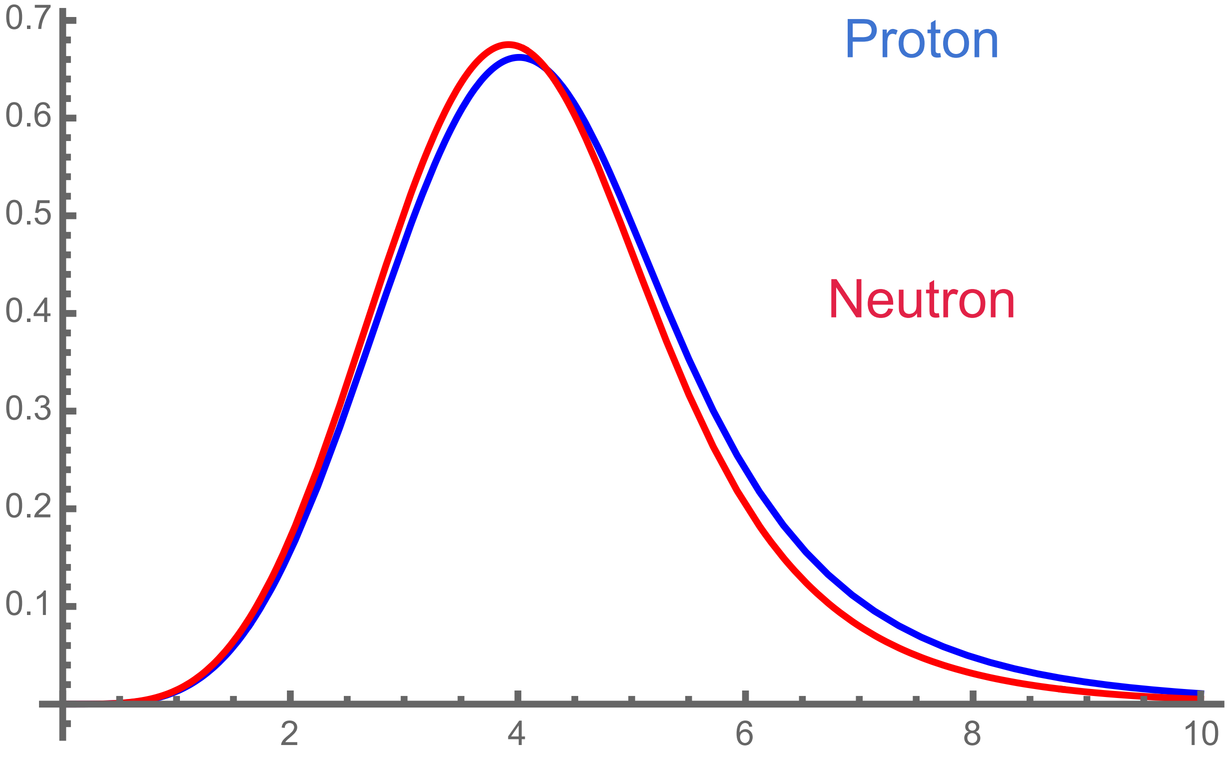
simplest example in nucleus $p \rightarrow n + e^+ + \nu$

Proton feels nuclear Coulomb potential, neutron does not , wave function overlap <1

What's the problem, why reassess?

Overlap is $1 - \Omega,\ \delta_C = 2\Omega$

$^{46}V\ 0f_{7/2}$



What is δ_C?

$0^+ \to 0^+$ nuclear β decays generated by isospin operator

If nuclei are pure isospin states, matrix element is known, but they are not, so correction needed

- Greater accuracy needed now
- Towner & Hardy **did not** use the isospin operator
- They used an operator designed to fit in a small shell-model space. Their operator DOES NOT obey isospin commutation relation. MS (2008,2009) pointed out the problem, suggested new formalism
- New experimental findings since 2008, find short-ranged correlations are very important. Backed by theory. Refs in paper. Relevance to β decay- nucleon in lowest orbital only about 80-85 % probability
- *Schematic estimates: isospin correction sensitive to effects of short range correlations. Isospin correction may be decreased by 20%* . This matters because of high accuracy needed for V_{ud} PHYSICAL REVIEW C **106**, L062501 (2022)

Summary

High momentum transfer matters in low-energy nuclear physics

- High momentum transfer related to short relative distances
- Three examples:
- EMC effect
- Nuclear charge radii
- Super-allowed beta decay