Quasi-free knockout reactions

Ingo Sick

Purpose

review what have learned

how can apply to future data from RIB

topics covered

- spectroscopic factors
  - mainly from (e,e'p)
  - partial occupation of low-momentum states
- strength at high momentum
  - physical origin, measurement
- radial distribution of low-k $\leftrightarrow$ high-k strength
  - relevance for transfer reactions
- lessons for interpretation of transfer reactions
- conclusions

Often used framework: shell model

mean field + residual interaction
important, but drastic, simplification
helps qualitative understanding
still useful despite shortcomings (see below)

spectroscopic factors = overlap of nature with the simple single-particle model

Talk: cover several approaches aiming at spectroscopic factors, mainly from (e,e'p)

requires discussion of *both* low-k and high-k aspects

high-k only accessible in (e,e'p)

hierarchy of probes

	cleanliness	feasibility
(e,e'p)	++	−
(p,2p)	+	+
transfer	−	++

Spectroscopic factors, occupations, ... paraphrasing Omar's discussion

Nuclear matter (NM)

with no correlations = Fermi Gas FG , orbits fully occupied up to E_F

with short range correlations SRC

partial occupation for $E < E_F$ ($n(E)$) and $E > E_F$ ($n_c(E)$)

part of correlated continuum-strength at $E < E_F$ → QP strength $z(E) < n(E)$

Finite nuclei (*e.g.* Pb)

configuration mixing, coupling to surface

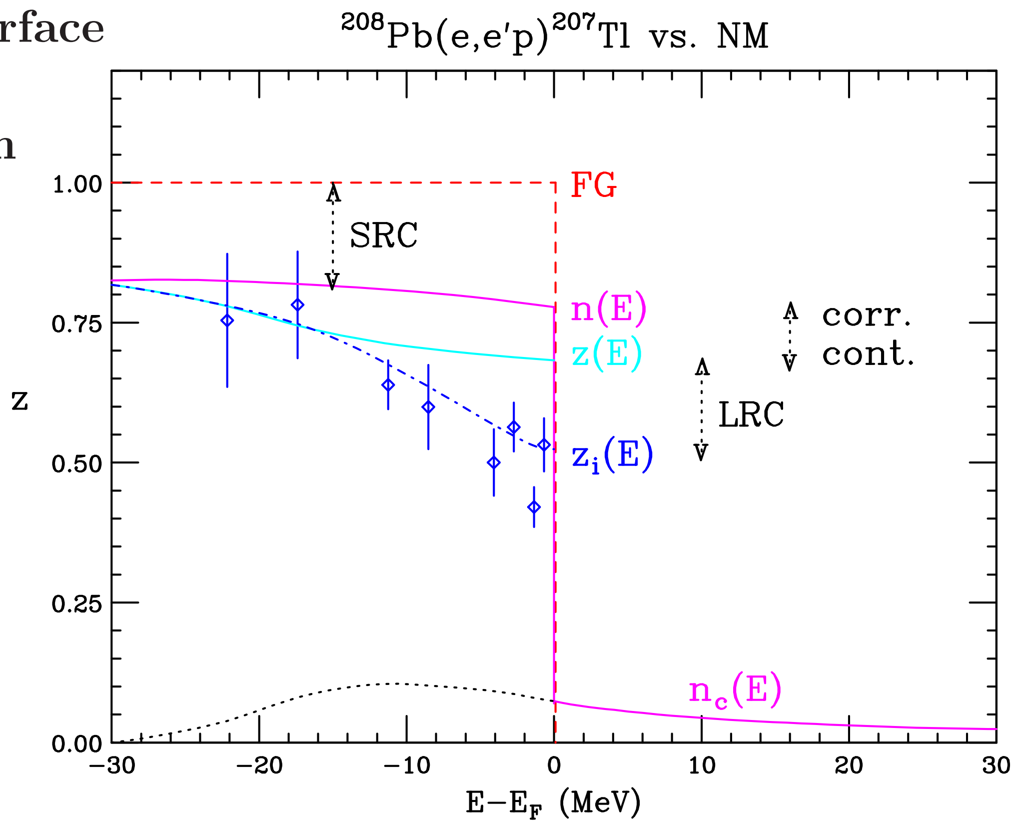
spreading of n, l, j strength

one state often carries most strength

= Quasi-Particle state

spectroscopic factor z_i

$$\sum_{fixed\ n,l,j} z_i \longrightarrow \text{occupation of } n, l, j$$



Orbits: calculation vs. measurable quantities

which orbitals should one use as basis?

overlap, natural, mean field, ... ?

see Pandharipande *et al.* RMP 69(97)981

exact calculation: Lewart *et al.* PRB 37(88)4950

studies *strongly correlated* system

drops of liquid Helium-3

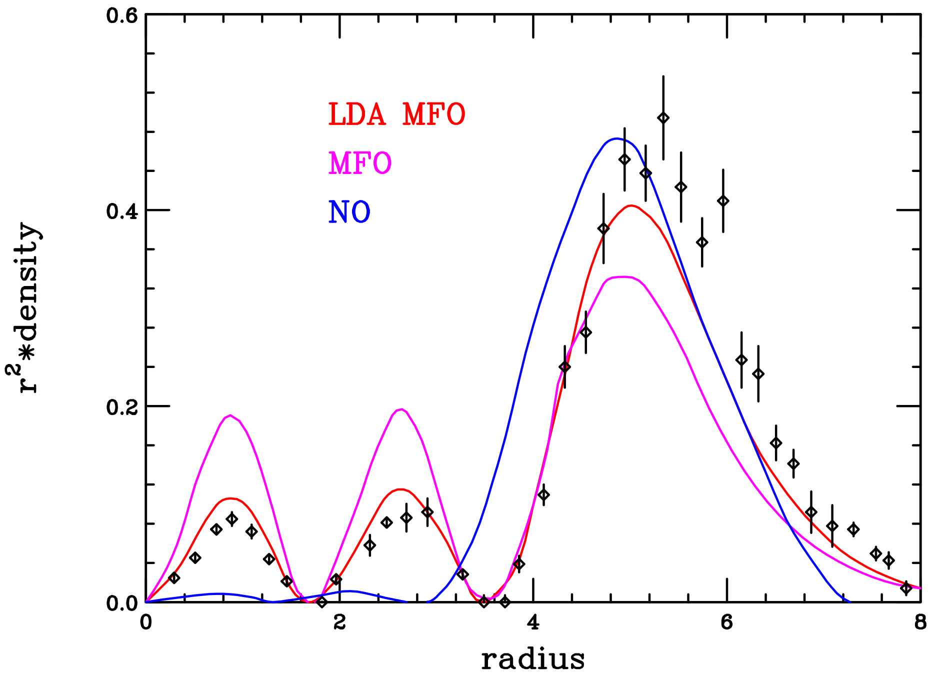
V_{He-He} simpler than V_{NN}

can do Variational Monte Carlo

finds for A, A–1 difference for A=70

70^{est} He-atom in 3s-state

(analogous to ^{206}Pb-^{205}Tl)



quasi-hole orbital close to MF orbitals +LDA (———)

$\psi_{QH} = \psi_{MF}\sqrt{z(\rho(r))}$ z=renormalization

= quantities observable in transfer, (e,e), (e,e'p)

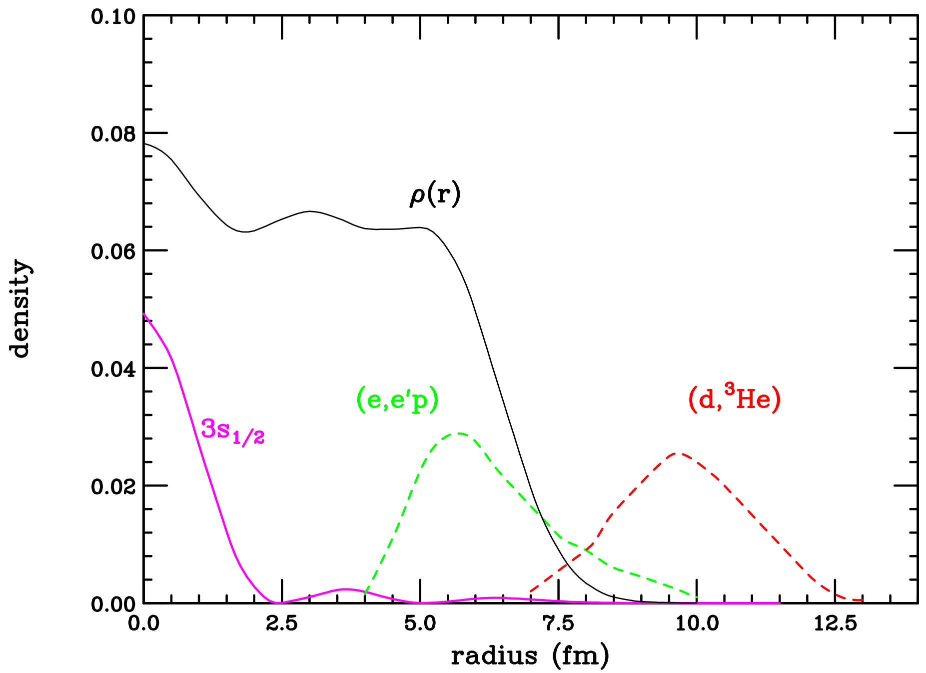
Traditional tools used to measure *s*:

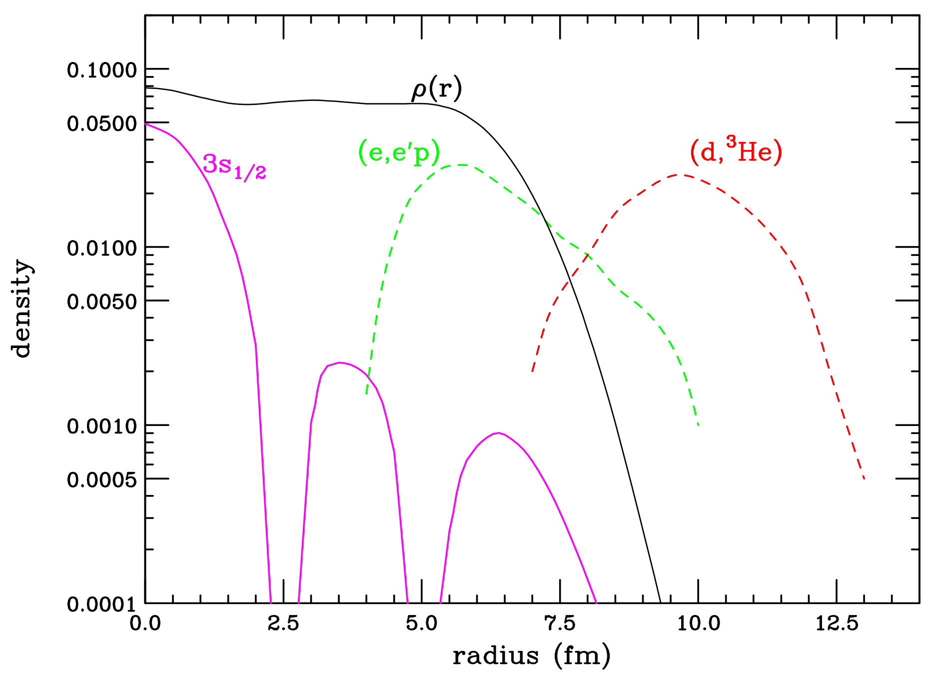
(d,^{3}He), (p,d), ..., (p,2p), ..., (e,e'p)

What do they *really* measure?

consider radial sensitivity of probes, for Pb (e,e'p) - - - - (d,3He) - - - -

sensitivity of (e,e) flat, (p,2p) further outside than (e,e'p) [more absorption]





transfer reactions are sensitive where $\rho(r) \sim 0.01\rho(0)$

measure asymptotic norm, not *s*

should really only quote this quantity! ... but somehow people want *s*

Why want s?

better intuitive meaning than asymptotic norm

(typical) HO-based calculations only give s

If want s from transfer: suffer from strong dependence on assumed $R(r)$

s changes typically 10% for a 1% change of rms-radius of $R(r)$

since rms-radius poorly known $\rightarrow$ s rather arbitrary

Past prejudice

$\sum_i s_i$, summed over final states i, gives occupation $n_{p,h}$ (pickup, transfer)

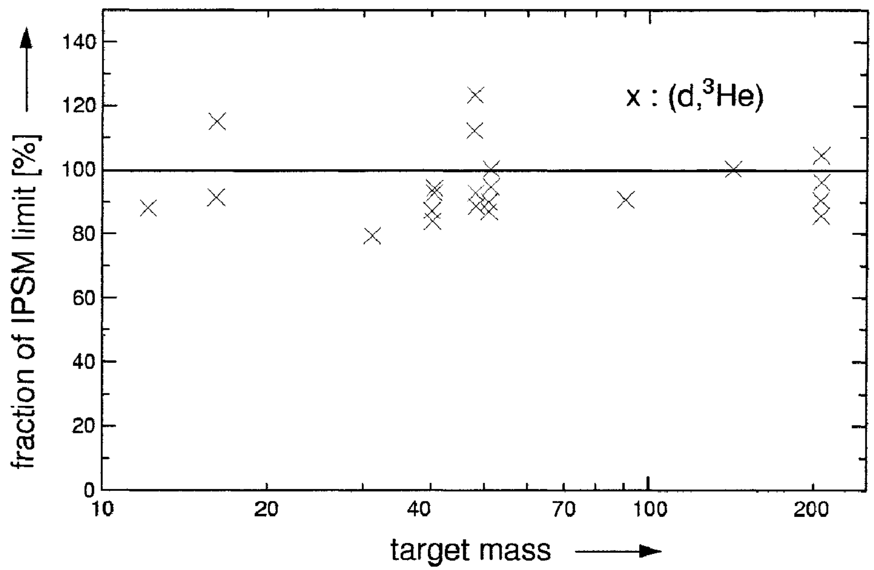
$n_{particle} + n_{hole} = 1$, *i.e.* 2j+1 particles in state j

choose $R(r)$ such as to get 1

Result

find small values for n_h

find n_p close to 1



Problem

cannot determine $\sum_{E=0}^{E=\infty} s_i$ as data restricted to $\sum^{few\ MeV} s_i$

$\sum$ does not contain all the strength

rest not identifiable as in continuum

Doubts in n∼1

- elastic M5 – M9 form factors
- form factors of high-multipole transitions E12, E14

little subject to configuration mixing

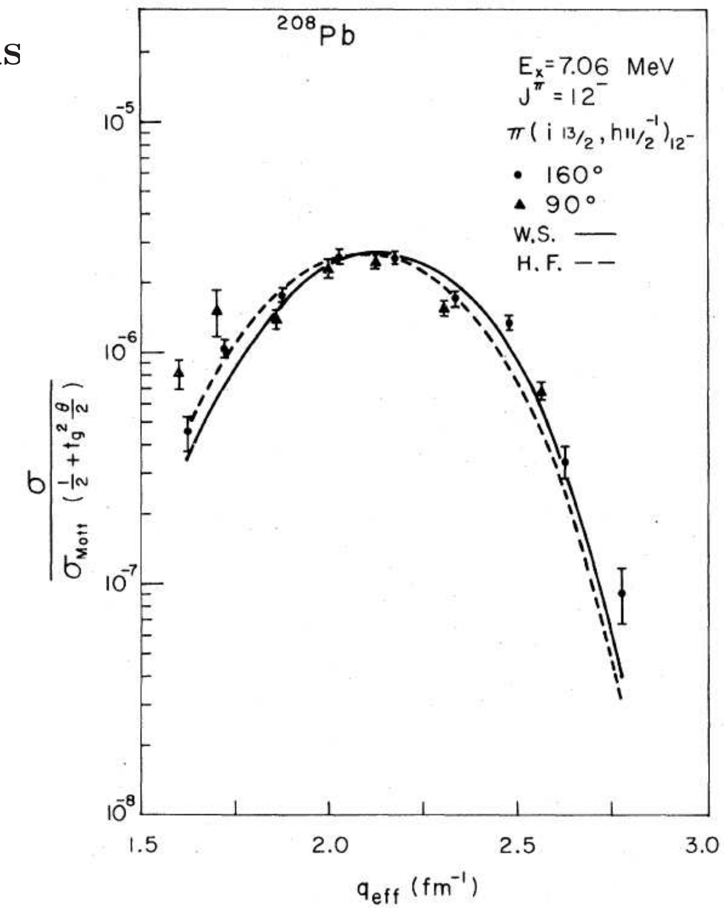
sensitive where $R(r)$ large

relative to MF F^2 reduced by factor ∼1.5÷2.

indicates occupation of ∼75%

Pandharipande *et al.* PRL 53(84)1133

- $\Delta\rho$ Pb - Tl: same conclusion



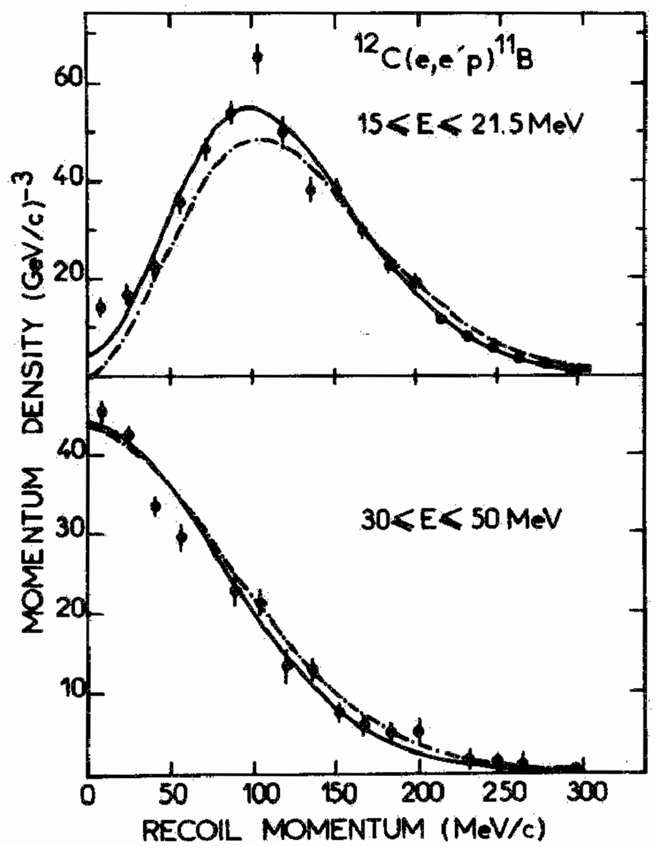
Better information on orbits: from (e,e'p)

measures $R(k)$ (hence $R(r)$), no need for (arbitrary) input

measures absolute strength as sensitive where $R(r)$ large

easier to treat as only *one* strongly interacting particle
no composite particles subject to strong absorption

Data: early results from Saclay



find orbits with $R(k) \sim$ MF
applicable even in nuclear interior

find n$\sim$0.7
not taken very seriously
doubts about DWBA treatment
... which however was OK

Distortion effects today

can be handled quite well, optical potentials known

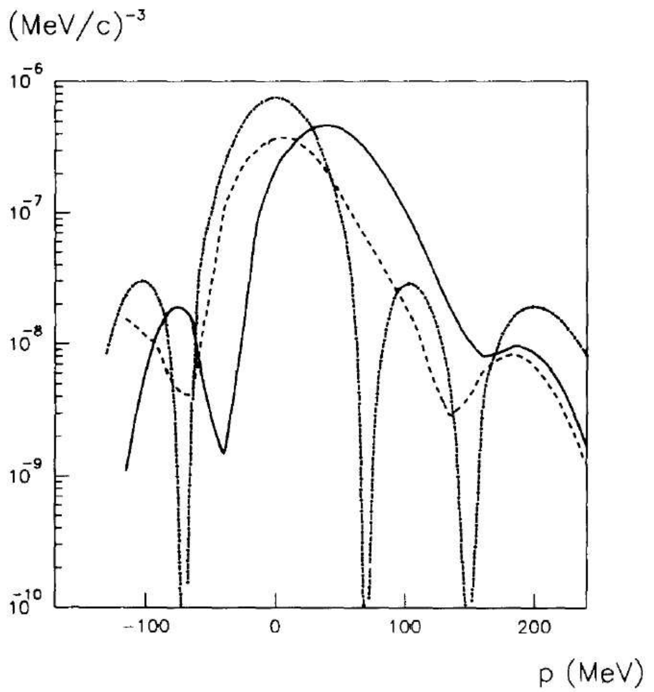
acceptable size even for heavy nuclei

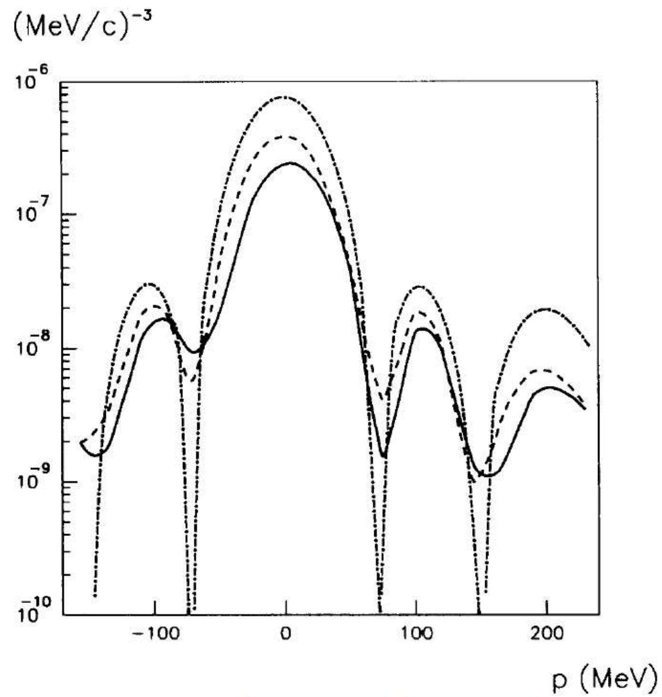
can be strongly influenced (minimized) via choice of kinematics

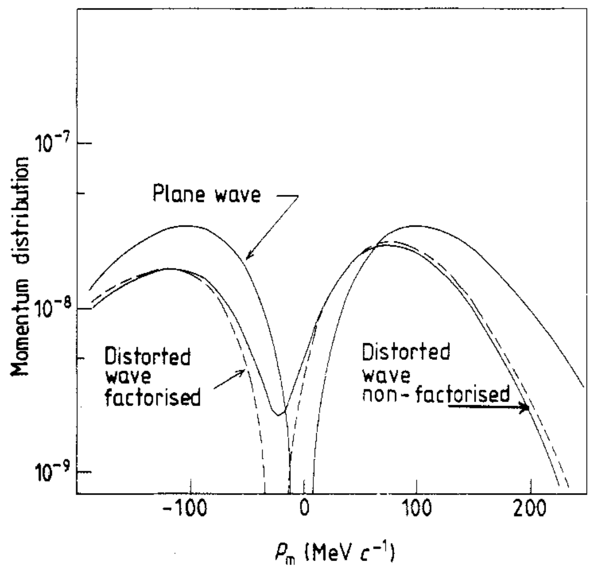
(*if* have GeV electron energy)

larger $q \rightarrow$ larger $E_p \rightarrow$ smaller FSI

e.g. effect kinematics for 3s in Pb: variable q vs. constant q,ω $^{12}C(e,e'p)$





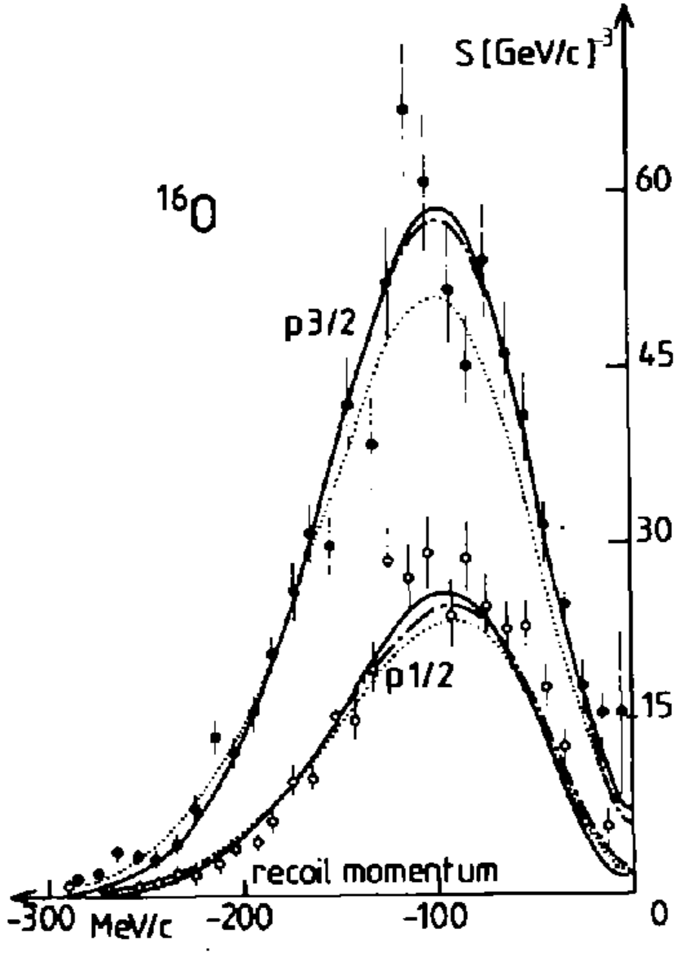


Boffi et al., E_e=410MeV, -.-.-.-. = PWIA, —— = full

Example for effect of V(r) (data from 1982)

use different global potentials (not fit to ^{16}O)

Jackson ———
Glassgold+Kellog -.-.-.-.
Giannini+Ricco ....



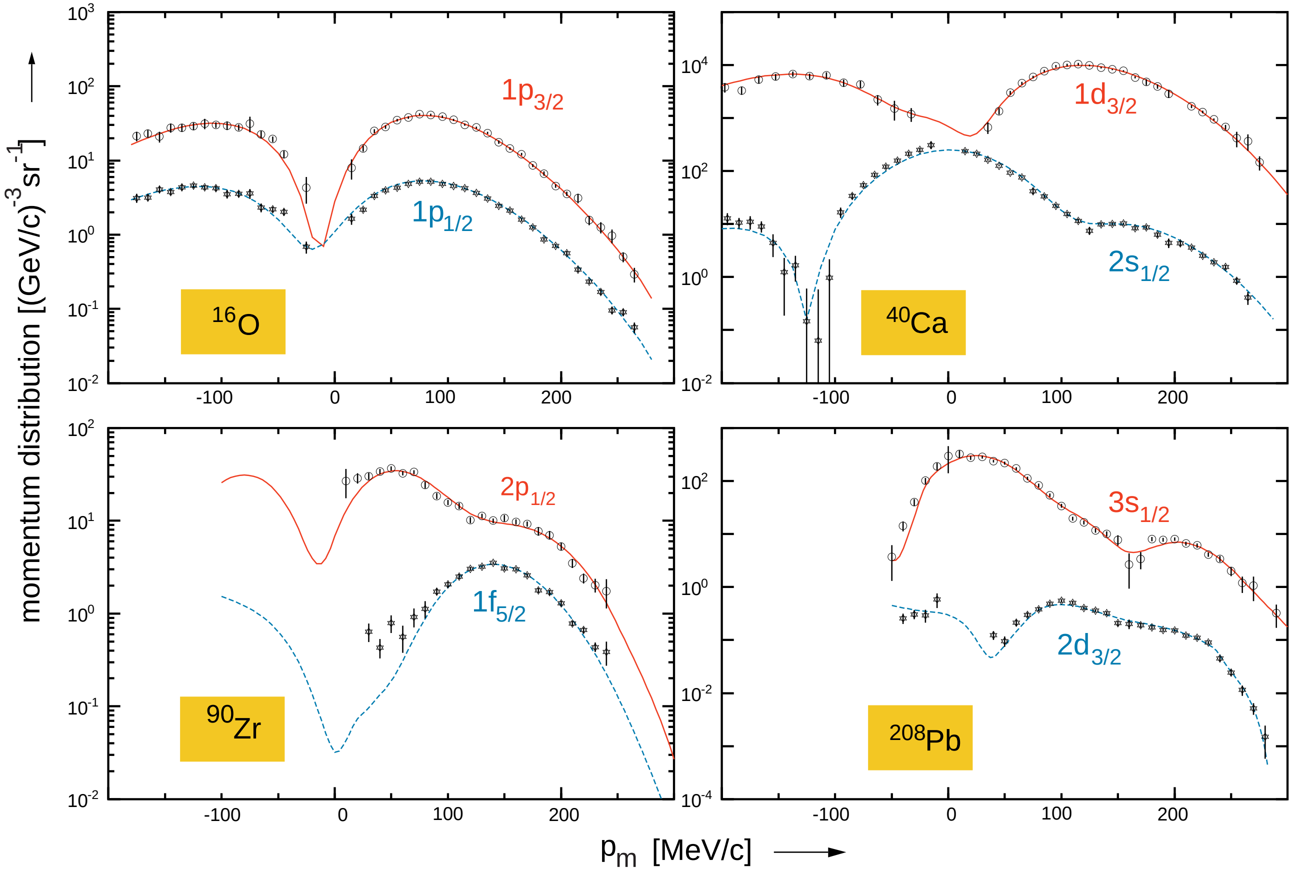
Example: ^{40}Ca(e,e'p), 2s
= unfavorable case

potential	s/s_{EEI}	s/s_{EEI}
EEI	1.00	1.00
PH	1.13	1.12
NL	1.05	1.03
Schwandt	1.00	0.97
EDADI	1.04	1.03
kinematics	//	$\perp$

find consistent values

Modern high-quality data from NIKHEF

sophisticated DWBA, Coulomb distortion of e, *etc*



⇒ quantitative measurement of momentum distributions

available for fair number of outer shells, see table

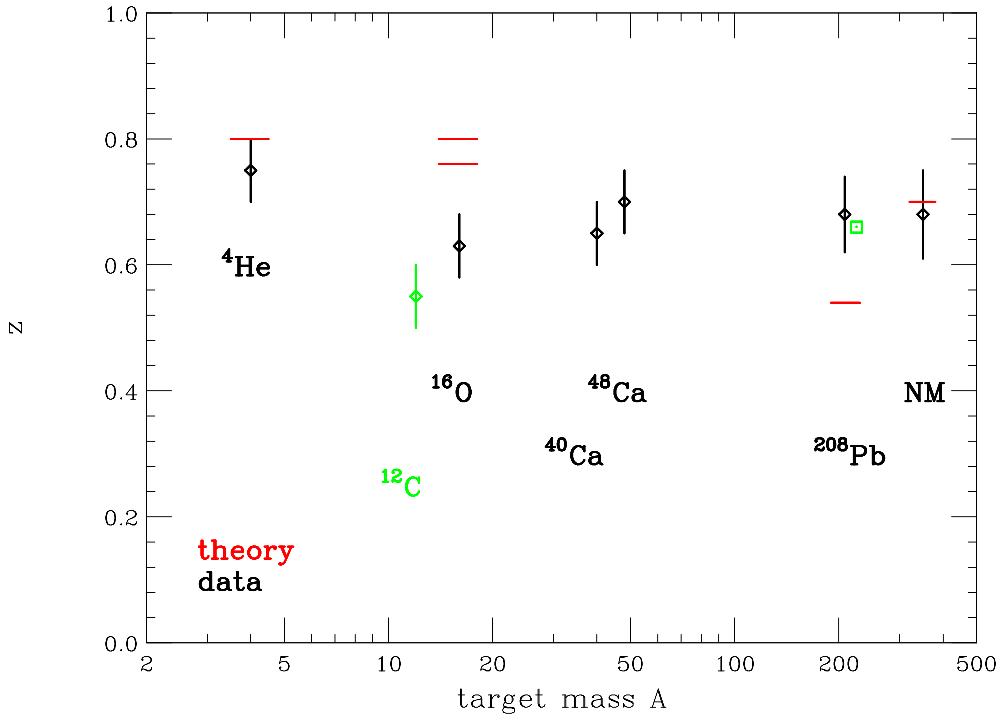
Not quite complete summary of data

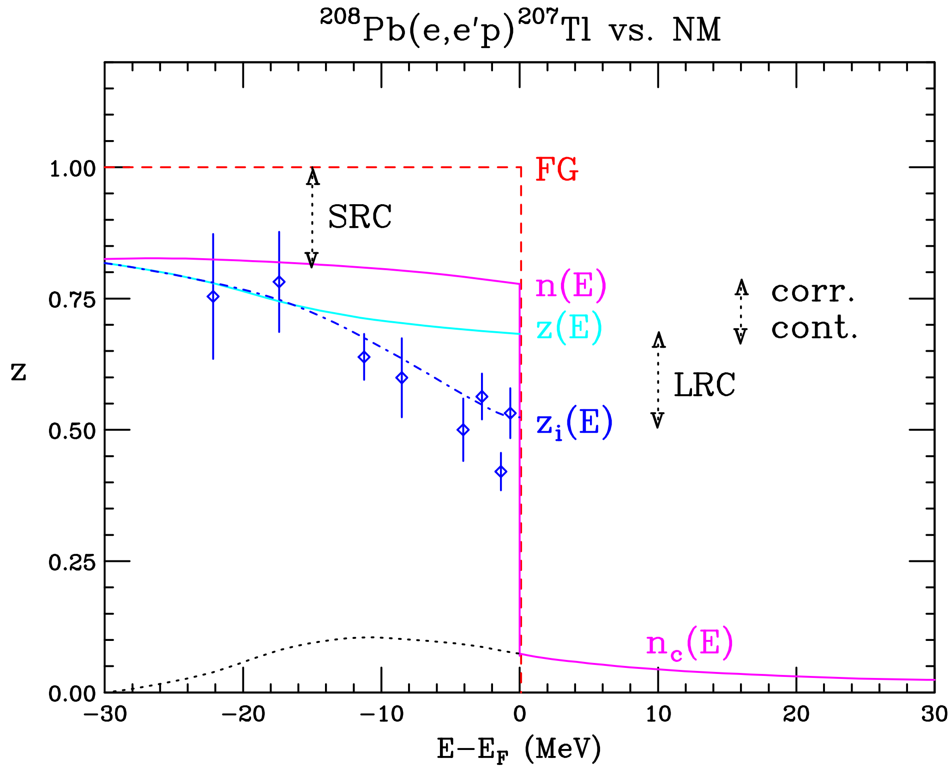
omit: data for A$\leq$4, data $\longrightarrow$ transparency, CT, in-medium G_{ep} via (e,e'$\vec{p}$), ...

target	observable	orbitals	E* MeV	p_m MeV/c	T_p MeV
^{6}Li	R(k)	1s,1p	0 - 25	–100 - 200	65
^{10}B	R(k)	1s,1p	0 - 25	–160 - 250	78
^{10}B	R(k)	1s,1p	0 - 25	–160 - 280	139
^{12}C	R_G	1p	0	–90 - 100	70
^{12}C	R(k)	1p	0 - 5	–170 - 210	70
^{12}C	R(k)	1s,2s,1d,1f	4-12	–170 - 210	70
^{12}C	R(k)	1p,1s	0 - 50	–300 - 300	350 - 970
^{16}O	R_{LT}	1p	0 - 6	–200 - 200	160
^{16}O	$R_{L,T,LT}$	1p	0 - 6	–200 - 200	84
^{16}O	R(k)	1p,2s,1d	0 - 6	–180 - 280	100
^{16}O	$R_{L,T,LT}$	1p	0 - 120	–360 - 340	400
^{16}O	R(k)	1p	0 - 6	120 - 700	196
^{16}O	R(k)	1p	0 - 28	–180 - 270	96
^{30}Si	R(k)	1d,2s,1p	0 - 24	–40 - 240	90
^{31}P	R(k)	1d,2s,1p	0 - 24	–40 - 240	90
^{32}S	R(k)	1d,2s,1p	0 - 24	–40 - 240	90
^{40}Ca	R(k)	1d,2s,1f,2p	0 - 4	0 - 270	100
^{40}Ca	R(k)	1d,2s,1f,2p	0 - 22	–220 - 270	100
^{40}Ca	R(k)	1d,2s,1f,2p	0 - 7	–225 - 240	70
^{40}Ca	R(k)	1d,2s,1f,2p	0 - 7	–180 - 250	135

similar for A$\geq$ 40
data available for A=48, 51, 90, 142, 146, 205, 206, 208

Summary on QP strength for outer shells





convincing proof for spectr. factors ∼ 0.7 (outer shells)

occupation ∼ 0.8 without surface + LRC effects

(note: peculiar behavior of ^{12}C, see below)

main drawback of available (e,e'p) (mainly NIKHEF) data

E_e rather low → E_p too low → FSI larger than would be ideally possible

E_e rather low → perpendicular kinematics → MEC not negligible

Consistency with transfer reactions?

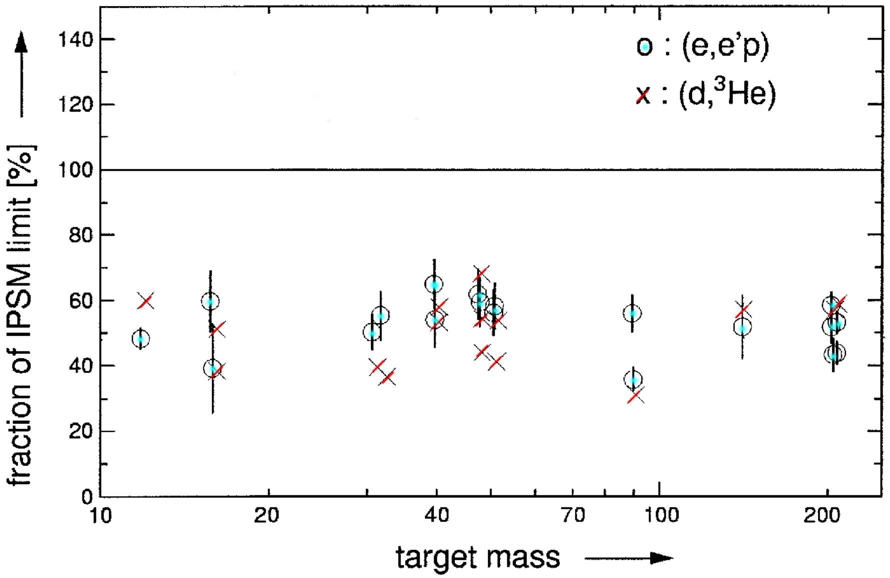
transfer data reanalyzed by Kramer *et al.* NPA 679(01)267

use $R(r)$ from (e,e'p)

use modern DWBA

find good agreement with (e,e'p)

main change: due to input $R(r)$ (measured by (e,e'p))



emphasizes importance to use good $R(r)$!!

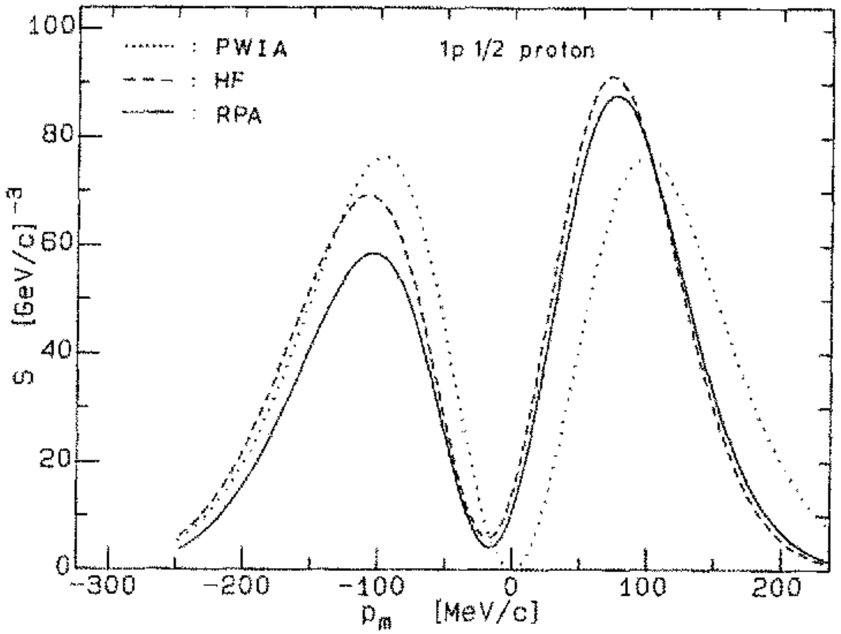
Side-remark: how about (e,e'n)?

obvious difficulty:

smaller e-n cross section, n-detection ⇒ little data
only transverse scattering (→ MEC)

additional problem:

multi-step process: (e,e'p) followed by (p,n)
simulates (e,e'n), more important than (e,e'n) followed by (n,p)
could become substantial correction



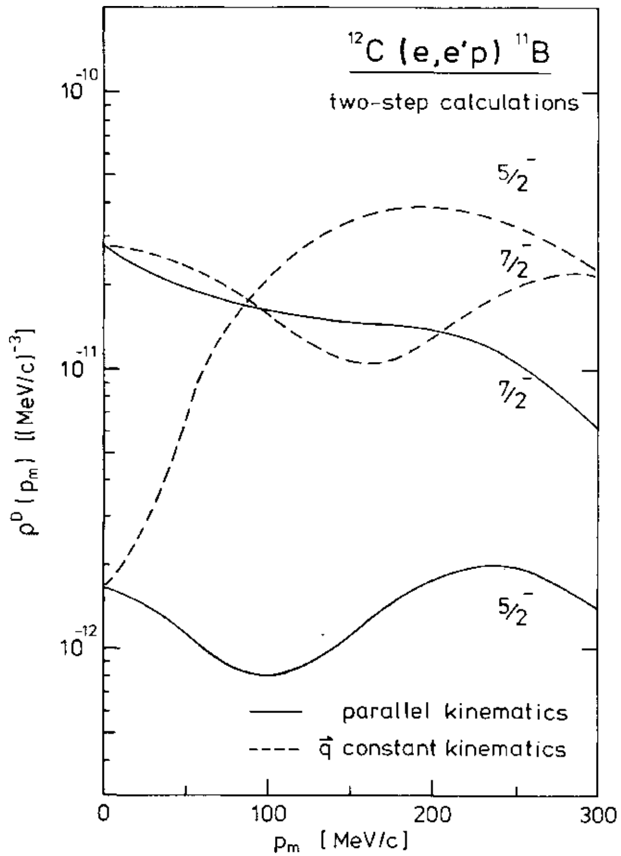
Ryckebusch *et al.*
NPA 503(89)694

other calculations (Kelly, Giusti) find ≤20%-effects, depending on kinematics

Open problems on $R(k)$ at low k from (e,e'p)

σ_{ep} off-shell: only of concern for deeply-bound states

coupled channel effects: problem for very weak transitions



meson exchange currents

not a problem at the larger q's and in $\parallel$ kinematics

should be calculated using *correlated* wave functions

$\Rightarrow$ bigger effects + solve R_L/R_T difficulty?

poor agreement between results of different groups

requires some more attention

multi-step reactions

have been given too little attention

most results analyzed using DWIA

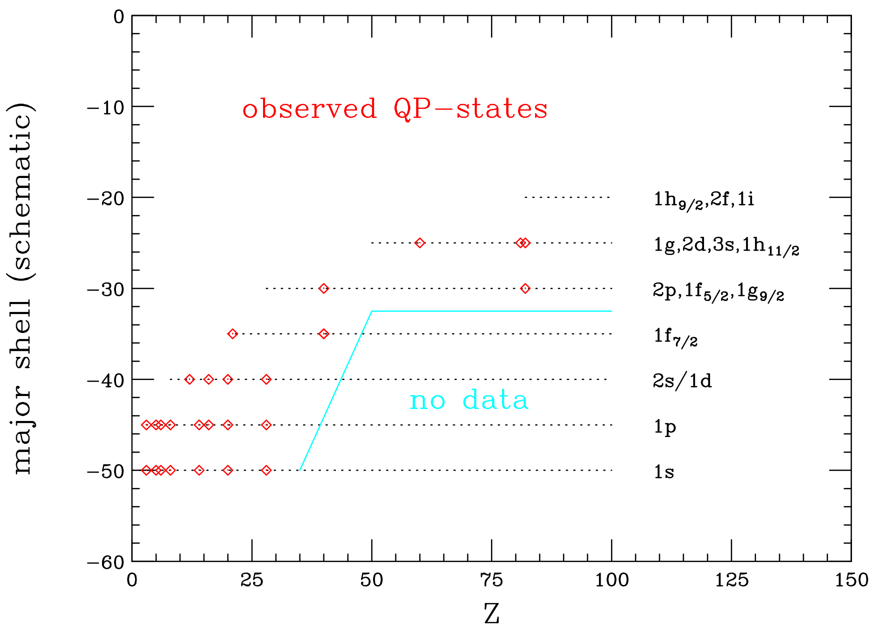
opt. potential describes 'disappearance' of protons, but not 'reappearance'

need simulations using Glauber to really gauge effect

deeply bound shells

no systematic effort made

$\Rightarrow$ real lack of information



optimal for future studies:

E_p >150MeV (absorption)

E_p > several-100 MeV (validity Glauber)

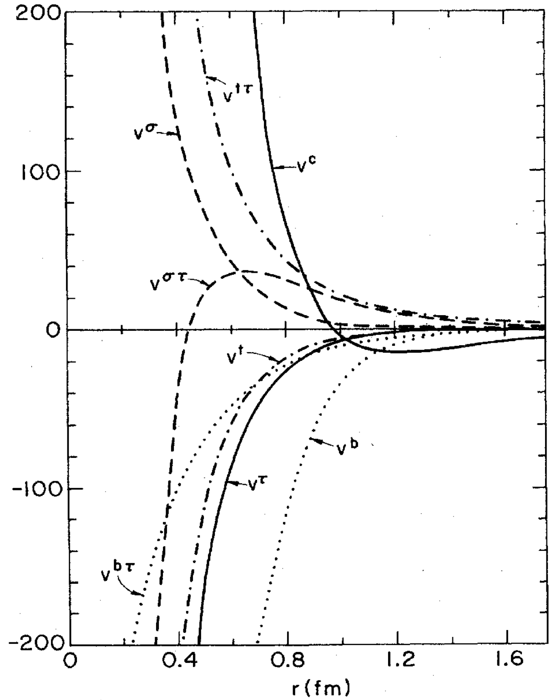
note: E_p^{max} at MAMI 340MeV

Understanding and independent measurement of z∼0.7

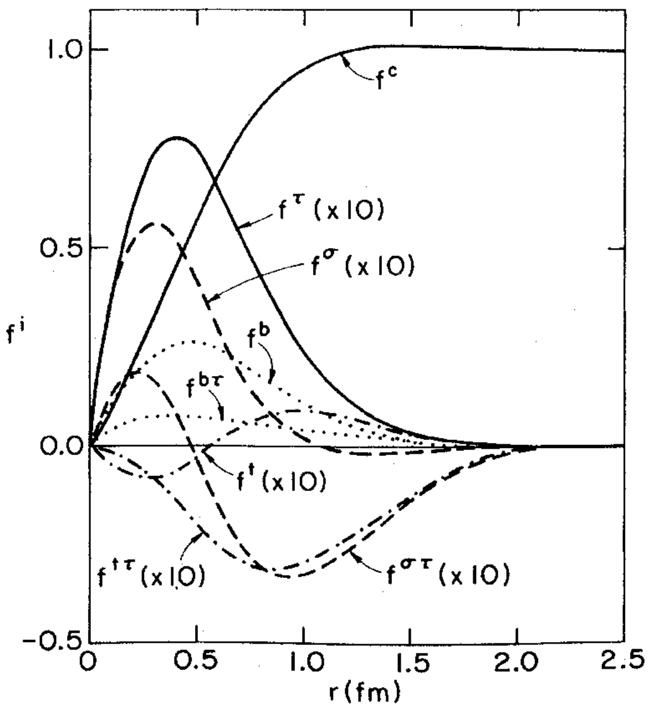
nature is poorly represented by mean-field approaches

the short-range properties of V_{NN} lead to strong central and tensor correlations

components of potential



f(r_{ij})



best seen in CBF-approach

$$|N) = S \prod_{j>i} \sum_n f^n(r_{ij}) O^n(i,j) |N]$$

$|N]$ = MF state

O = operators of V_{NN}

f = correlation functions variationally determined

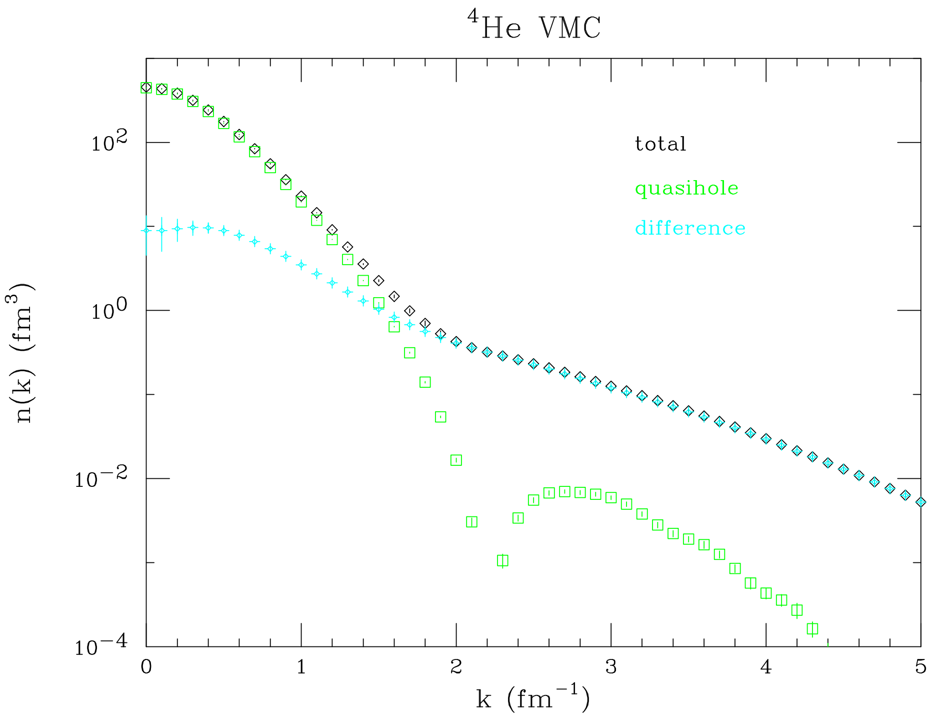
correlation-hole in f for some components, short-range enhancements for others

nucleons scattered to very high-lying orbits

Big difference QP ↔ correlated strength

QP strength: $R(k)$ falls quickly at large k
correlated strength: has long tail towards large k

example: ^4He from Variational Monte Carlo
***i.e.* exact calculation for realistic V_{NN}**



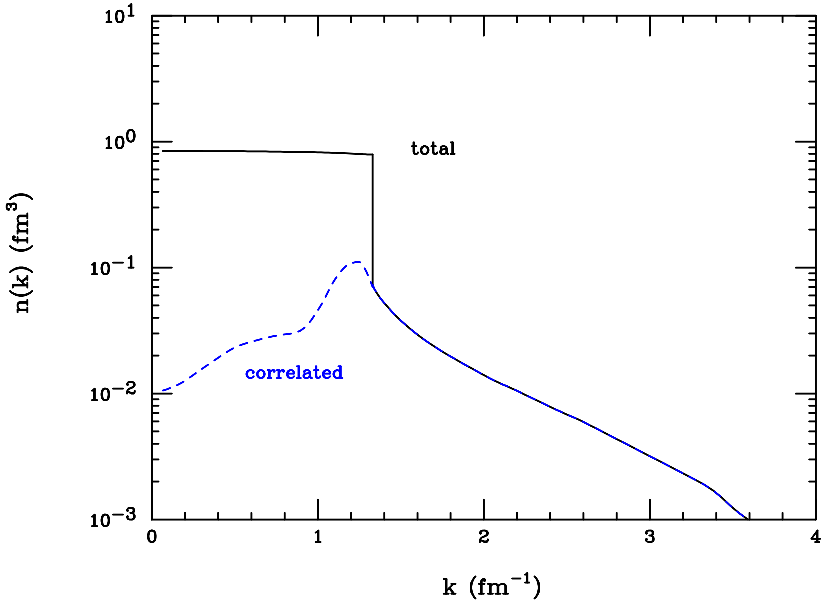
□□□□□ **QP orbital, observable *e.g.* in $^4He(e,e'p)^3H$**

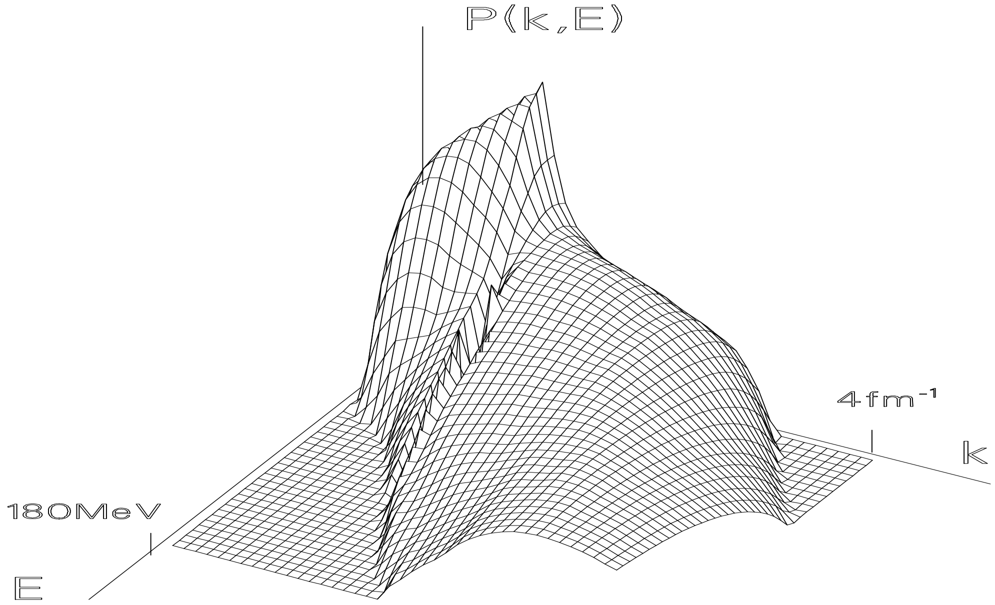
+ + + ++ **correlated strength, observable in continuum at large E**

More typical for nuclei: nuclear matter

exact calculations also feasible: CBF-theory (Benhar *et al.*)

consequences for NM momentum distribution and spectral function $S(k,E)$:





- correlations give strength at *simultaneously* large k and large E *not* large k, small E
- note: for $n(k < k_F)$ correlated- and QP-strengths overlap
- strength *very* spread out, hard to identify experimentally
- similar for finite nuclei as S_{corr} weakly dependent on NM density

Correlated N have ~20% probability (NM)

but give 37% of average removal energy

47% of average kinetic energy

(CBF calculation of Benhar, Fabrocini, Fantoni 1989)

→ mean-field approach cannot work!

exception (?): *differences* of energies, spect. factors

certainly not: absolute energies, occupations, densities

Correlated strength distributed over 100-200MeV

not observable in transfer reactions to low-lying states

invalidates 2j+1 sum-rule

Till recently: unsatisfactory situation of experiment:

have identified *missing* strength

have fair theoretical understanding

but: have not *seen* correlated strength

measured: (1–correlated strength) → large uncertainty of correlated part

(1–....) blows up uncertainty by factor of 5

Past attempts to identify strength at large k

- reactions of type (x,p)

    low momentum transfer q from x, observe high momentum p

    e.g. (γ,p), (p,p) with high-momentum backward p

problem: Amado+Woloshyn, 1977

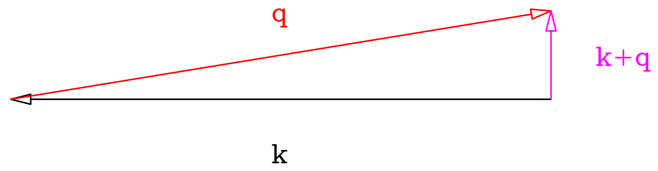
- in limit $q \to 0$ Ψ_i, Ψ_f must be $\perp$, FSI cancels IA-contribution of n(k)

    no quantitative interpretation possible

    (applies also to (p,2p), ...)

- (e,e') at large q, low ω

    idea: if $\omega \sim (\vec{k}+\vec{q})^2/2m$ small and $\vec{q}$ large, then $\vec{k} \sim -\vec{q}$, large



problem: FSI

- see Benhar, Fabrocini, Fantoni,... (1991)

    provide first treatment of FSI using Glauber, find that dominates at low ω

    but: not entirely satisfactory, still in the works

for either case: cannot address large k anyway as strength is at large E

.... this insight has yet to sink in!

Best tool to measure strength at large k *and* E: (e,e′p) at large q

must look at *both* large E *and* large k

but new complications appear:

- strength spread out over 100-200MeV

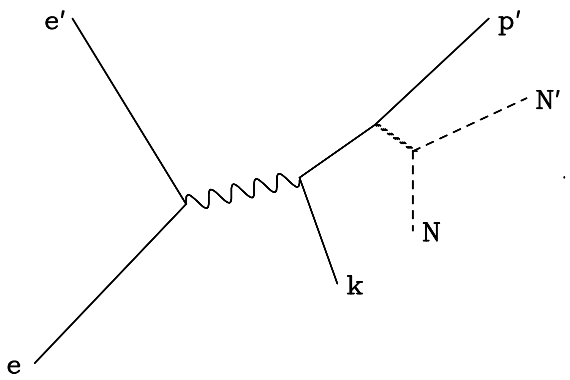
  small in given (k, E)-bin

- competing reaction mechanisms

  p rescatters, reappears at lower $k_{p'}$

  simulates large missing energy E, large k

  covers small genuine strength



- similar for $(e, e'\Delta)$, with $\Delta \rightarrow p + \pi$(undetected)

study of all available data

- compare experimental $d\sigma/d\Omega d\omega$ to IA using realistic $S(k, E)$
- understand how $(p, p'N)$ and $(e, e'p\pi)$ move strength

identify optimal kinematics: parallel, *i.e.* $\vec{q} \parallel \vec{k}$ (most data: perpendicular kin.!)

parallel kinematics minimizes rescattering *and* MEC effects

confirmed by MC calculations of Barbieri

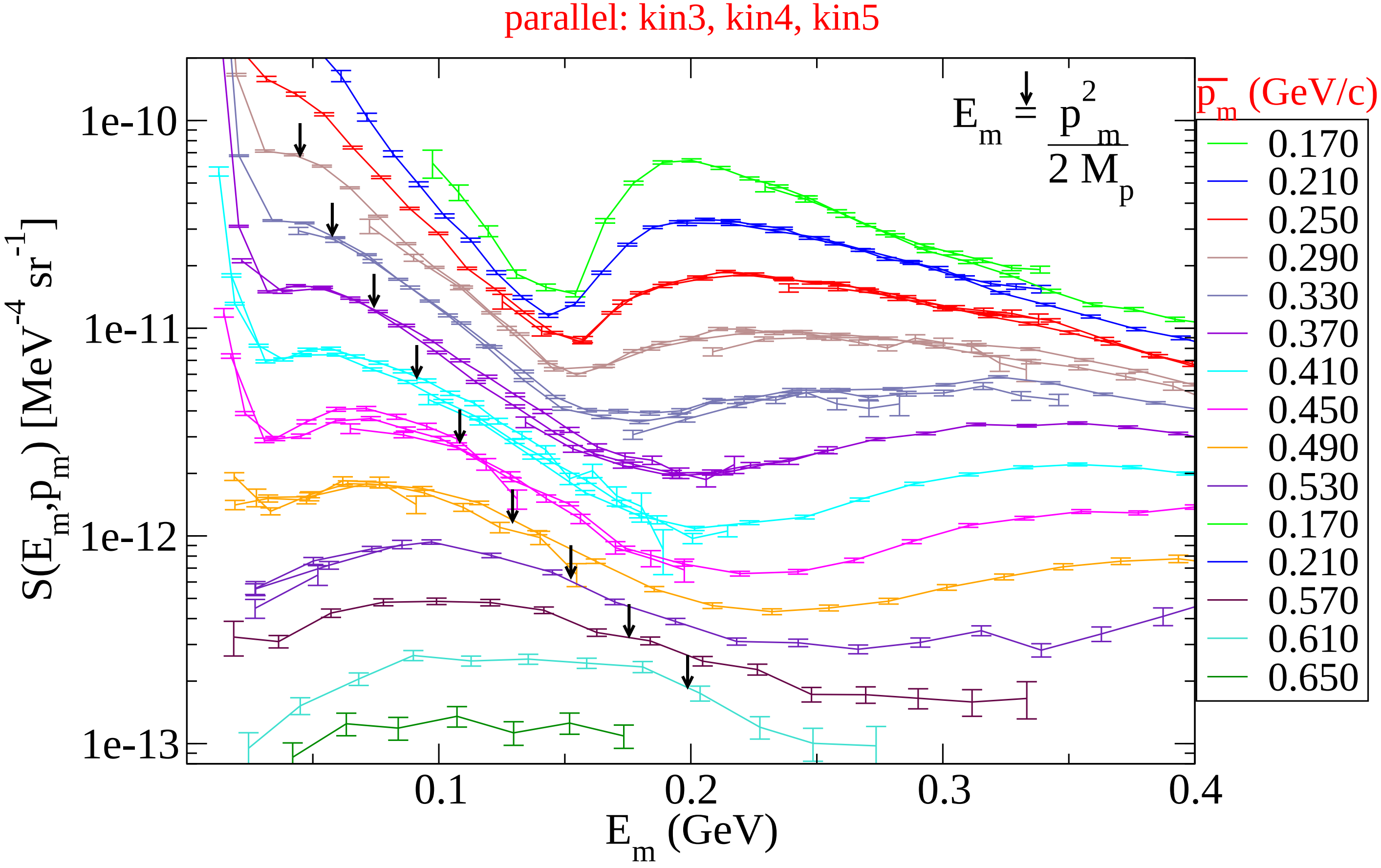
NB: if FSI substantial, must treat using Glauber or similar

optical potentials only good for outermost shell

Dedicated (e,e'p) experiment at JLab, hall C

E_e=3GeV, CW, large q, large E_p, parallel kinematics, D. Rohe *et al.* PRL 93(04)182501

Results for correlated region

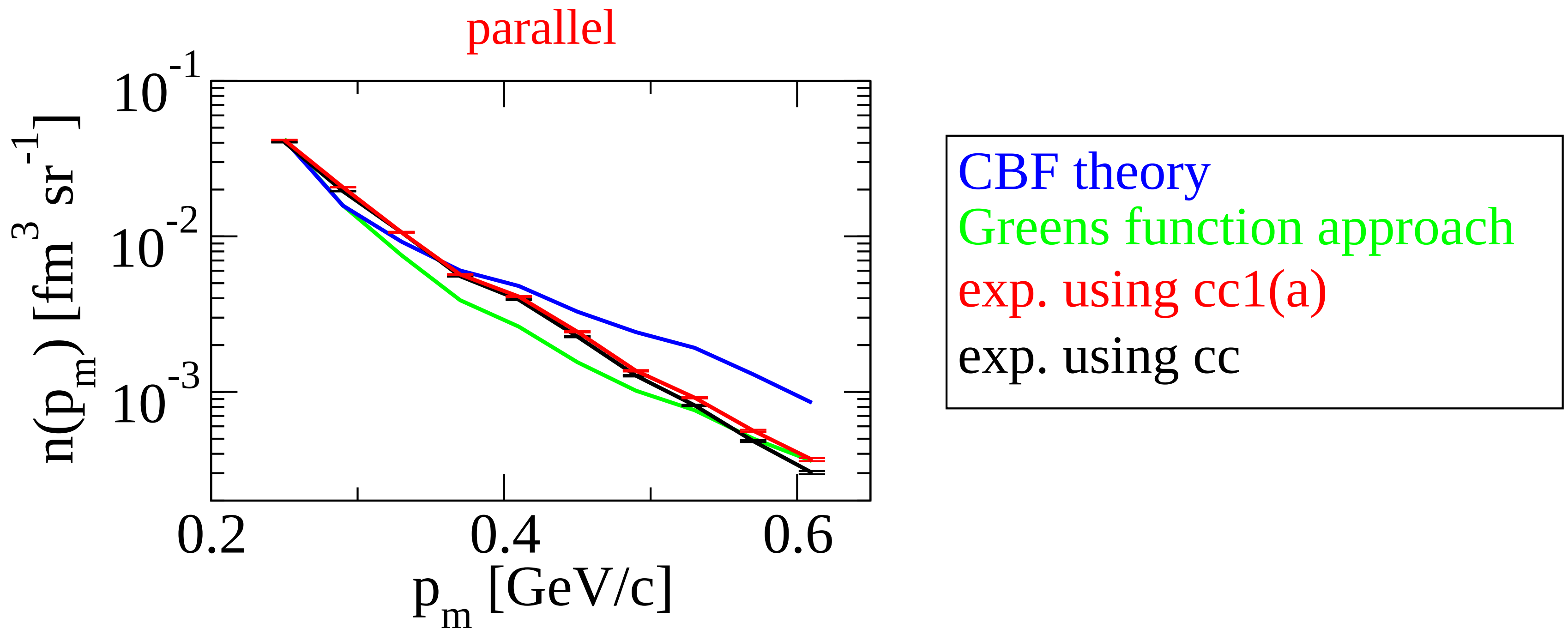


Do observe ridge at large k, E

maximum of $S(k, E)$ of data at somewhat smaller E than naively expected

understood by recent selfconsistent GF calculation of Müther+Polls?

Momentum dependence (shown only for $k > k_F$)



→ do observe predicted high-momentum tail

→ theory and experiment ± agree

→ most high-k-strength is indeed at high E

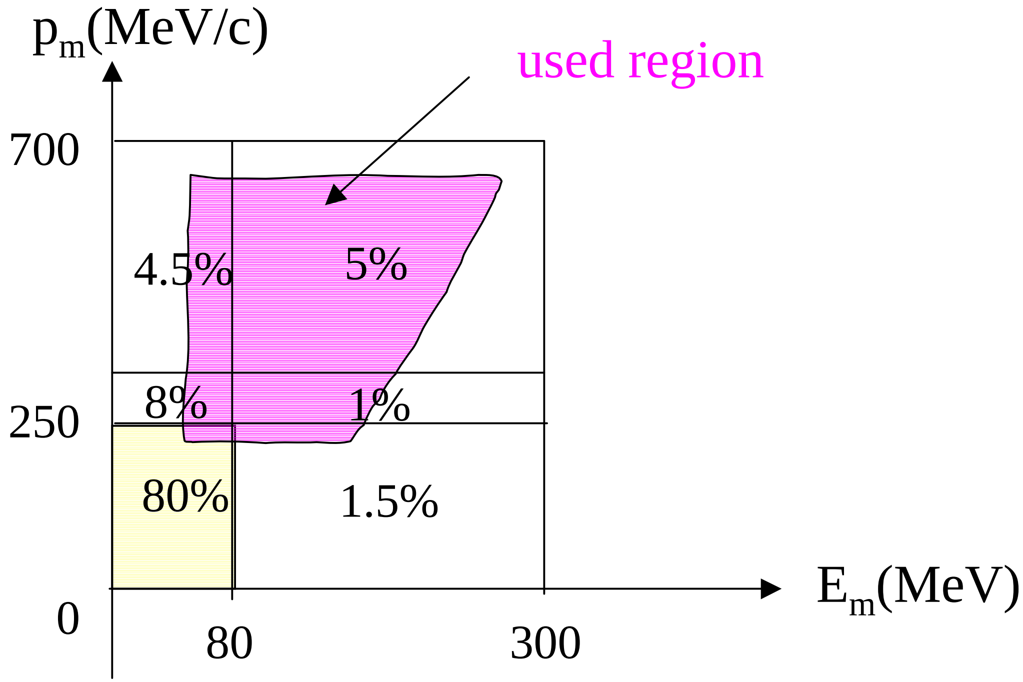
still not understood by some (see Egiyan *et al.*, PRL 96(06)82501)

How much correlated strength??

cannot integrate over entire correlated region

Δ-excitation and QP strength cover part of correlated strength

Integrate $S(k,E)$ over 'clean' region, same for data and theory



# of correlated protons in ^{12}C	used	total
integral over S from experiment	0.59	
integral over S from CBF+LDA	0.64	1.32
integral over S from SCGF	0.61	1.27

→ good agreement for 'used' region

→ can believe total from theory

→ 22%, integrated over all k, E

Overall

- have now experiment with optimized kinematics
  to minimize multi-step contributions

- have identified strength at large k, E

- theory produces $S(k, E)$ with $\pm$ correct strength
  SCGF, CBF+LDA
  E-dependence does not entirely agree
  strength at too low E
  enhancement for large A not entirely understood (not shown)

important: QP + correlated strengths add up to 1!

Intermediate summary on "mean-field vs. correlated" states

- correlations produce strength at very large k, E
- low-lying orbitals can be described by mean field (for caveat see below)
- main consequence for MF-orbitals: depopulation

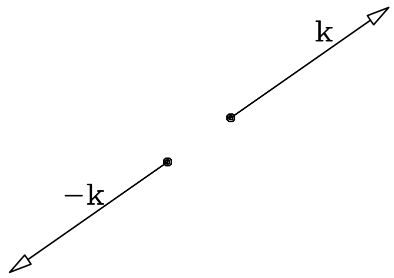
Progress of theory: can include SRC for finite nuclei
SCGF (Polls,..), FHNC (Có, ..), AFDMC (Fantoni, ..), UCOM (Roth,..)

Desirable: (e,e'p) experiment with even better optimized kinematics

Physical origin of strength at large $\boldsymbol{k}, \boldsymbol{E}$:

correlated nucleon pairs

large, opposite momenta $\boldsymbol{k}$, $-\boldsymbol{k}$

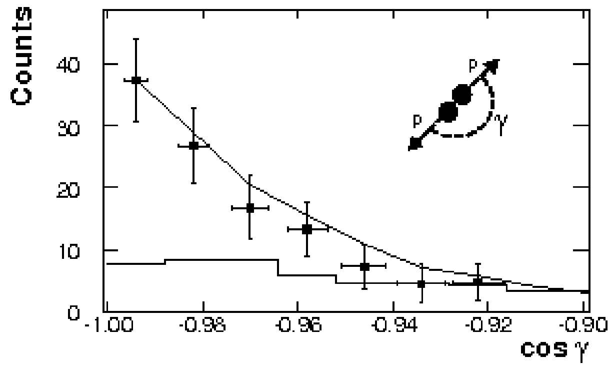


electron hits proton with $\boldsymbol{k}$, transfers $\boldsymbol{q}$

correlated partner leaves nucleus with $-\boldsymbol{k}$

kinetic energy $\boldsymbol{E} \sim (-\boldsymbol{k})^2/2M \rightarrow$ ridge in $S(\boldsymbol{k}, \boldsymbol{E})$

Shneor *et al.*, PRL



direct observation via (e,e'2p), $|\boldsymbol{k}_p| >$400MeV/c

confirms anti-correlation of p-momenta

interpretation:

a) ratio strength $\frac{^{12}C(e,e'pp)}{^{12}C(e,e'p)} \sim 0.1$

(extrapolated to full kinematical coverage)

b) add result of Schiavilla *et al.*

ratio strength $\frac{pp+np}{pp} \sim 6$ for ^{4}He and $\boldsymbol{k} >$400MeV/c

c) add transparency for second high-$\boldsymbol{k}$ proton of $\sim$0.7

$\rightarrow \frac{^{12}C(e,e'pN)}{^{12}C(e,e'p)} \sim 0.1 \cdot 6 \ / \ 0.7 \sim 0.9$

$\rightarrow$ high-$\boldsymbol{k}$ protons in (e,e'p) $\pm$ indeed all from correlated pairs, *i.e.* (e,e'p)N

Important consideration: where is correlated strength in r-space?

what is its role at large r where transfer reactions, (p,2p), .. are sensitive?

Two opposing tendencies:

- large E pulls correlated strength to small r
- higher (angular) momenta tend to shift it to larger r

which wins? 2 independent answers:

1. ρ_{corr} from Green's function theory SCGF (Müther, Polls, ..) for ^{12}C

split ρ into QP plus correlated piece

find

ρ_{corr} contributes little at large r

there tail of QP dominates completely

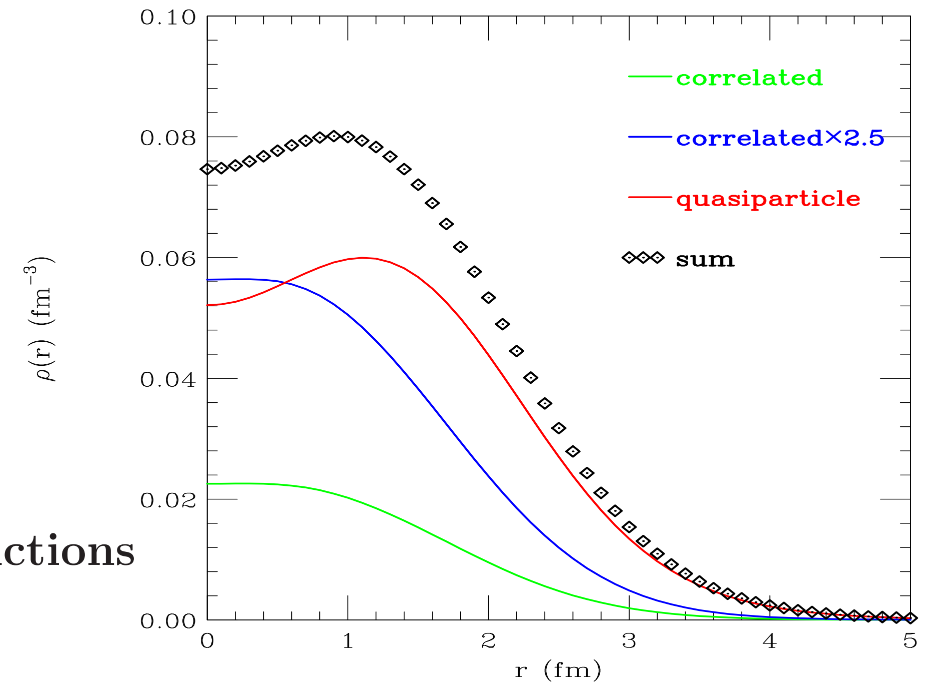
ρ_{corr} at small r *despite* contributions of large l

31% l=0, 37% l=1, rest large l

large E of states pulls $R(r)$ to small r

r ρ_{corr} contributes ∼30% of $\rho(0)$

explains small-r failure of QP wave functions



2. ρ_{corr} of ^{12}C from (e,e)+(e,e′p): $\rho_{corr}(r) = \rho(r)_{point} - \sum_{QP-orbits} FBT(R_{QP}(k))^2$

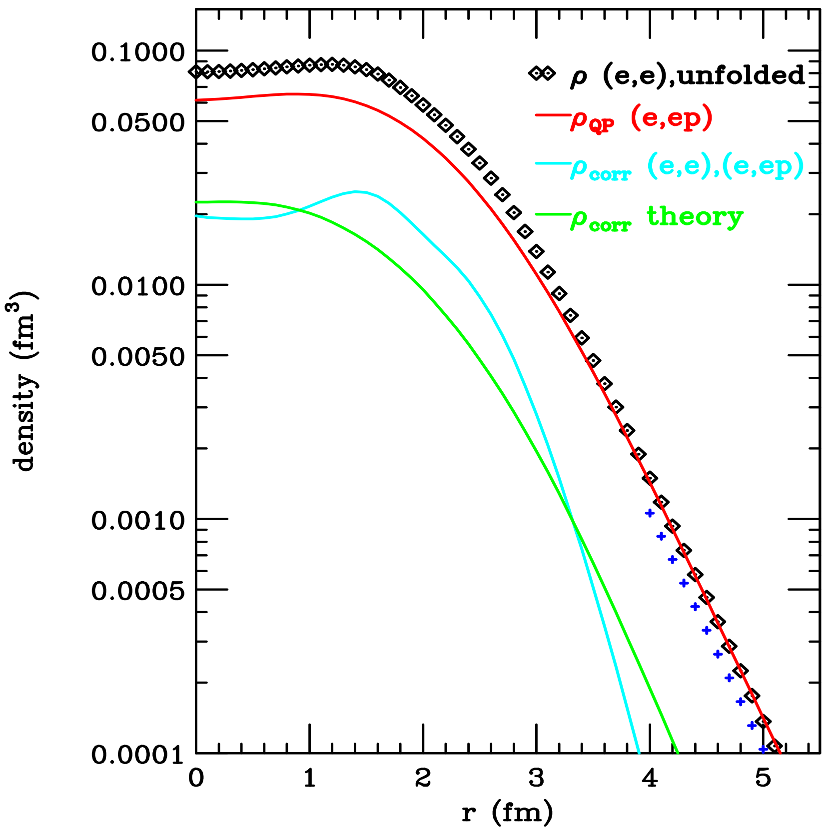
point density of C

model-independent analysis of extensive set of (e,e) data $\longrightarrow \rho_{charge}$

unfold nucleon size to get point density ρ_{point}

QP radial wave functions in r-space

Fourier-Bessel Transform of QP momentum distributions from (e,e'p), sum



Observations

ρ_{corr} concentrated toward small r

as was seen in theory

effect of large E dominating

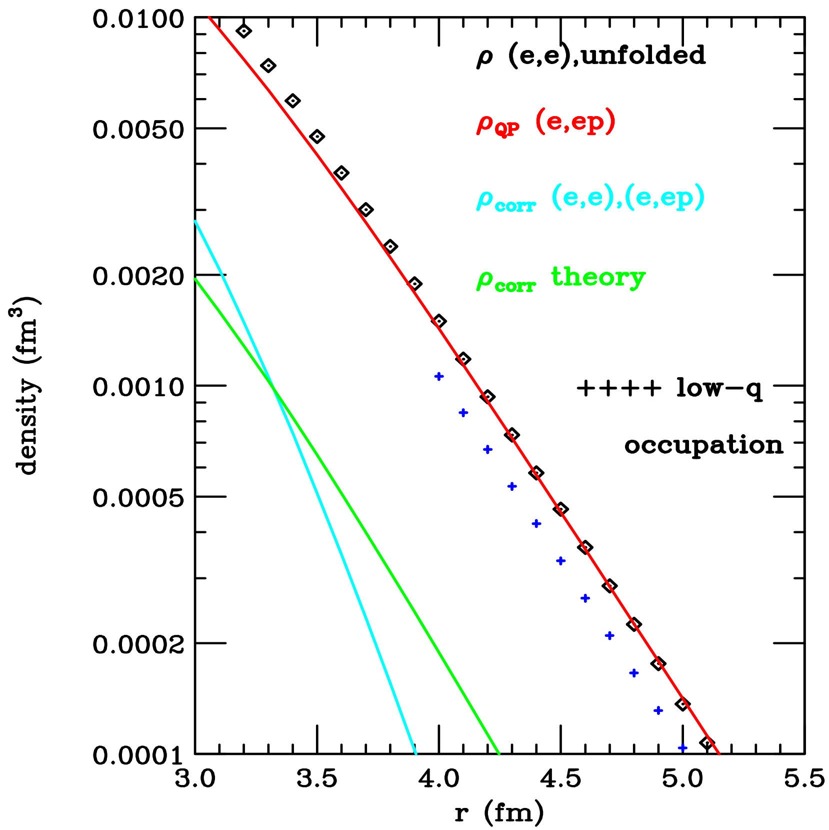
reasonable agreement with theory for ρ_{corr}

(uncertainty of ρ_{corr} ~20%)

see Müther+Sick, PRC 70(2004)41301

Important consistency check: large r

perfect agreement ρ_{QP} ... ρ_{point}
should occur as ρ_{corr} cannot contribute



surface-dominated reactions $\not\Longrightarrow$ high-k

large-r = *the* region where MF ± OK
but *is* affected by reduced occupation
(contrary to *e.g.* Tsang *et al.*, PRL 95(05)222501)

large-r = *the* region of interest to transfer, (p,2p)

large-r = *the* region where $R(r)$ is needed to get s from transfer, (p,2p),...
⇒ needs attention for study of unstable nuclei!

Cannot emphasize enough: for peripheral reactions need good $R(r)$

e.g. Gade *et al.*, PRL 93(04)42501

"Reduced occupancy of the deeply bound $d_{5/2}$ n-state in ^{32}Ar"

study reactions of type ^{9}Be(A,A–1)X, with A = exotic nucleus in beam, 65MeV/N

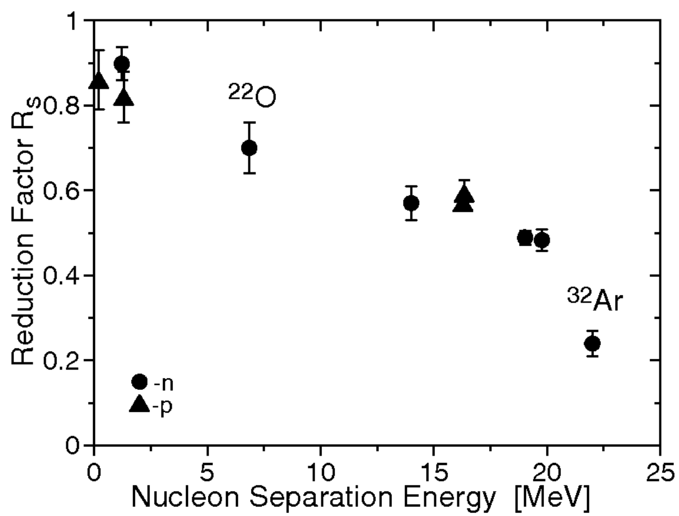
measure N-removal cross section at small θ

assume $\sigma_{exp} \sim \ R_s \ \ S \ \ \sigma_{sp}$

R_s= empirical reduction factor, S = shell-model spectr. factor

σ_{sp} = single-particle cross section, from $\rho(r)$ and t_{NN}

Find



interpret "reduction factor" R_s as reduced occupation

find *strong* reduction with increasing separation energy, R_s=0.25 for SE=23MeV

Understanding ?? no clear explanation

(e,e'p) shows *increase* of occupation for increasing SE

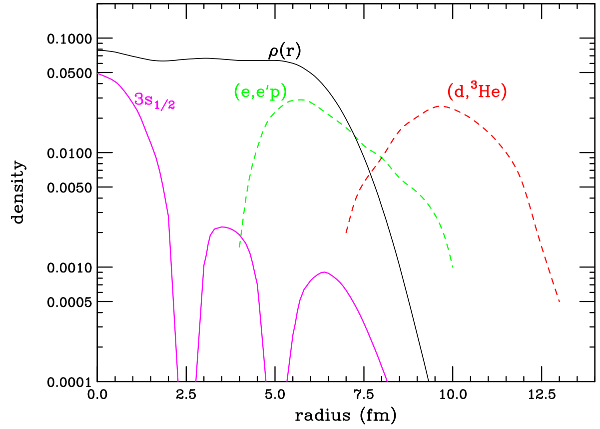
calculations for nuclear matter show *weak* dependence of occupation on N/Z

Note

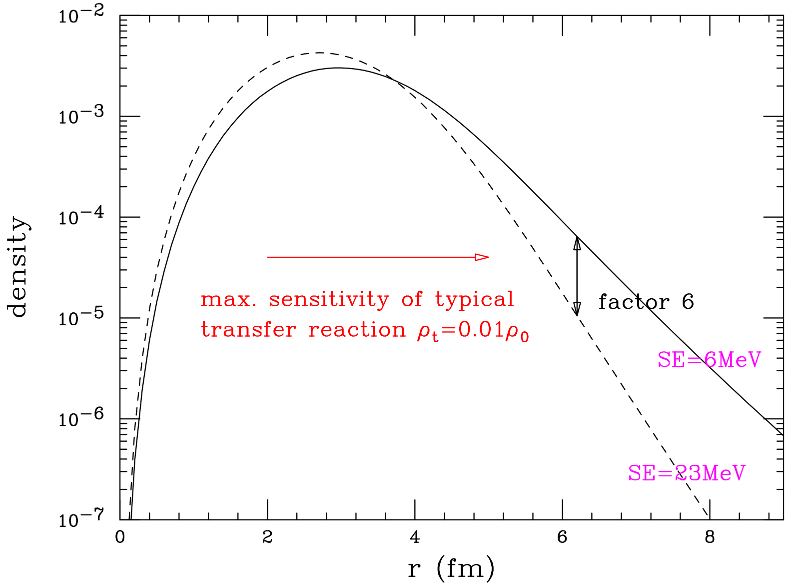
fragmentation with Be-target even more peripheral than (d,^{3}He)   (absorption!)

already (d,^{3}He) measures $R(r)$ at large radii where $\rho(r) \sim 0.01\rho(0)$

fragmentation measures only $R(r)$ at very large r



Effect of SE on $R(r)$ at large r for fixed shape of $V(r)$:



rapid fall-off of $R^2(r)$ with increasing SE

at r where $\rho = 0.01\ \rho(0)$:

SE $= 5 \longrightarrow 23$MeV changes R^2 by factor of 6

not accounted for in $\sigma_{exp} \sim\ R_s\ \ S\ \ \sigma_{sp}$

peripheral reactions measure asymptotic norm

not s, not occupation

How get $R(r)$ for exotic nuclei?

(e,e'p) would measure $R(k)$ (*i.e.* $R(r)$), transfer and (p,2p) need input-$R(r)$

most important: avoid like the plague past recipes for $R(r)$!

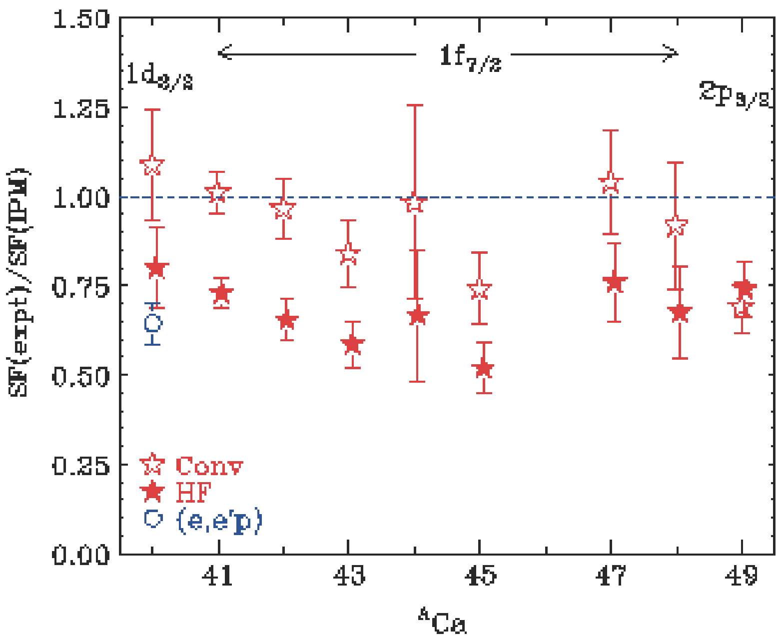
be aware of radial sensitivity of probe

Good beginning: J. Lee *et al.*, PRC 73(06)44608

use $R(r)$ from Hartree-Fock using SKX force

SKX fit to energies *and* densities of stable nuclei (fit to $\rho(r)$ important!)

radial information from $\rho(r) \rightarrow$ realistic R(r)



find spectr. factors in agreement with (e,e'p)

★ ★ ★ ★ ★

contrary to analyses with standard recipes for $R(r)$

☆ ☆ ☆ ☆ ☆

For exotic nuclei

use this SKX+HF to extrapolate *shape* of potential $V(r)$ to exotic N,Z

MF theories like HF miss much physics

but do parameterize nuclear properties $\rightarrow$ useful for extrapolation in Z or N

adjust depth of $V(r)$ to get exact SE of state

Better:

recognize that ρ_{QP} and ρ_{corr} different, particularly at large r

recognize that HF should only be compared to ρ_{QP}

make new SKX+HF-type fit (stable nuclei)

include extreme N,Z (^{48}Ca, ^{112}Sn, ^{124}Sn, ...)

fit energies + *only* large-r density (where $\rho(r)$ dominated by QP-strength)

note: $\rho(r >>)$ *is* surprisingly well determined by (e,e)

use n=0.8; at large r only QP-piece contributes

use this HF to 'extrapolate' shape of $V(r)$ to exotic N,Z

adjust depth of $V(r)$ to get exact SE

But: this does not tell how to get potentials for scattering states!

needs some further thinking (see Omar's talk)

Conclusions

different probes → different advantages/disadvantages

(e,e'p)

gives access to short-range properties (if have E_e, L!)
measures $R(k)$, s for ±all orbits — need more data on deep-lying orbits
low rates (stable isotopes for time being)

(p,2p)

measures s, $R(k)$(?) for ± all outer orbits (if have L!) — would want better data
rates OK for measuring asympt. norm at lower L (extreme N, Z), need $R(r)$

transfer

measures asymptotic normalization of outer shells
gives early access to extreme N, Z
rates OK even at rather low L
need input-$R(r)$ — learn from past experience

to make most of measured quantities

combine the advantageous features of the different probes

Some literature

overview on orbits, occupations, ...

V.R. Pandharipande *et al.*, Rev. Mod. Phys. 69 (97) 981

(e,e'p) experiments

J. Mougey *et al.*, Nucl. Phys. A262 (76) 461
P. deWitt-Huberts, J. Phys. G 16 (90) 507
L. Lapikas, Nucl. Phys. A553 (93) 297

review (e,e'p) formalism

J. Kelly, Adv. Nucl. Phys. 23 (96) 75
A. Dieperink *et al.*, Ann. Rev. Nucl. Part. Sci. 40 (90) 239
S. Boffi *et al.*, Phys. Rep. 226 (93) 1

data correlated strength

D. Rohe *et al.*, Phys. Rev. Lett. 93 (04) 182501
D. Rohe, Habilitationsarbeit, Univ. Basel, 2005