A tale of three scales

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Discovery versus precision in nuclear physics:
A tale of three scales
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Why did I write this paper? Why am I giving this talk at SRC meet?

Some physicists deny the existence of SRC.

Referee report on our paper on SRC in beta decay

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  The authors still estimate the value of Z_s=1-\kappa to be
approximately 0.85 based solely on the values of the spectroscopic
factors.   I
don't see a reason to prefer the value of kappa=0.14 (and constrain
the correlation function according to this value) over the values of
kappa obtained using the modern correlation function models available
in the literature, which are significantly smaller. The latter leads
to a much smaller impact of short-range correlations
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Z_S is the occupation probability
Believed by folks here to be 0.8
With $\kappa = 0.2$

Can SRC be measured?

- Why ask? Everyone knows wave functions can't be measured and src are part of wave function

Matrix elements are measured. Normal procedure:
use wave functions to compute measured matrix elements and
verify wave functions.

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

- Many examples show that 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.

So experience teaches us that 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.

In nuclear physics the interaction is well described in terms of OPEP and one
parameter to account for short-distance effects.

My opinion- SRC can be measured

Why do I say that?-remainder of this talk
SRC have been measured, see other talks

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 $R_A \sim 5\text{ fm}$, average separation distance between nucleons $d \approx 1.7\text{ fm} \sim 1/\mathrm{m}_\pi \approx 1.4\text{ fm}, r_N \text{ nucleon radius} = 0.84\text{fm}$

- Nuclear scales are about the same-no scale separation

- **We must treat all scales**

EFT works with given scale suited for precision work
Discovery of new phenomena not treated by scale separation
because a new scale is found
Example nuclear EFT before Rutherford- plum pudding model of atom electrons & protons
distributed over atomic radius

Theory: Discovery vs Precision phases

Discovery- there is a puzzle to be solved, main mechanisms to be identified.

1953 -discovery of binding based on nucleon-nucleon interaction in the medium

1975 - main pieces identified, corrections needed

Precision - 1980's relativistic effects put in

late 1990's -2000 chiral eft

2000- now soft interactions, similarity renormalization

Sometimes pursuit of precision obscures the basic elements and leads to confusion

Experiments on short-range correlations -still in discovery phase, but moving rapidly to precision

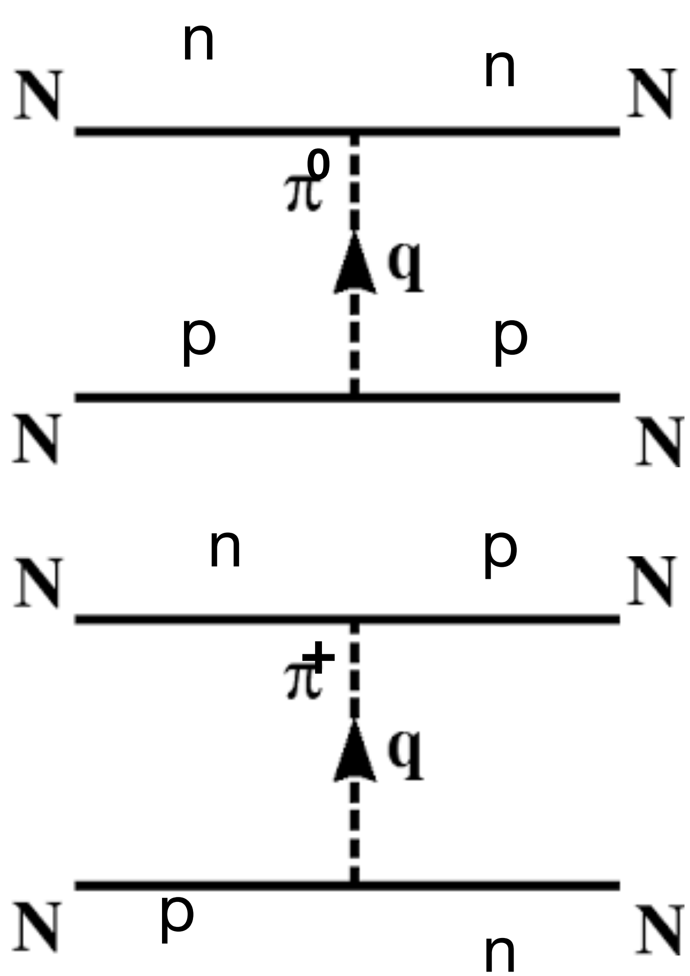
Next step - quick review of nucleon-nucleon scattering

Basic features hit you in the face

One pion exchange (OPE)

np scattering

Symmetry about 90



Forward scattering looks like backward scattering

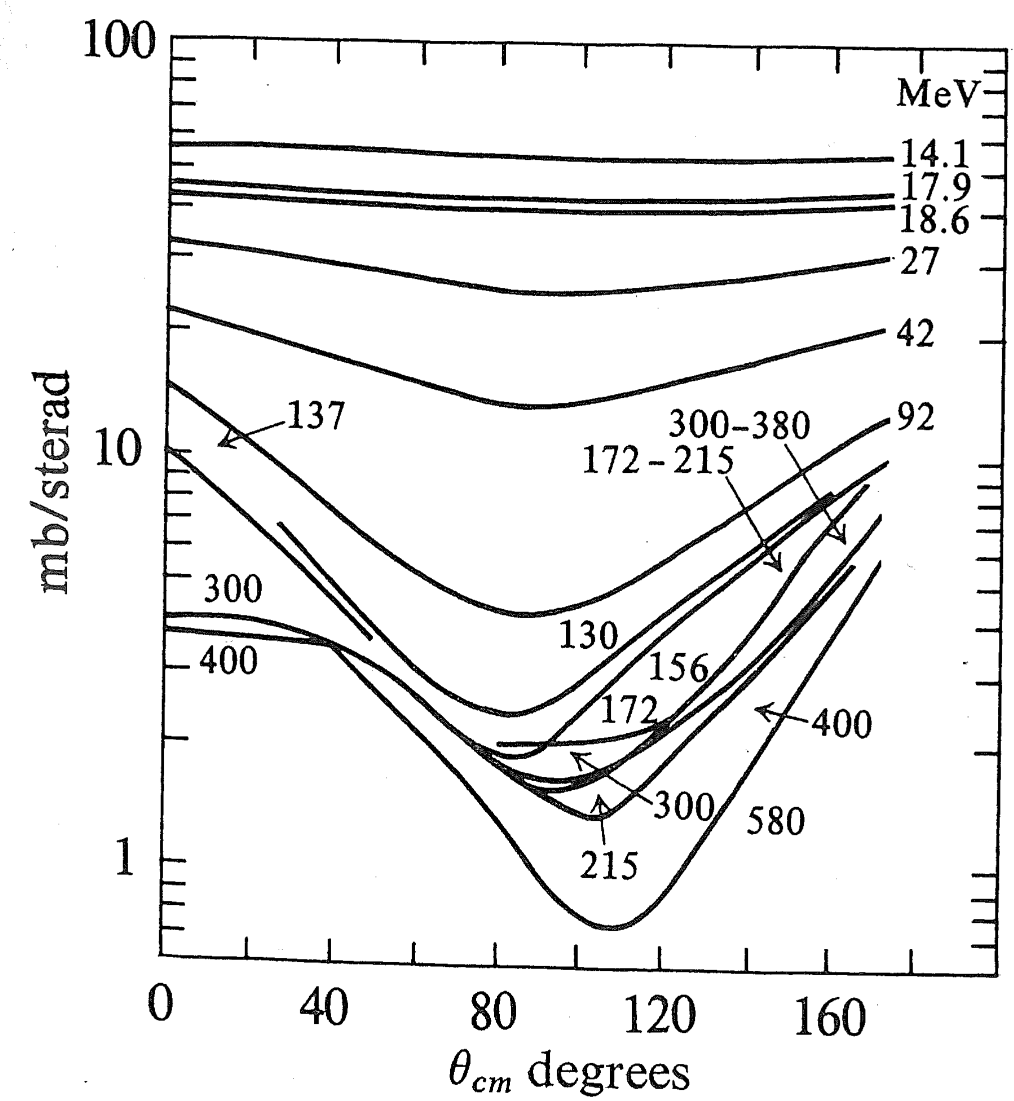


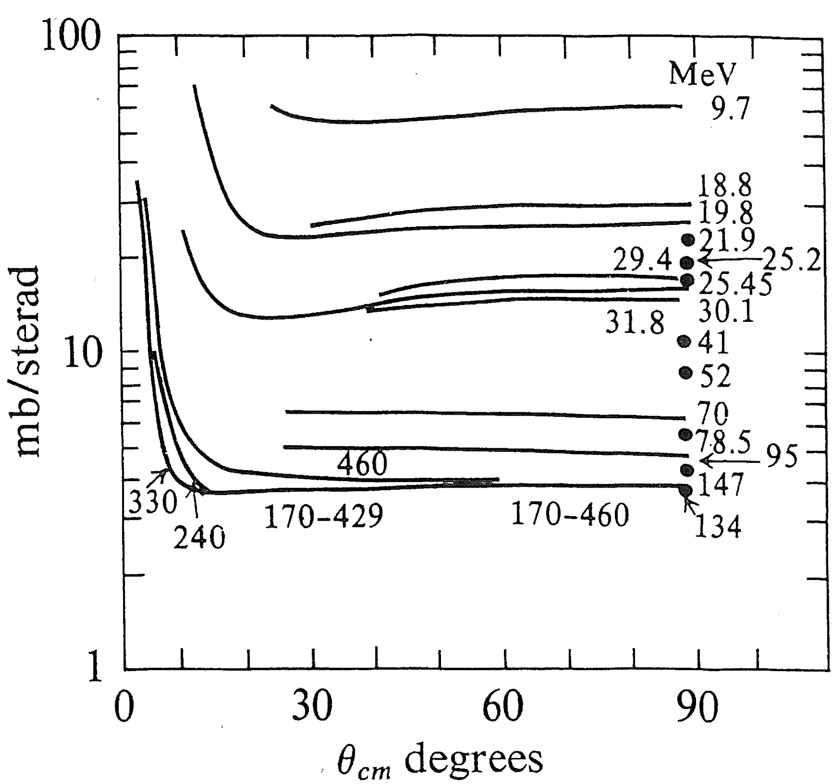
Fig. 38.1 Experimental *n-p* differential cross section in the center-of-momentum system at various laboratory energies (in MeV). (From

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

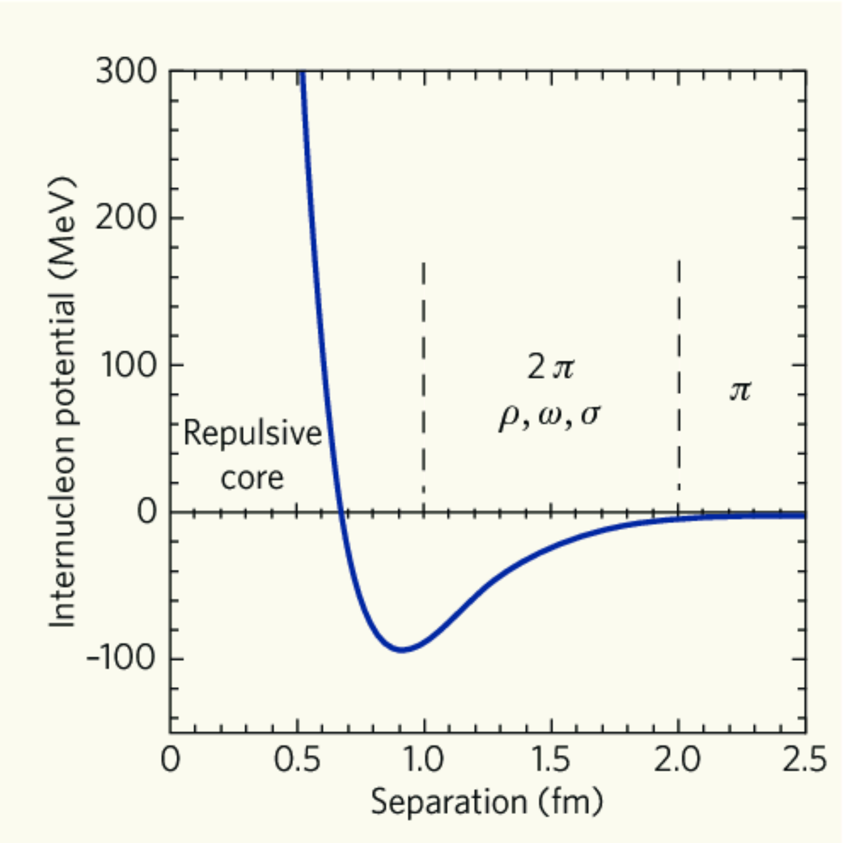
Jastrow PR 81, 165(1951)

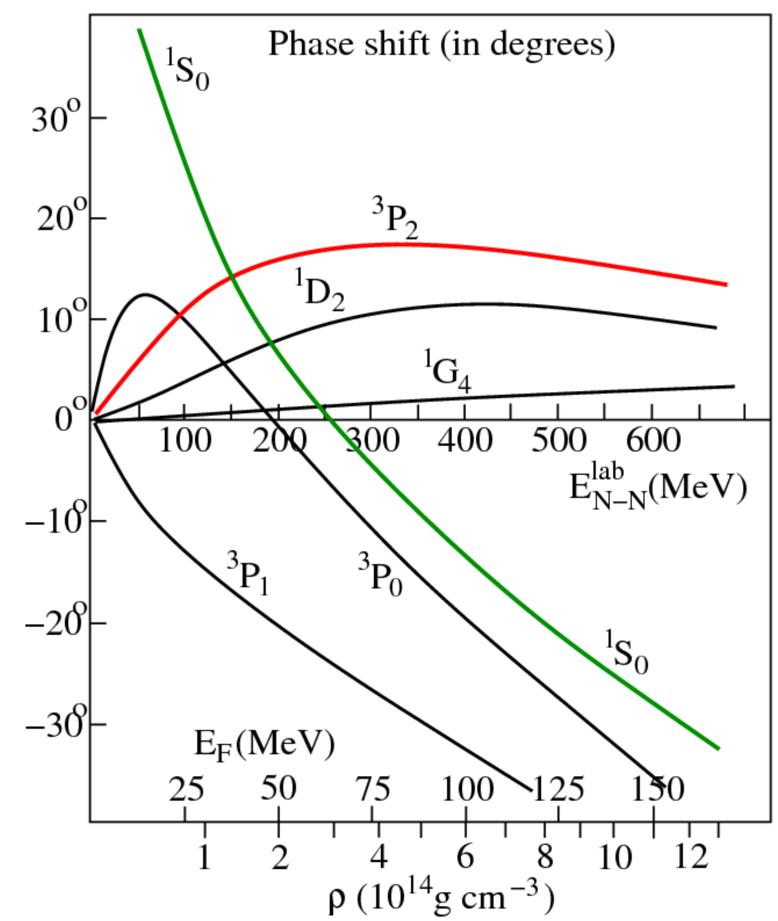


Very different than np

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 -.

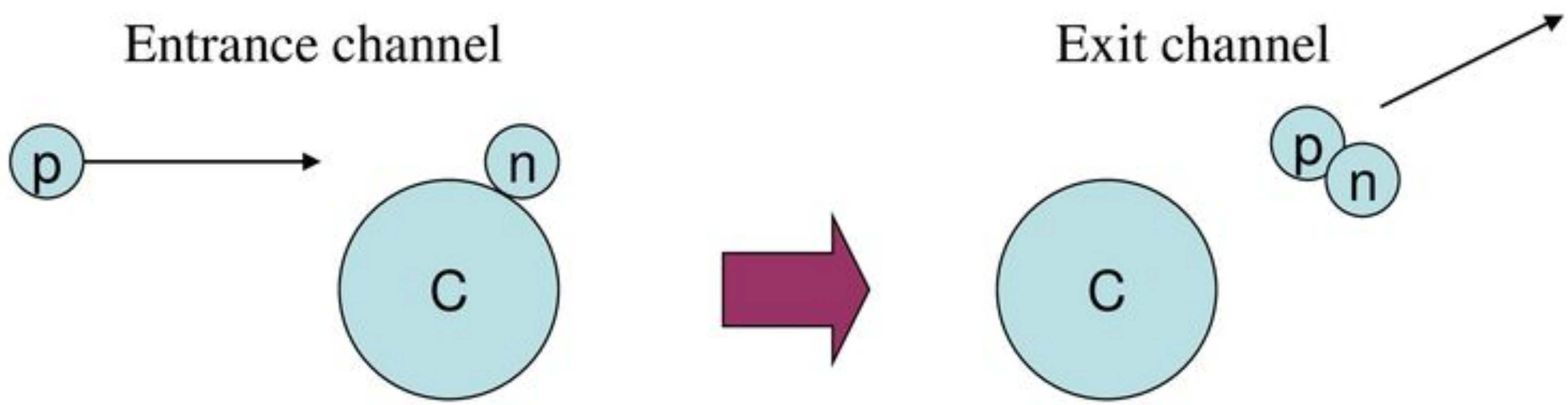




Charge dependence of potential is maintained

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.

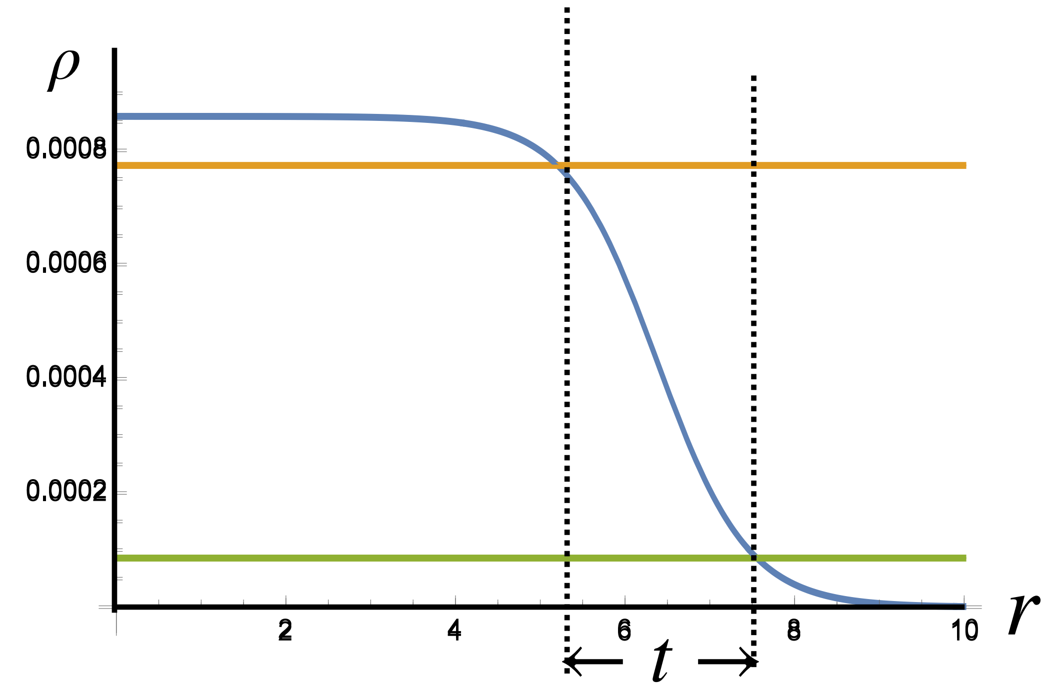


If p has high momentum, n in nucleus must have high momentum to make high-momentum deuteron

Summary of NN scattering

- OPE Tensor force very important for deuteron and np scattering
- pp scattering can be described by 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 1 nuclear radius



- Charge density $\rho(r) = \dfrac{\rho_0}{1 + e^{(r-R_A)/a}}$
- $R_A = 1.1\,\text{fm A}^{1/3}, \text{a} = 0.54\,\text{fm}$
- $\rho(r) \sim e^{-r/a}, a \approx 1/(2\sqrt{2MB}) \approx 0.57\,\text{fm}$
- Large r controlled by binding energy
- $t = 4.4a \approx 2\,\text{fm} \ \approx \text{range of NN force no accident}$
- Two small distance scales t, a needed to understand nuclear radius - a contributes about 14 % to mean square radius

Scale 2 range of NN force

The Lippmann-Schwinger (LS) equation for scattering at 0 energy is given by

GCF wave function

$$\varphi^{\alpha}_{NN}(k) = \frac{-M}{k^2}\int \frac{d^3r}{(2\pi)^{3/2}} e^{-i\mathbf{k}\cdot\mathbf{r}} V(r)\varphi^{\alpha}_{NN}(r).$$

If the potential is an approximate delta function in coordinate space, then $\varphi^{\alpha}_{NN}(k) \sim \frac{1}{k^2}$

Simplify notation : $\mathrm{S-states}, \varphi^{\alpha}_{NN}(r) \to u(r)/r \quad \psi(k) = -\frac{M}{\sqrt{2\pi}k^3}\int_0^{\infty} dr \sin kr V(r) u(r),$

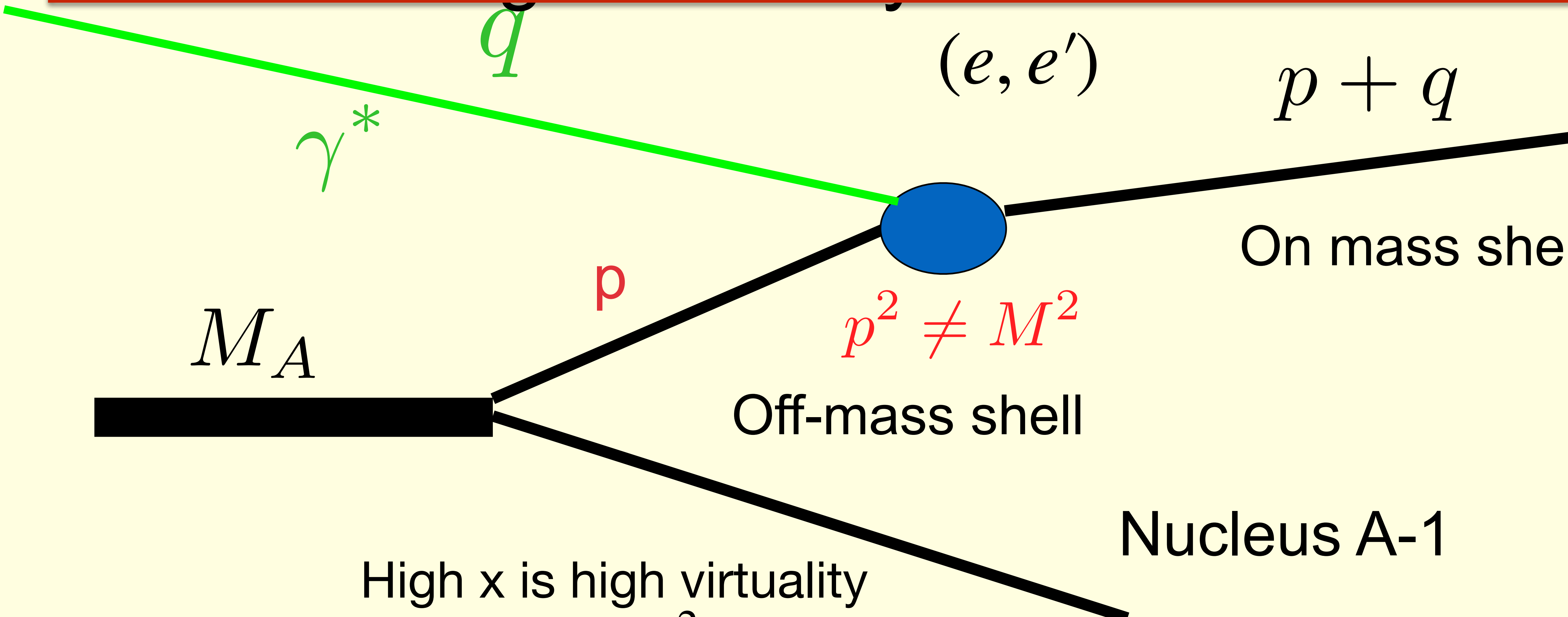
Asymptotic values of the momenta: $\sin(kr) \to \frac{-1}{k}\frac{d\cos kr}{dr}$. Then one can get higher-order terms by writing $\cos(kr) = \frac{1}{k}\frac{d\sin kr}{kr}$. The result, defining $K \equiv \frac{M}{\sqrt{2\pi}}$ and assuming that the potential is not a delta function, and that Vu and its derivatives exist at $r=0$ is:

$$\psi(k) = \frac{K}{k^4}\int_0^{\infty} dr \frac{d\cos kr}{dr} V(r)u(r) = \frac{K}{k^2}[-V(0)u(0) - \int_0^{\infty} dr \cos kr (Vu)']$$
$$= \frac{K}{k^4}V(0)u(0) + \frac{K}{k^6}(Vu)''(0) + \frac{K}{k^8}(Vu)''''(0) + \cdots$$

One may classify the asymptotic behavior obtained from different classes of potentials.

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

Scale 3: High Virtuality =1/ short distance

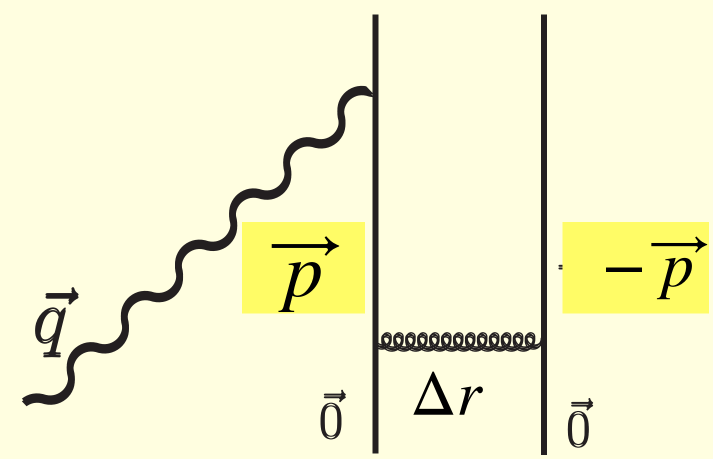


High x is high virtuality

$$x = \frac{Q^2}{2p \cdot q}$$

$(p+q)^2 = M^2$ gives

$$M^2\mathscr{V} = p^2 - M^2 = Q^2(1 - 1/x)$$



If $x = 2$, $p^2 - M^2 = Q^2/2$, large

Only way to get large $\mathscr{V}$ is by interaction with nearby nucleon $\Delta r \sim 1/|\vec{p}| \approx r_N$

Plateaus exist, so must have high $\mathscr{V}$

What is a virtual nucleon?

- $$|N(\mathscr{V})\rangle = \sum_n c_n |N_n\rangle$$
- Large Q^2 means large $\mathscr{V}$, many excited states n, quark language is better
- Quark structure of nucleons in nucleus is not same as that of free nucleon
- There is an EMC effect

Summary

- OPE and short-range repulsion obvious features of nucleon-nucleon force, correlations exist
- Three nuclear scales
  $R_A, d(\text{NN separation distance}), r_N\,(\text{nucleon size})$

  Are needed to understand nuclear physics