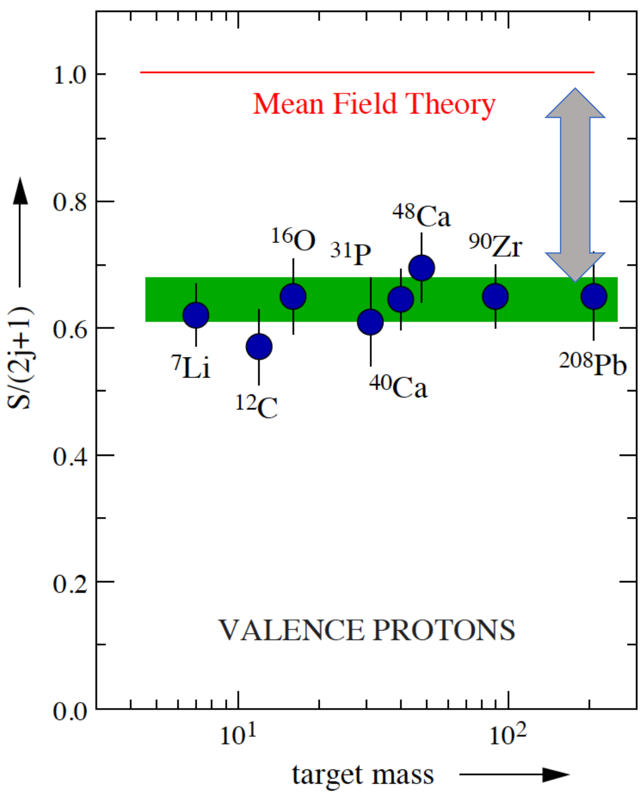
Deuteron quasi-free scattering reactions: a tool to probe nucleon-nucleon short-range correlations in atomic nuclei

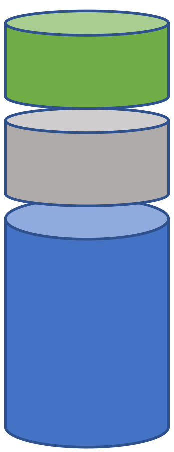
Marina PETRI

University of York

(e,e'p) experiments on stable nuclei

W.H. Dickhoff, C. Barbieri / Progress in Particle and Nuclear Physics 52 (2004) 377–496





NN Correlations (depletion of the single-particle strength)

Single-particle strength: probability of nucleons to be found as independent particles in a mean field

The nature and strength of these correlations has been the topic of intense research effort

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

High-Energy Reactions and the Evidence for Correlations in the Nuclear Ground-State Wave Function*

K. A. Brueckner, R. J. Eden,† and N. C. Francis
Indiana University, Bloomington, Indiana
(Received January 13, 1955)

V. CONCLUSIONS

We have analyzed evidence derived from a variety of high-energy experiments which has bearing on the problem of nuclear structure. This evidence is particularly significant since it is for these (or similar) processes that the possible departure of the nuclear ground-state wave function from an independent-particle wave function is most apparent. The result predicted uniformly by the group of quite diverse experiments which we have examined is that the nuclear ground-state wave function must have a very marked admixture of high-momentum components and hence must depart quite appreciably from an independent-particle-model wave function. Consequently it follows that the usual assumptions of the shell-model theory of the nucleus, that the particles move independently in a uniform potential, cannot be other than very approximately correct.

1.D.2

Nuclear Physics **A112** (1968) 204—208; © *North-Holland Publishing Co., Amsterdam*

EFFECTIVE MASS IN NUCLEI

G. F. BERTSCH and T. T. S. KUO

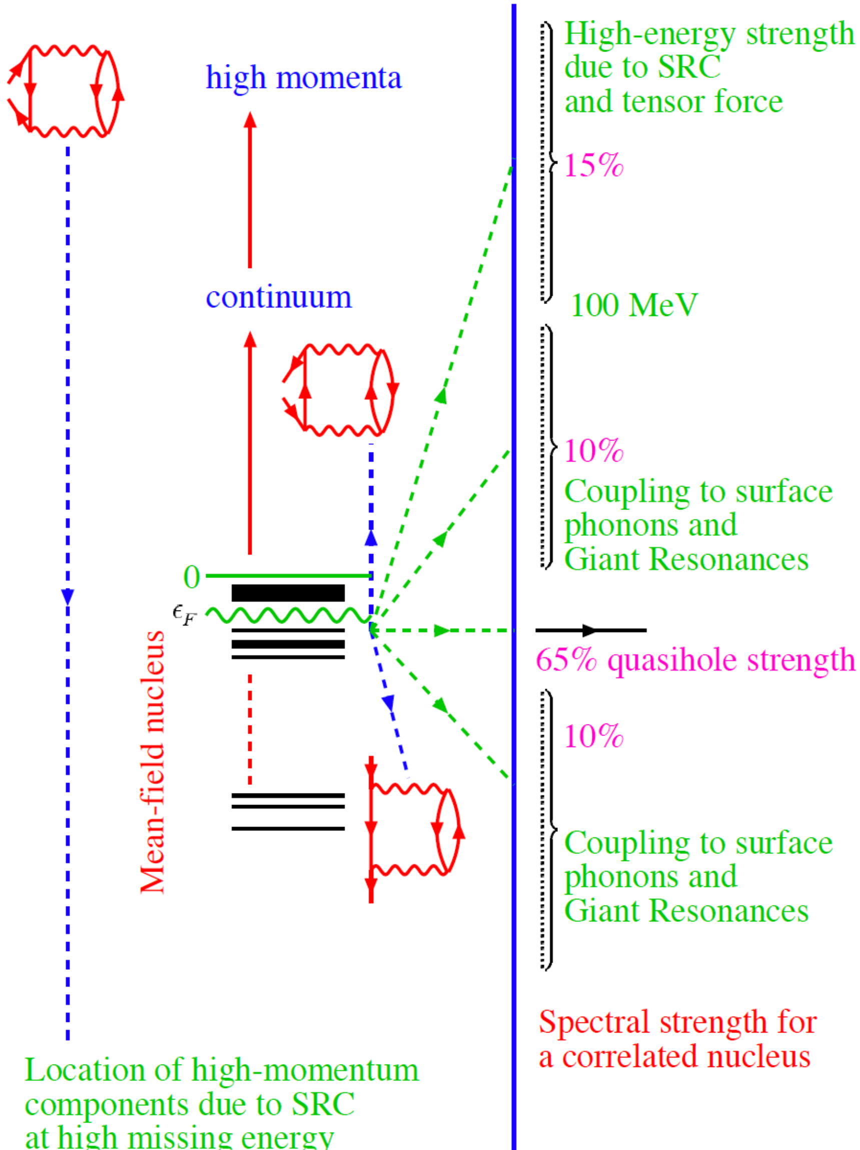
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey †

Received 6 February 1968

Abstract: Core polarization renormalizes the single-particle strength by ≈ 25 % in intermediate and heavy nuclei. This produces a corresponding increase in the effective mass of particles near the Fermi surface.

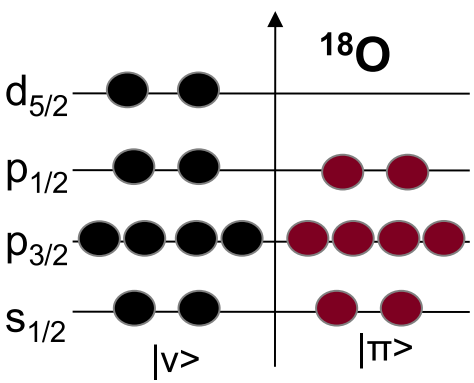
Also, the short-range correlations give a single-particle strength depletion of the order of 15 %. The effect from low energy excitations is considerably larger, of the order of 25 %, so it is clear that proper counting will not change the result very much.

Short-Range vs Long-Range Correlations (SRC vs LRC)


high momenta
continuum
0
ϵ_F
Mean-field nucleus
Location of high-momentum
components due to SRC
at high missing energy
High-energy strength
due to SRC
and tensor force
15%
100 MeV
10%
Coupling to surface
phonons and
Giant Resonances
65% quasihole strength
10%
Coupling to surface
phonons and
Giant Resonances
Spectral strength for
a correlated nucleus

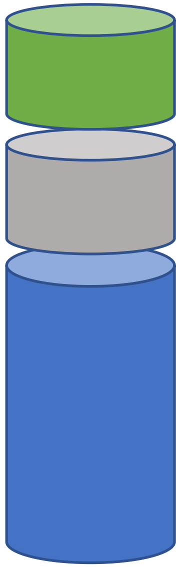
How do we probe the (quenching of) single-particle strength?

through cross sections for removing/adding a nucleon from a given nucleus and ending up at a given final state



Removal by:

- High-energy electron scattering
- Transfer reactions
- Hadronic quasi-free scattering
- One-nucleon removal reactions



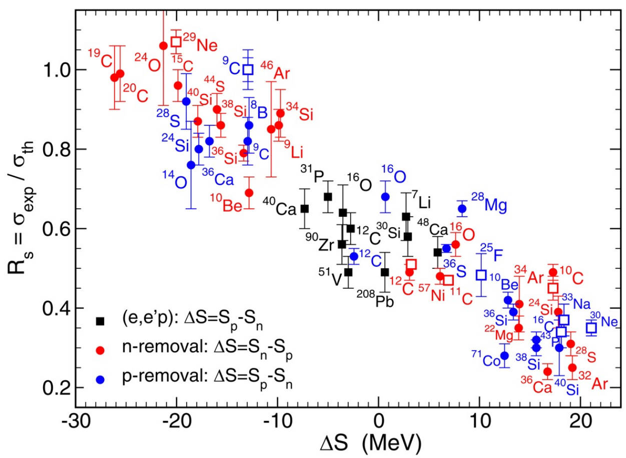
The depletion of single-particle strength is quantified as quenching of spectroscopic factors (SFs) with respect to the IPM limit.

The depletion of single-particle strength is quantified as quenching of spectroscopic factors (SFs) with respect to the IPM limit.

PHYSICAL REVIEW C **103**, 054610 (2021)

Updated systematics of intermediate-energy single-nucleon removal cross sections

J. A. Tostevin[1] and A. Gade[2,3]

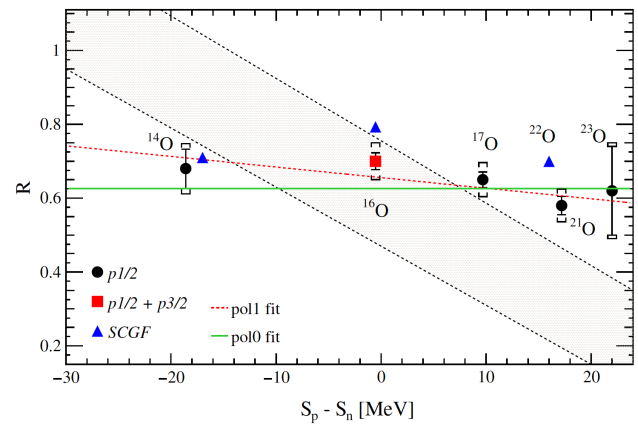


PHYSICAL REVIEW LETTERS **120**, 052501 (2018)

Quasifree (*p*, 2*p*) Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength

L. Atar,[1,2*] S. Paschalis,[3,1] C. Barbieri,[4] C. A. Bertulani,[5] P. Díaz Fernández,[6] M. Holl,[1] M. A. Najafi,[7] V. Panin,[1,8] H. Alvarez-Pol,[6] T. Aumann,[1,2,†] V. Avdeichikov,[9] S. Beceiro-Novo,[6] D. Bemmerer,[10] J. Benlliure,[6] J. M. Boillos,[6,2]

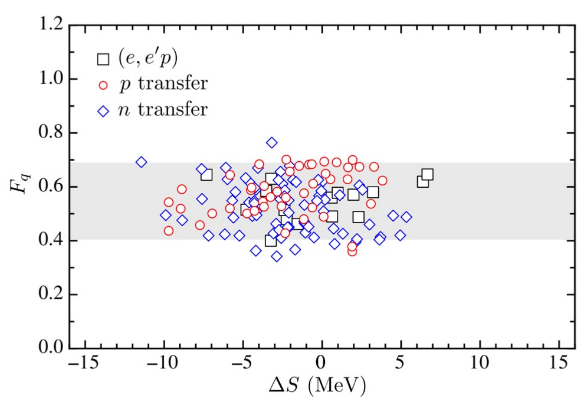
.....



PRL **111**, 042502 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

Quenching of Cross Sections in Nucleon Transfer Reactions

B. P. Kay,[1,2,*] J. P. Schiffer,[1] and S. J. Freeman[3]



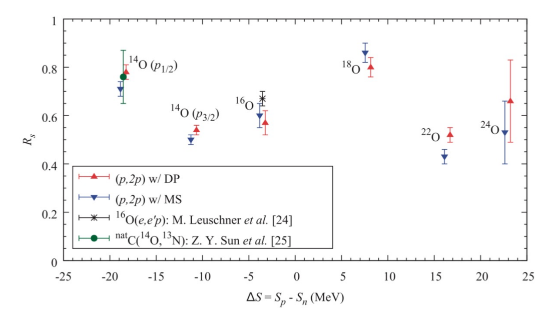
PTEP

Prog. Theor. Exp. Phys. **2018**, 021D01 (8 pages)
DOI: 10.1093/ptep/pty011

Letter

Exclusive quasi-free proton knockout from oxygen isotopes at intermediate energies

Shoichiro Kawase[1,14,*], Tomohiro Uesaka[2], Tsz Leung Tang[1], Didier Beaumel[3],
.....

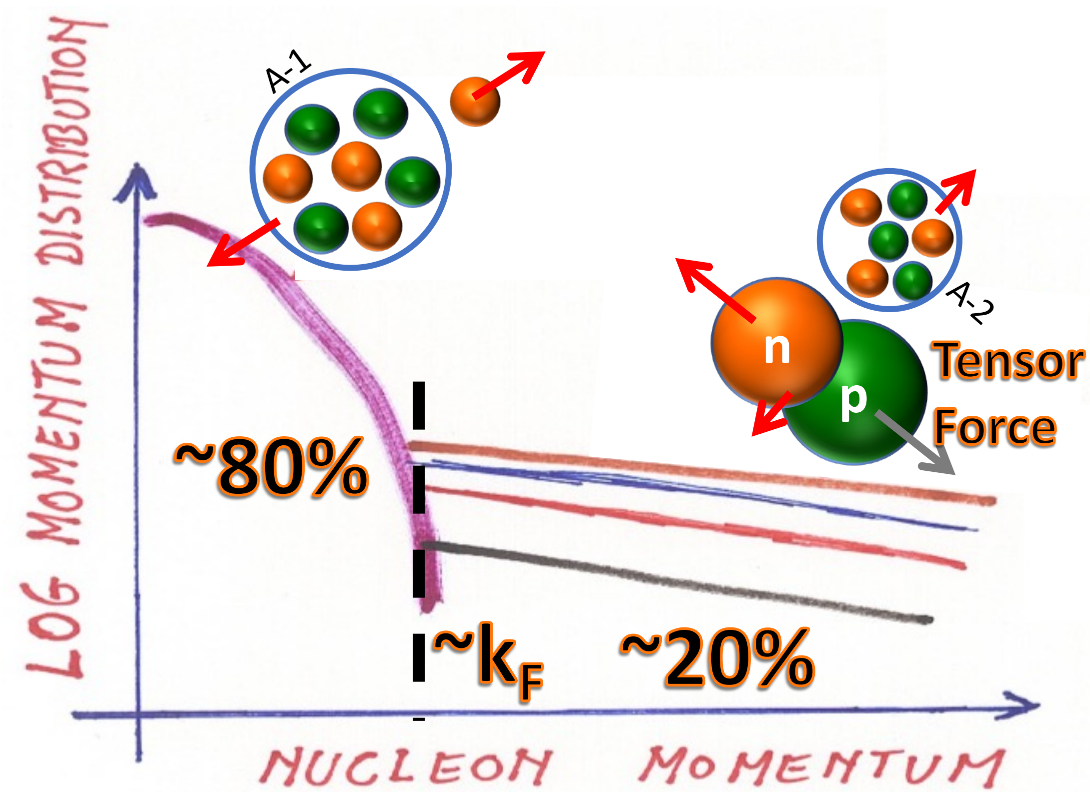


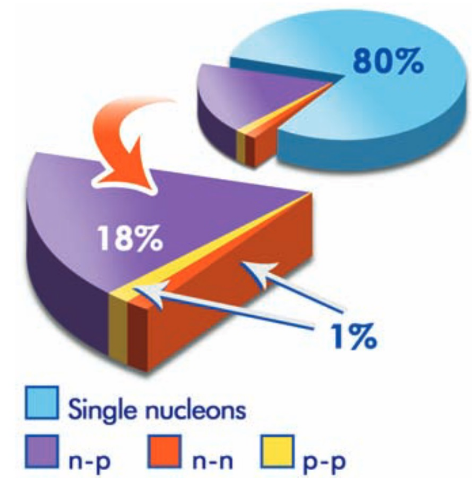
Open questions:

- What are the individual contributions of LRC and SRC to the observed depletion (quenching) of single-particle strength?

- What is the isospin dependence of these contributions, and how do they compete in very asymmetric nuclei?

Results from JLab on Short-Range Correlations (SRC)

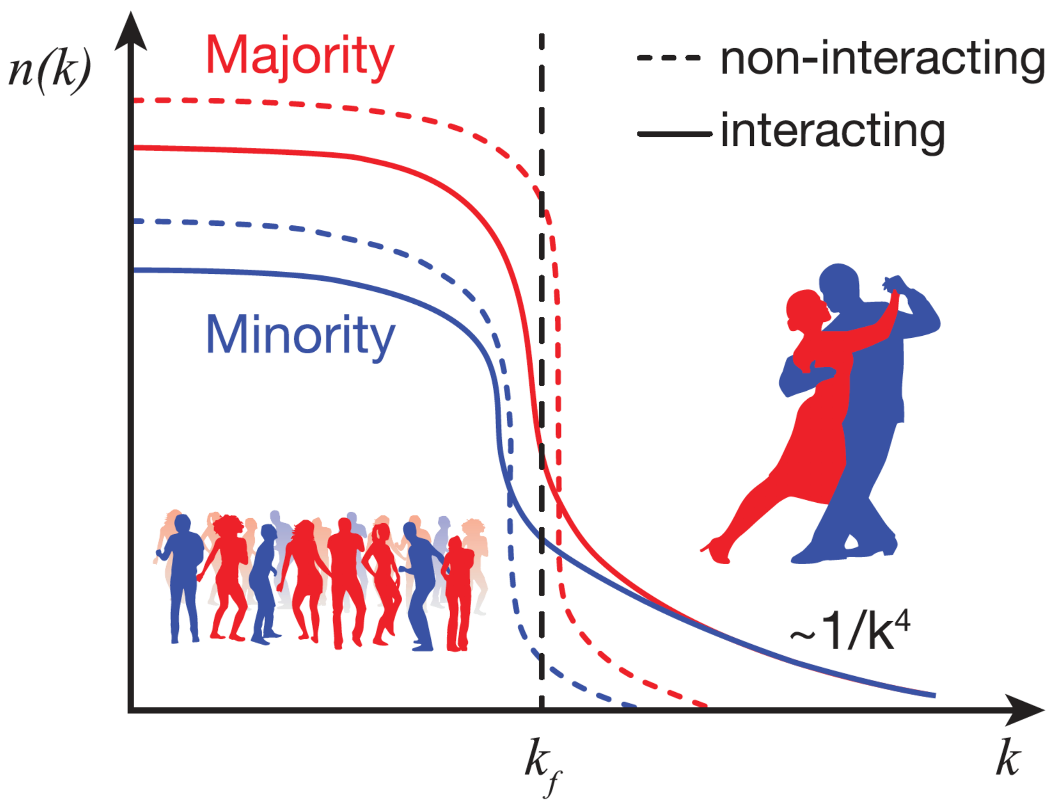




Manifestation of tensor part of the NN interaction which favours the S=1, T=0 (quasi-deuteron) channel

Duer, Nature (2018); Cohen, PRL (2018); Hen, RMP (2017); Hen, Science (2014); Hen, PLB (2013) Korover, PRL (2014); Fomin, PRL (2012); Subedi, Science (2008); Piasetzky, PRL (2007); Egiyan, PRL (2006)

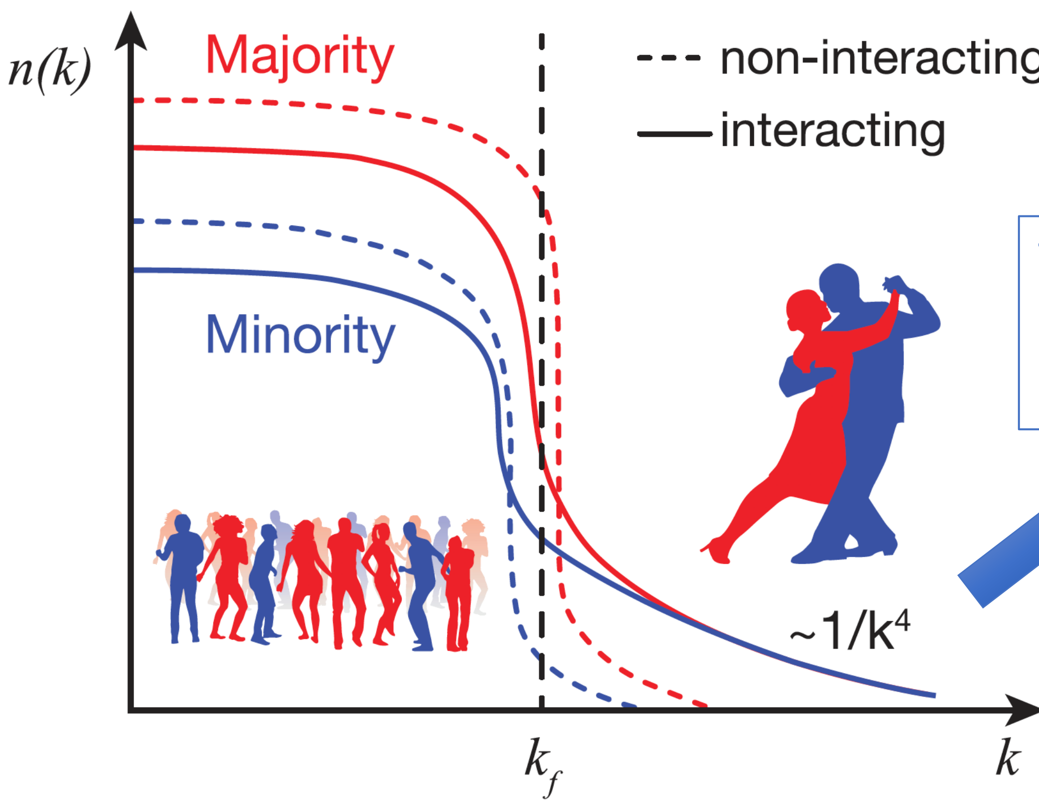
In asymmetric nuclei, the minority nucleons must be moving on average with higher kinetic energies than the majority as they have to pair more often with their partners in SRC pairs, i.e., they spent more time in the high momentum part of the momentum density distribution.



O. Hen et al., Science **346** (2014) 614

The concept

Minority nucleons have on average much higher kinetic energy

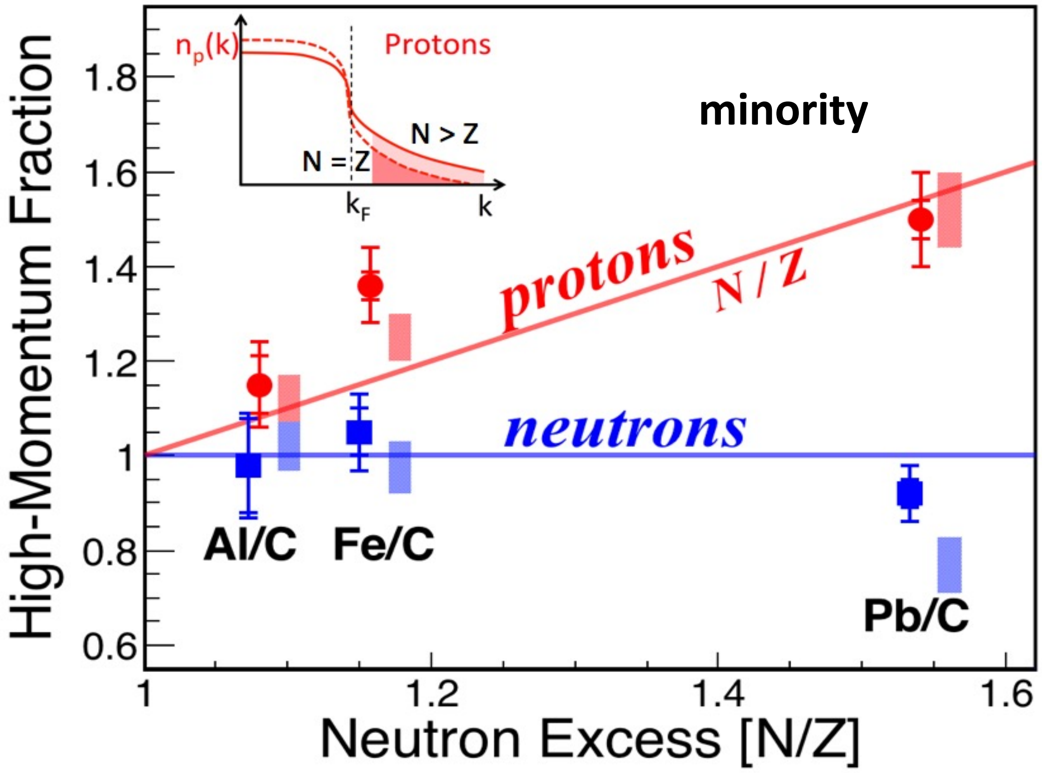


This must be reflected in the SF of the minority nucleons (protons)

Discussions with Stefanos Paschalis and Augusto Macchiavelli

SRC: Quantitative information from JLAB

The double ratio of the number of (e,e'p) high-momentum proton events to low-momentum proton events for a nucleus A relative to carbon



M. Duer et al., Nature **560** (2018) 617

To study the consistency between SRC experimental results and SFs, we introduce a phenomenological model to estimate the total "missing strength" in terms of contributions from LRC and SRC components.

Physics Letters B 800 (2020) 135110

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PHYSICS LETTERS B

Nucleon-nucleon correlations and the single-particle strength in atomic nuclei

Check for updates

S. Paschalis [a,*], M. Petri [a], A.O. Macchiavelli [b], O. Hen [c], E. Piasetzky [d]

[a] *Department of Physics, University of York, York, YO10 5DD, UK*
[b] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[c] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[d] *School of Physics and Astronomy, Tel Aviv University, Tel Aviv, 69978, Israel*

single-particle configuration

Particle-vibration coupling

Pairing correlations

Short-range correlations

$$|\mathrm{qp}\rangle = K_{SP}|SP\rangle + K_{PVC}|PVC\rangle + K_{PC}|PC\rangle + K_{SRC}|SRC\rangle$$

$$\underbrace{K_{PVC}|PVC\rangle + K_{PC}|PC\rangle}_{\text{LRC}}$$

-Probability to find a nucleon in the pure single-particle configuration is $R = K_{SP}^2$
-In the absence of NN correlations $R = K_{SP}^2 = 1$
-In the presence of correlations $R < 1$ (quenched)

We define R as the total single-particle quenching factor where the missing part of the single-particle strength is distributed to the correlation terms

$$R = 1 - \underbrace{(R_{PVC} + R_{PC} + R_{SRC})}_{\text{Missing strength}}$$

PVC

a single particle near a doubly-magic core is removed from its shell by coupling to surface phonons

R can be estimated by the amplitude of the coupling term, which is proportional to the collectivity of the phonon and the radial form factor:

$$R_{PVC} \propto \left(\frac{\varepsilon_\lambda}{\hbar\omega_0}\right)^2 \left(\frac{\partial V}{\partial r}\right)^2$$

The potential depth (V) for a proton is usually parametrized as:

$$V = V_0\left(1 + \kappa\frac{N-Z}{A}\right)$$

$$R_{PVC} = \alpha\left(1 + \frac{33}{51}\frac{N-Z}{A}\right)^2$$ potential by Bohr & Mottelson

PC

effect of fragmentation due to pairing (vibration) correlations

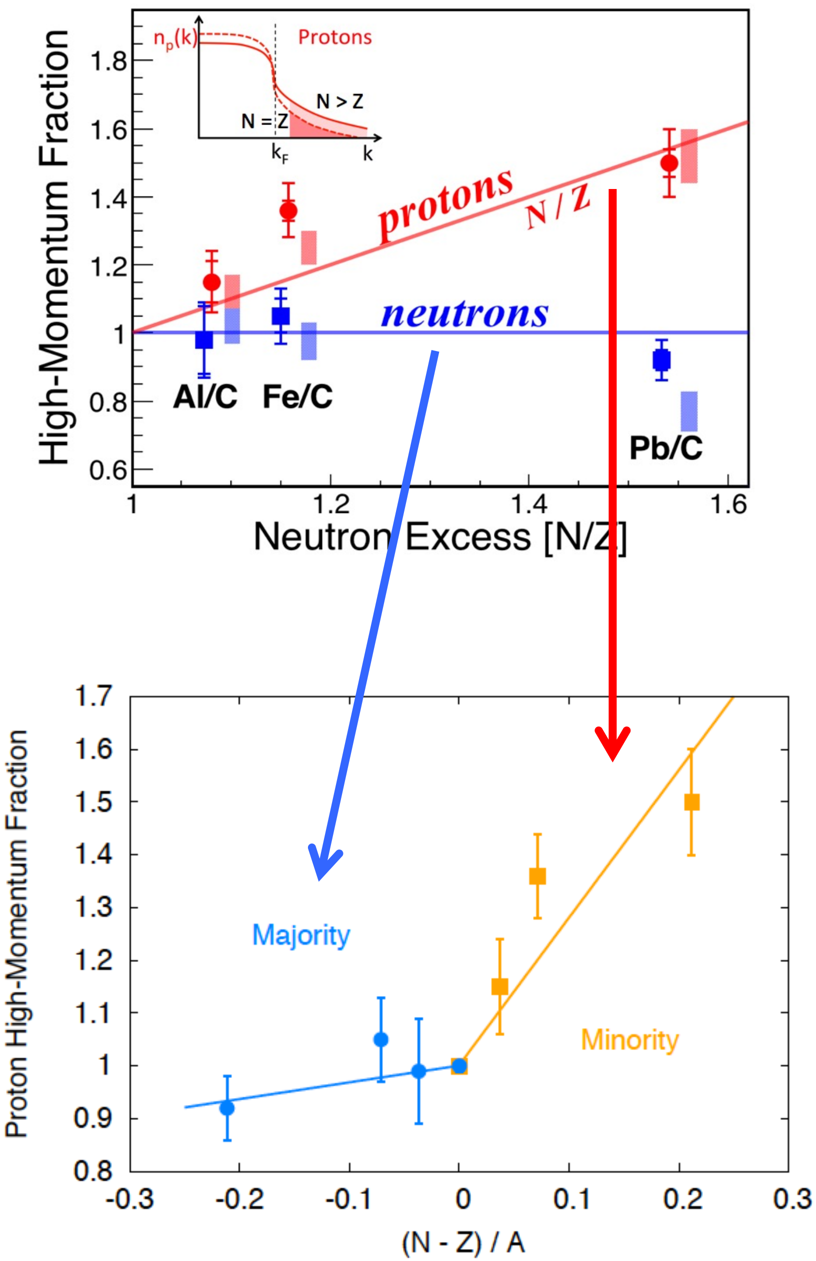
The mixing amplitude is proportional to lowest order to the ratio of the pairing gap to a typical shell gap $\Delta/\hbar\omega_0$

Pairing gap from Nuclear Physics A431 (1984) 393-418
© North-Holland Publishing Company

$$R_{PC} \propto \left(\frac{\Delta}{\hbar\omega_0}\right)^2 = \beta\left(1 - 6.07\left(\frac{N-Z}{A}\right)^2\right)^2$$

For doubly magic nuclei pairing vibrations will introduce 2p2h admixtures in the unperturbed 0p0h ground state configuration; we can make a simple estimate of β as $((7.55/A^{1/3})/(41/A^{1/3}))2 \approx 0.03$

JLAB, M. Duer et al.



SRC

$$N > Z:\ R_{SRC} = \gamma\left(1 + SL^{p}_{SRC}\frac{N-Z}{A}\right)$$

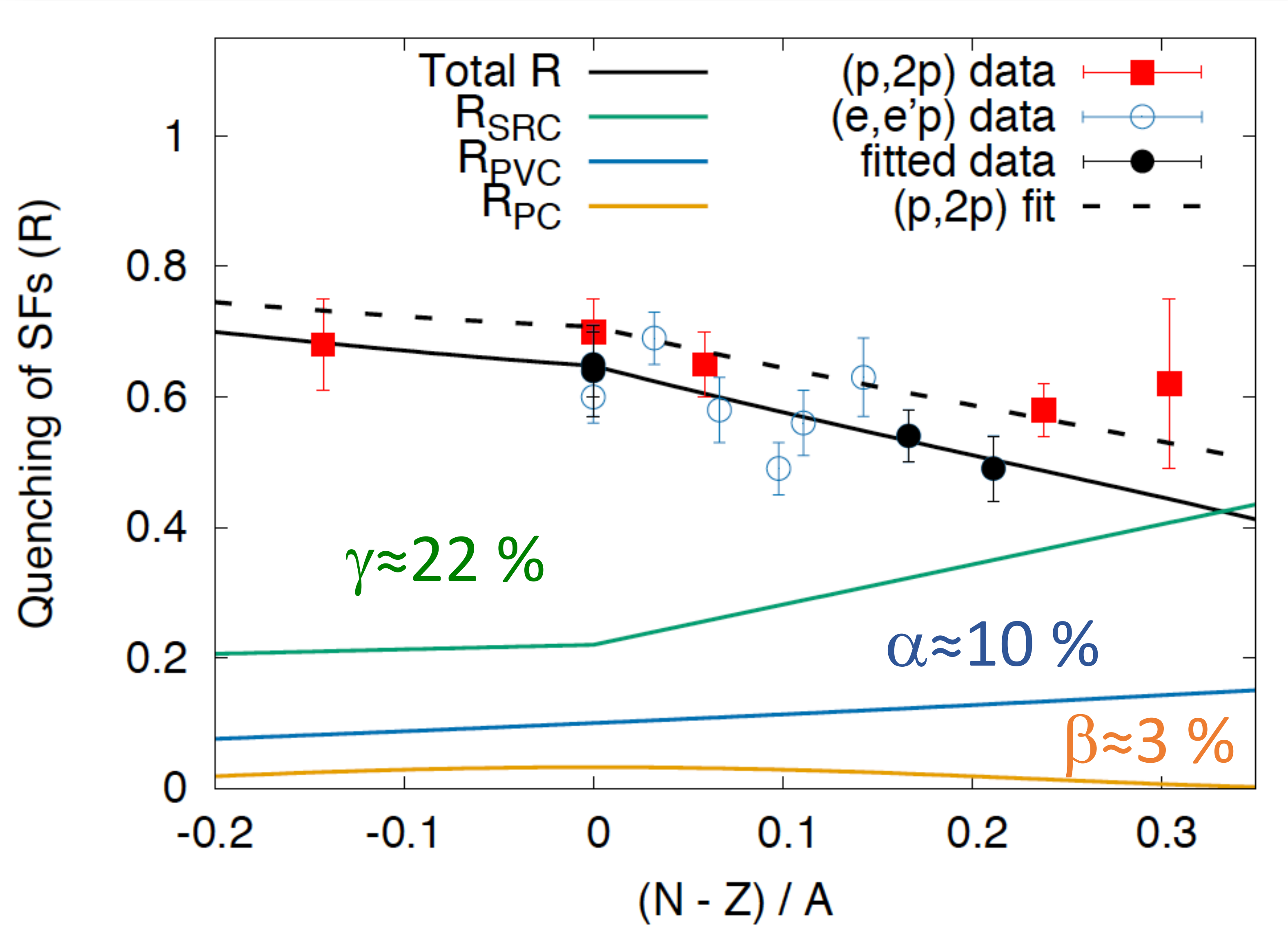
$$N < Z:\ R_{SRC} = \gamma\left(1 + SL^{n}_{SRC}\frac{N-Z}{A}\right)$$

$$SL^{p}_{SRC} = 2.8 \pm 0.7$$

$$SL^{n}_{SRC} = 0.3 \pm 0.2$$

We parameterize the dependency of the SRC component with isospin

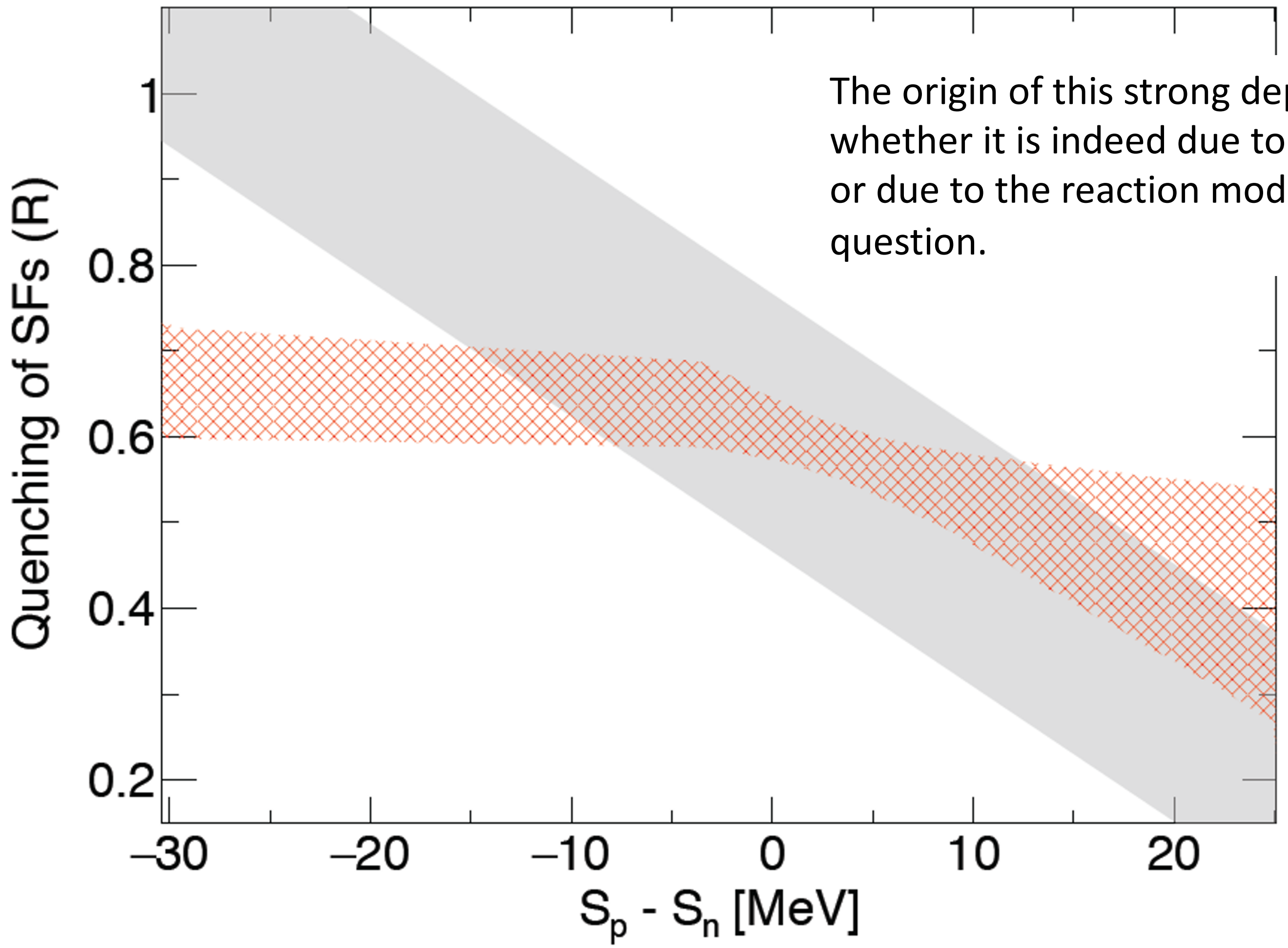
Our results



Kramer, et al., NPA **679** (2001) 267; Lee, et al., PRC **73** (2006) 044608; Atar et al., PRL 120 (2018) 052501

Our results compared to the trend from knockout data of Tostevin, Gade PRC 103 (2021) 054610

(converting A,Z,N → S_n and S_p)



The origin of this strong dependence (i.e. whether it is indeed due to NN correlations or due to the reaction model) is an open question.

Our results suggest that the theory of the reaction mechanism is playing a role in the strong measured ΔS dependency

Quenching of single-particle strengths in direct reactions

J. Manfredi,[1,2,*] J. Lee,[3] A. M. Rogers,[4] M. B. Tsang,[1,2] W. G. Lynch,[1,2] C. Anderson,[1] J. Barney,[1,2] K. W. Brown,[1,5] B. Brophy,[1] G. Cerizza,[1] Z. Chajecki,[6] G. Chen,[6] J. Elson,[5] J. Estee,[1,2] H. Iwasaki,[1,2] C. Langer,[1,7] Z. Li,[8] C. Loelius,[1,2] C. Y. Niu,[1,8] C. Pruitt,[5] H. Setiawan,[1,2] R. Showalter,[1,2] K. Smith,[9] L. G. Sobotka,[5] S. Sweany,[1,2] S. Tangwancharoen,[1,2] J. R. Winkelbauer,[1,2] Z. Xiao,[10] and Z. Xu[3]

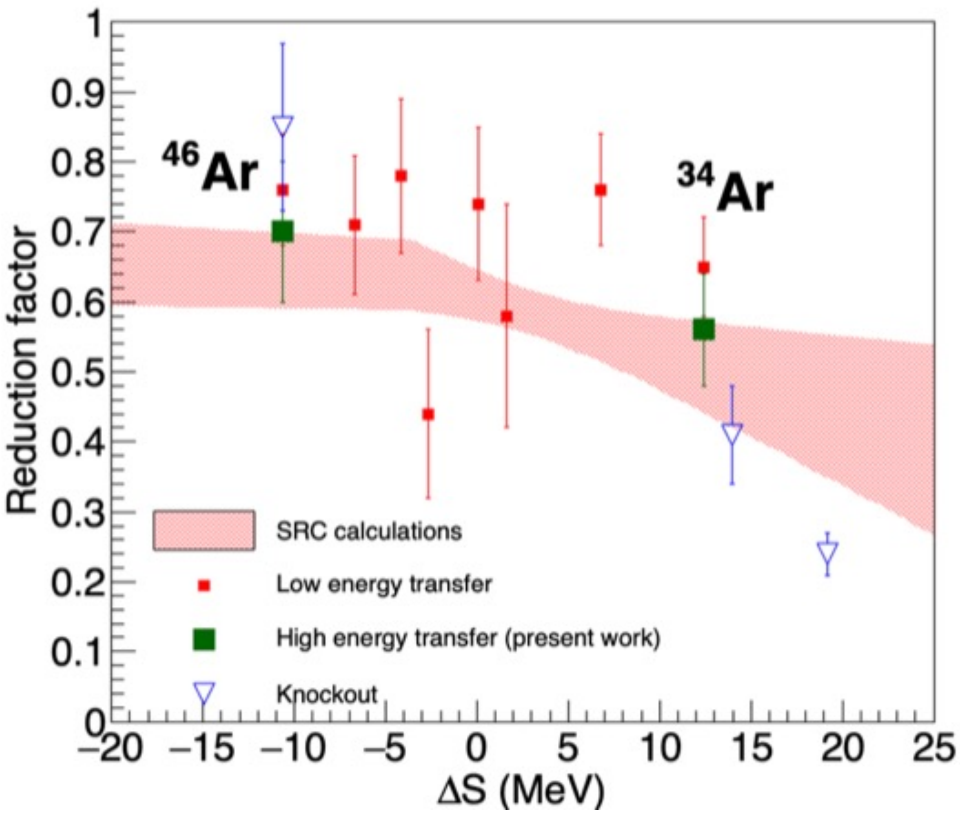
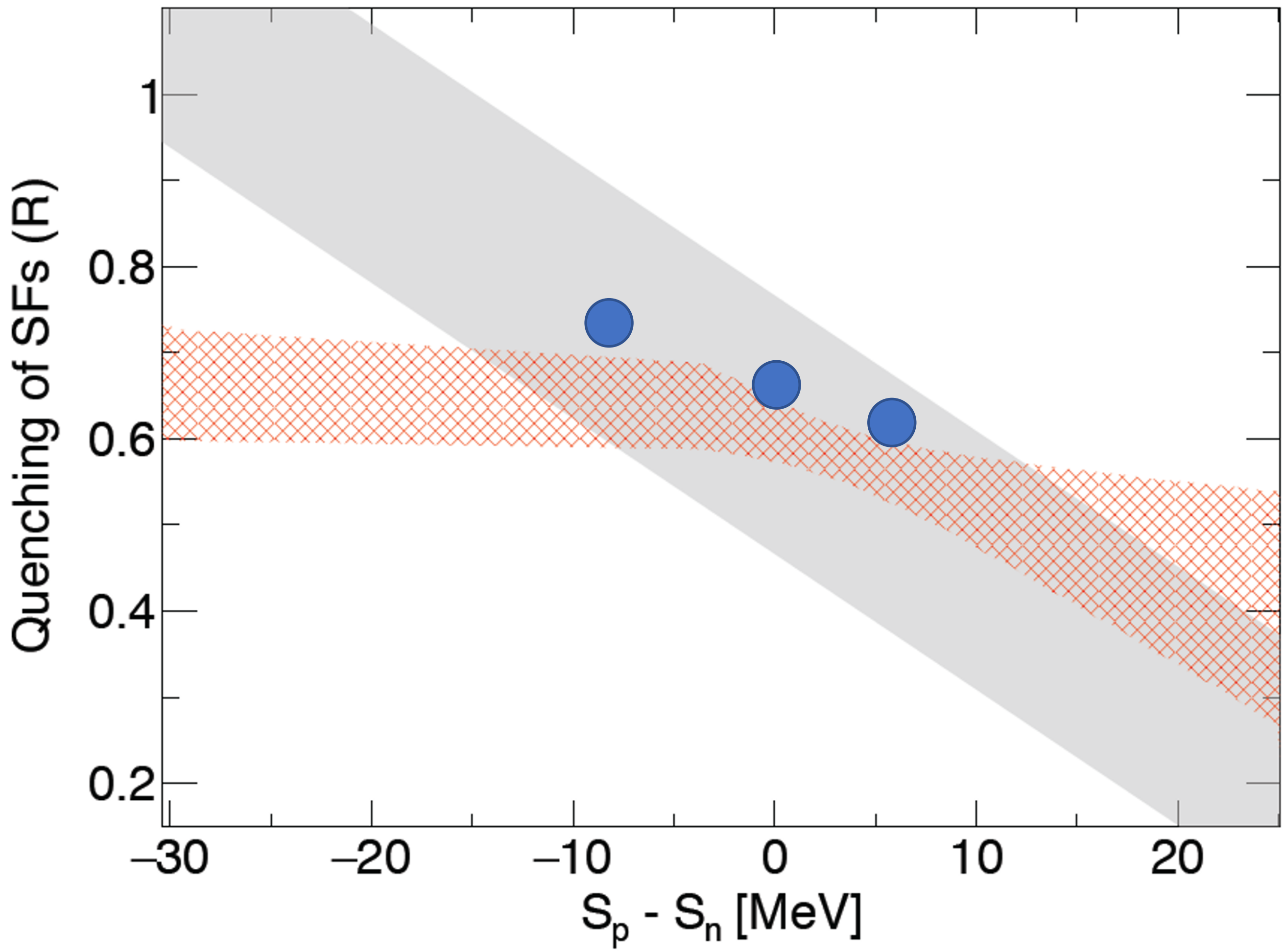


Figure adapted from the paper

DOM results – very roughly placed on the plot



W. Dickhoff, private communication

Further experimental work needed

- Measure the quenching of SFs in stable nuclei with higher precision (using EM and hadronic probes)
- Study of (p,2p) reactions in very asymmetric nuclei
- Extend those studies to neutron removal reactions

S467

Single-particle structure of neutron-rich Ca isotopes: shell evolution along Z=20

Start: late on **20.02.2020**

End: **26.02.2020**, 08:00

Spokespersons

S. Paschalis (UYork)

M. Petri (UYork)

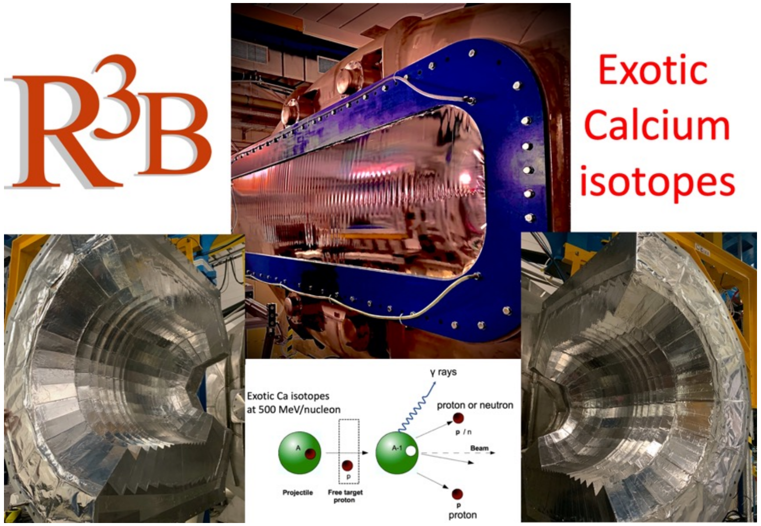
Ion: ^{86}Kr via FRS

Energy: 580 AMeV

Intensity: 2x10^{9} pps

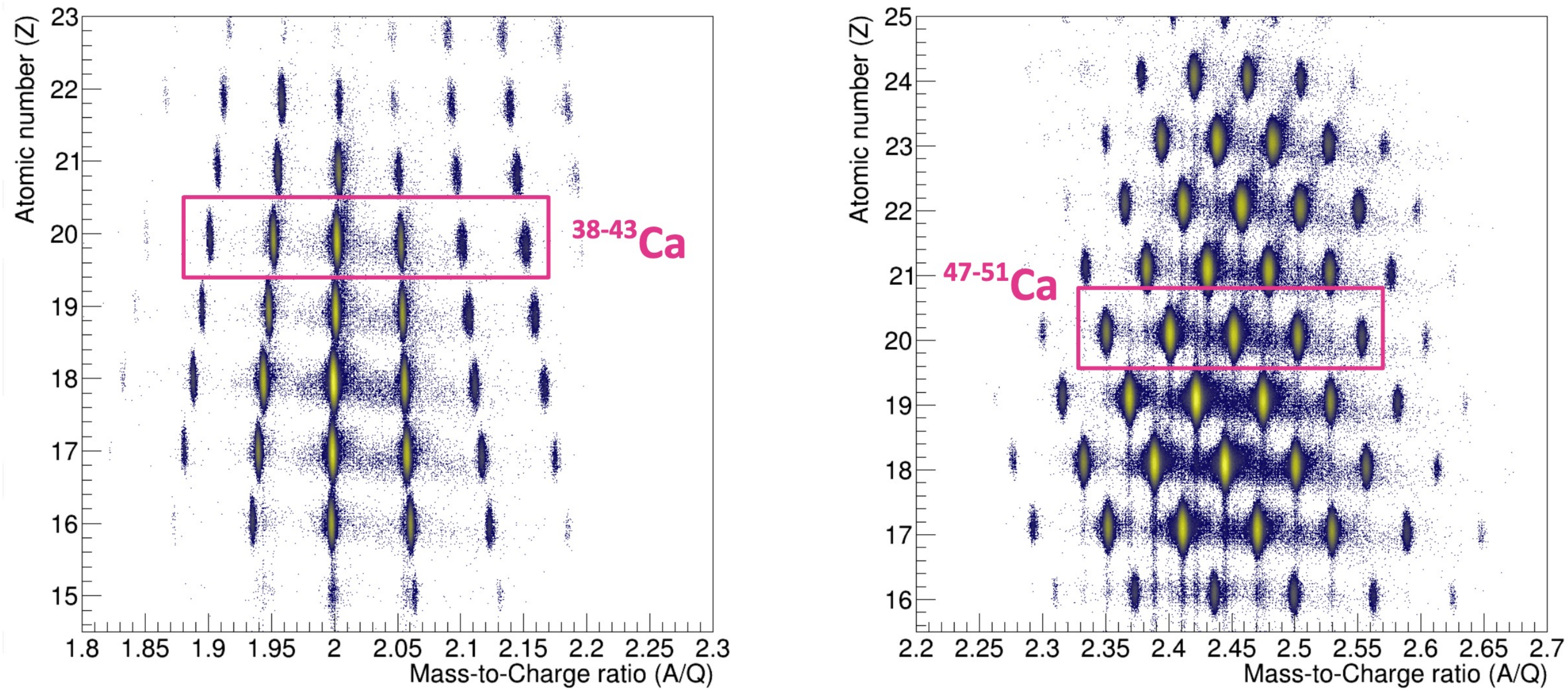
Pulse: 5-8 seconds, reduced microspill structure

We employed (p,2p) and (p,pn) quasi-free scattering reactions on a proton target to study the ground state configuration of the Ca isotopic chain (A=39-51). This measurement probes the quenching of spectroscopic factors as a function of isospin asymmetry (believed to originate from short-range correlations), and helps establish the evolution of the shell structure at Z=20 with N=28,30 and towards N=32; in particular, we probe the potential breaking of the Z=20 proton core as suggested by recent measurements of anomalously large charge radii in ^{50,52}Ca relative to ^{48}Ca.



Sudden removal of nucleons from exotic Calcium isotopes reveals their internal structure (copyright: R^{3}B Collaboration)

S467: Single-particle structure of neutron-rich Ca isotopes: shell evolution along Z=20



Both (p,2p) and (p,pn) reactions will be studied in several Ca isotopes covering a wide range of isospin asymmetry

R. Taniuchi, University of York, ongoing analysis

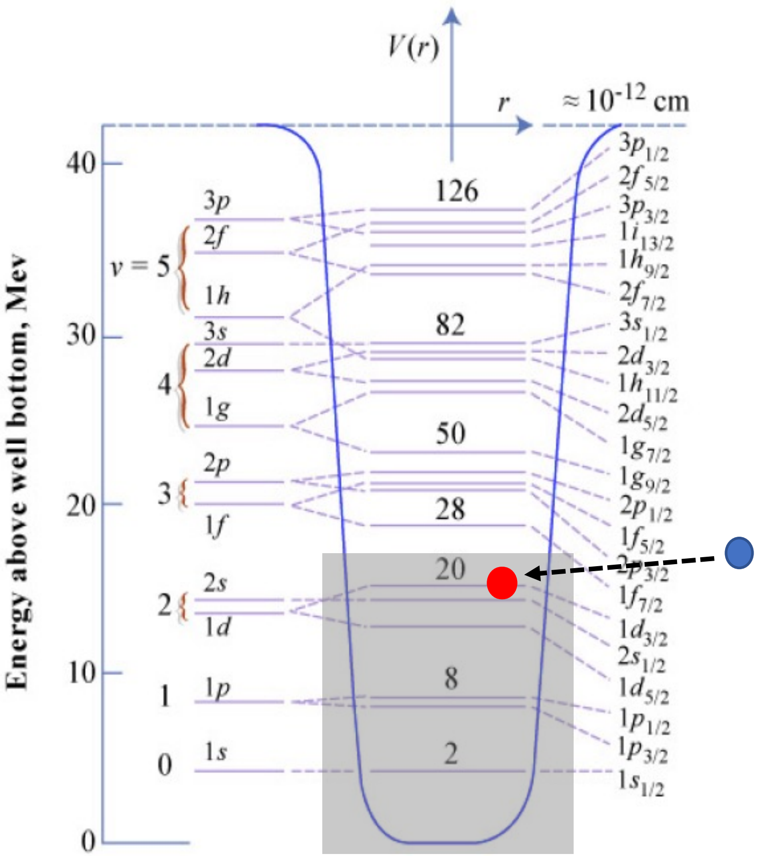
Summary (so far)

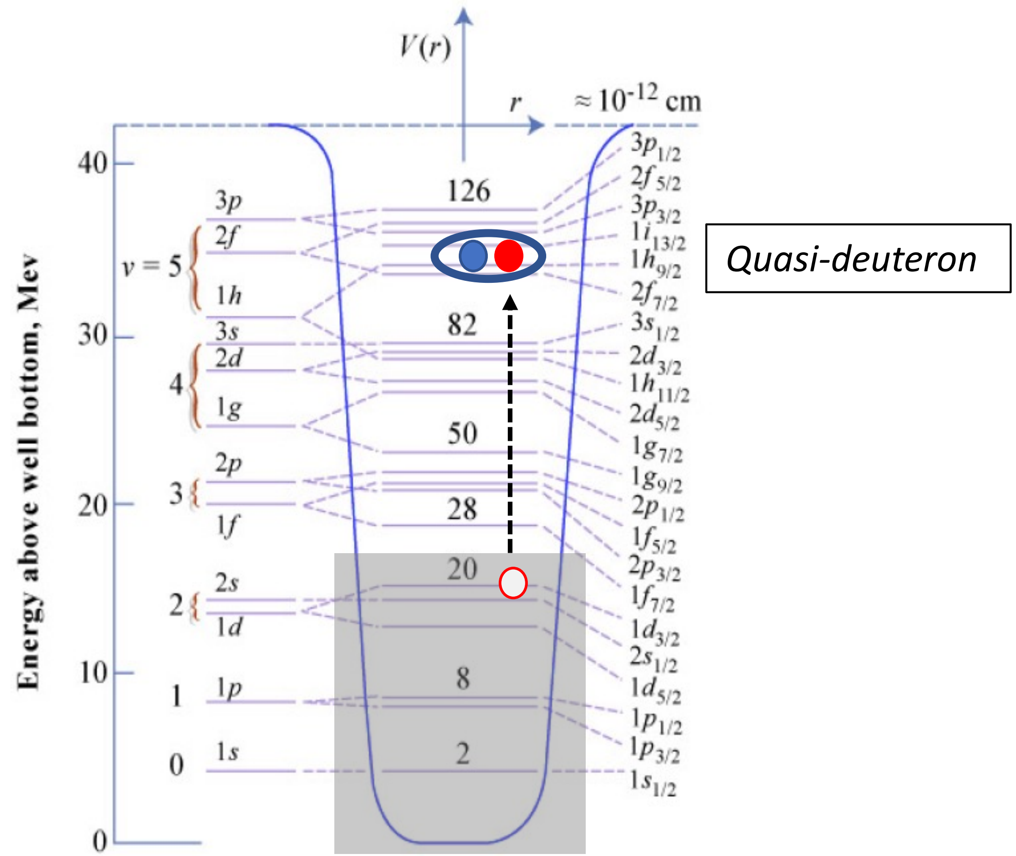
We proposed a phenomenological approach to examine the role of short- and long-range NN correlations in the quenching of single-particle strength in atomic nuclei and their evolution in asymmetric nuclei and neutron matter.

We showed that the recently observed increase of the high-momentum component of the protons in neutron-rich nuclei is consistent with the reduced proton spectroscopic factors.

Our approach connected results on short-range correlations from high-energy electron scattering experiments with the quenching of spectroscopic factors and addresses for the first time quantitatively this intriguing question in nuclear physics, in particular regarding its isospin dependence.

How do the IPM particles get dressed by the SRC?





$$|qp\rangle \sim 80\%|p\rangle + 20\%|h\rangle \otimes |qd\rangle$$

Probing nucleon-nucleon correlations in atomic nuclei via (p,pd) QFS Reactions

Experiment G-22-00091 (approved by the GSI PAC)

M. Petri[1], S. Paschalis[1], A. O. Macchiavelli[2]
for the R^3B Collaboration

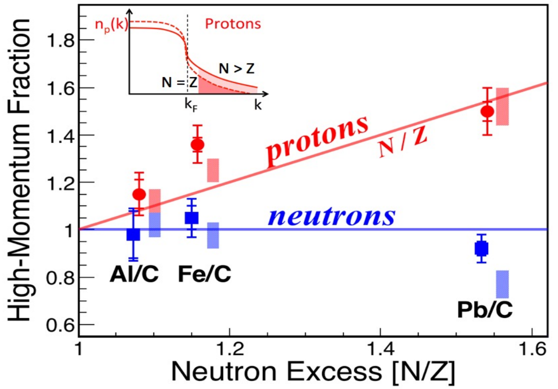
[1] Department of Physics, University of York, UK
[2] Physics Division, Oak Ridge National Laboratory, USA

Our motivation

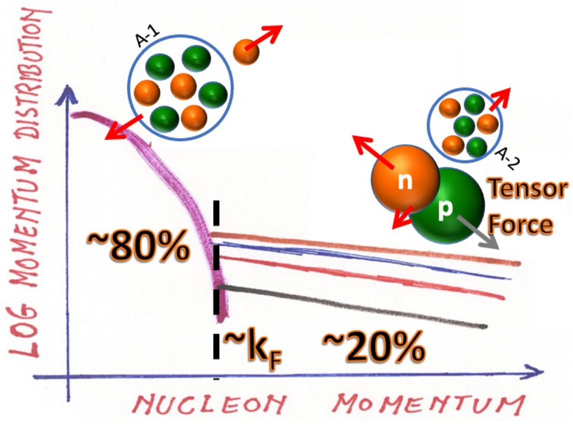
We follow the seminal discussions of Brueckner,

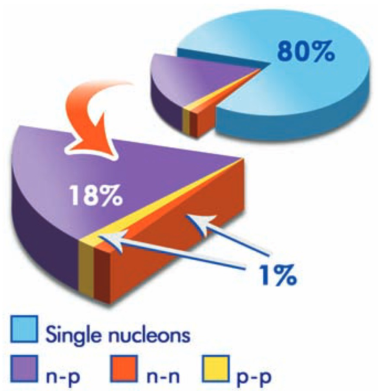
"The evidence is that for relative distances less than roughly 10^{-13}cm, nucleon pairs in nuclei are correlated in the same way as they are in the deuteron or in free scattering processes" [from K.A. Brueckner, Proceedings of the Rutherford Jubilee Int. Conf. Manchester 1961, Ed. J.B.Birks, London, **1961**]

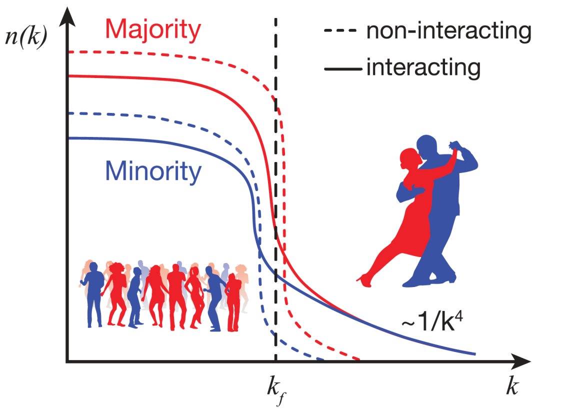
which are supported also by Jefferson Lab data on SRC studies:



Manifestation of tensor part of the NN interaction which favours the S=1, T=0 (quasi-deuteron) channel





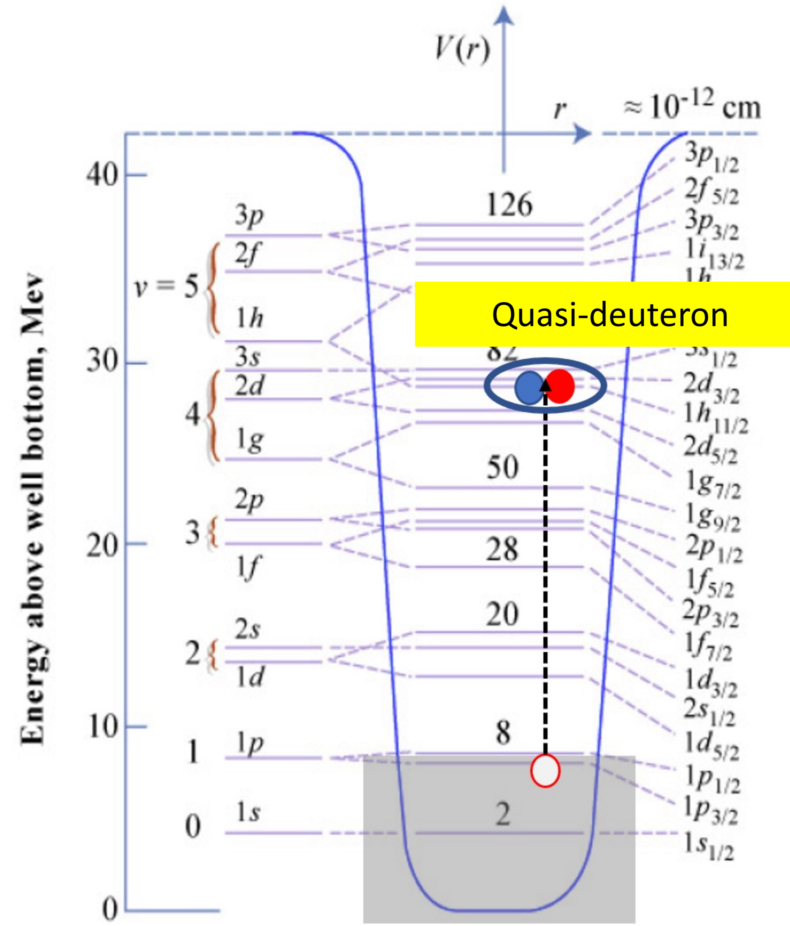


Duer, Nature (2018); Cohen, PRL (2018); Hen, RMP (2017); Hen, Science (2014); Hen, PLB (2013); Korover, PRL (2014); Fomin, PRL (2012); Subedi, Science (2008); Piasetzky, PRL (2007); Egiyan, PRL (2006)

Our motivation

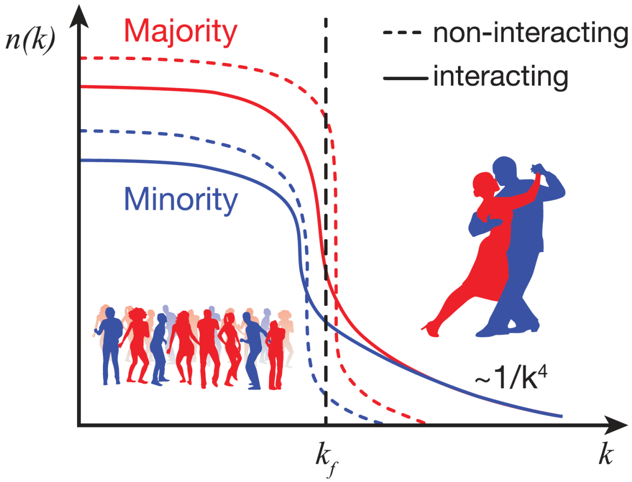
Our assumption is that a “bare” nucleon in the presence of the SRC components of the NN interaction becomes “dressed” in a quasi-deuteron cloud, about 20% of the time (for N=Z nuclei) and this is isospin dependent. In terms of the shell model, we can interpret the effect with a quasi-particle of the form:

$$|qp\rangle \sim \; 80\% \, |p\rangle \, + \, 20\% \, |h\rangle \, \otimes \, |qd\rangle$$

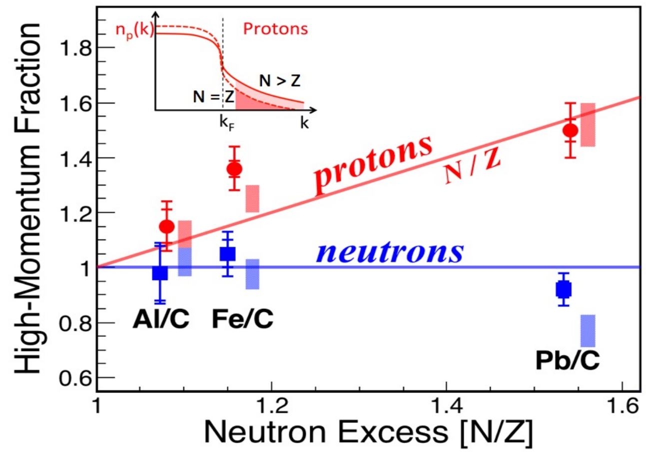


Thus, our motivation is to quasi-elastically remove those deuterons to confirm this assumption and determine its isospin dependency.

O. Hen et al., Science **346** (2014) 614



M. Duer et al., Nature **560** (2018) 617



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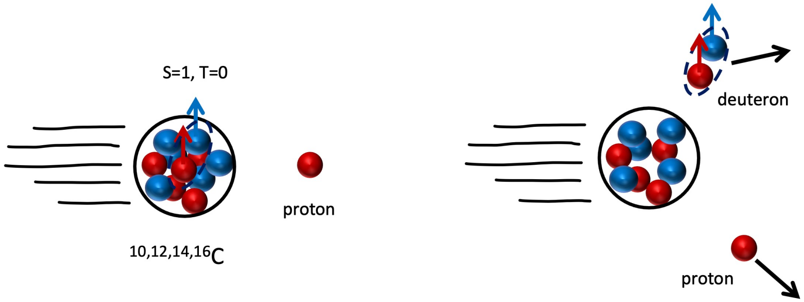
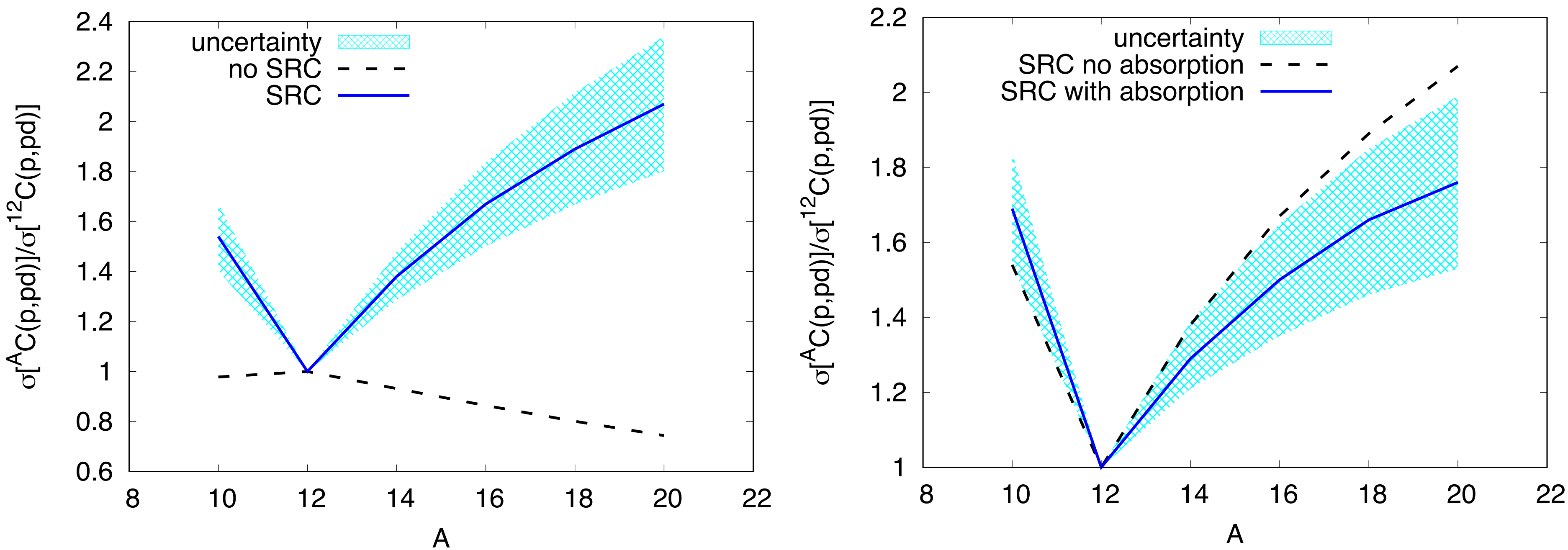
Nucleon-nucleon correlations and the single-particle strength in atomic nuclei

S. Paschalis [a,*], M. Petri [a], A.O. Macchiavelli [b], O. Hen [c], E. Piasetzky [d]

Our phenomenological approach **is consistent** with results from the dispersive optical model (**DOM**) that gives a clear dependence with isospin, as well as with **AV18 GFMC results**.

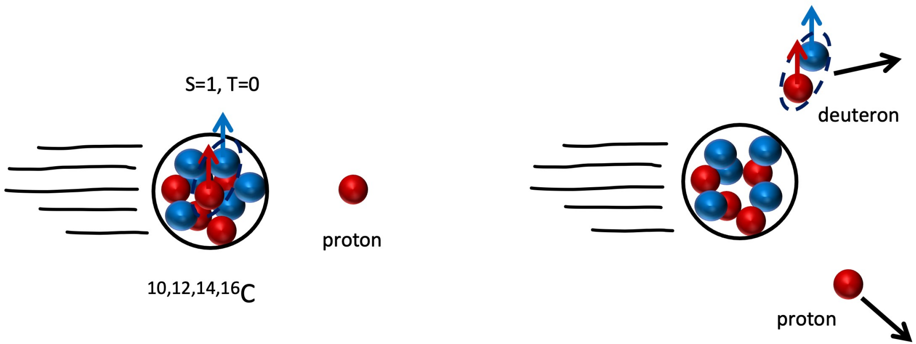


By measuring the (p,pd) cross section at **large momentum transfer**, along an isotopic chain, we are sensitive to SRC part of the wavefunction and to the suggested isospin dependence of SRC.

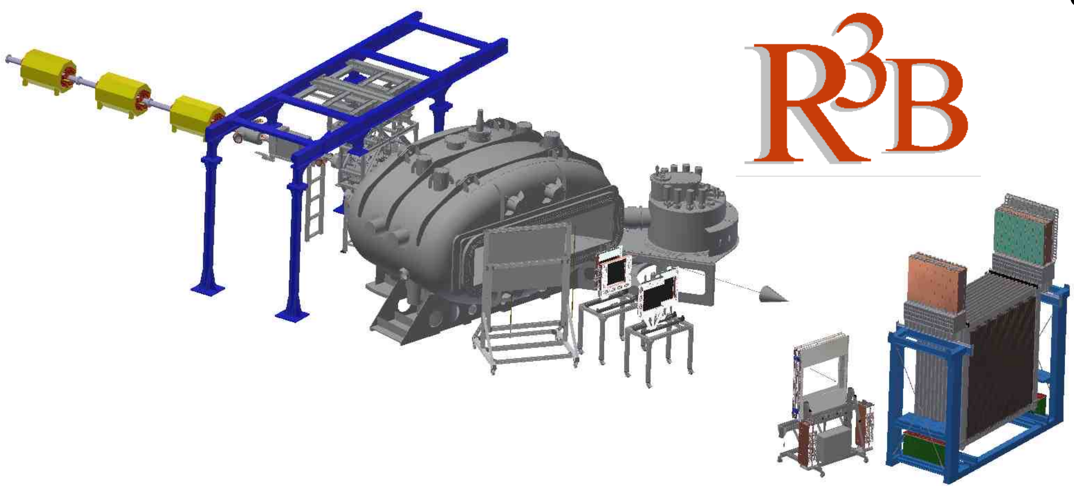


The (p,pd) cross section increases for the neutron-rich $^{14\text{-}20}C$ isotopes due to the minority nucleons (protons in this case) participating more and more into the quasi-deuteron formation as isospin increases.
In ^{10}C we predict an increase in quasi-deuteron content in its ground-state wavefunction but this time driven by the neutrons as the minority species.

(p,pd) QFS reactions

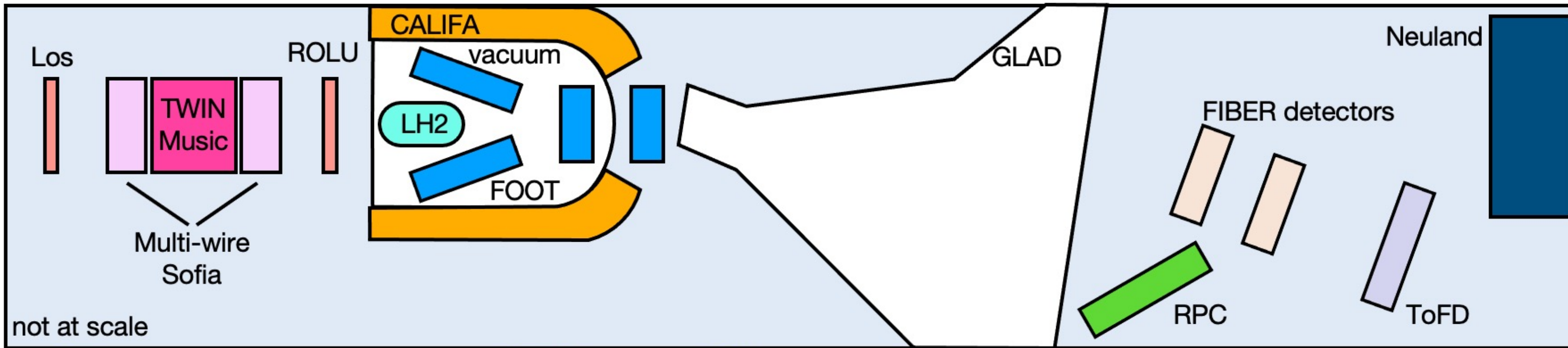


- Quasi-elastically knocking out deuterons along the C isotopic chain to probe the number of quasi-deuterons in a nucleus and their isospin dependence
- Kinematically complete measurements at R^3B using high purity beams from FRS at high energy (justifying the Quasi-elastic assumption)

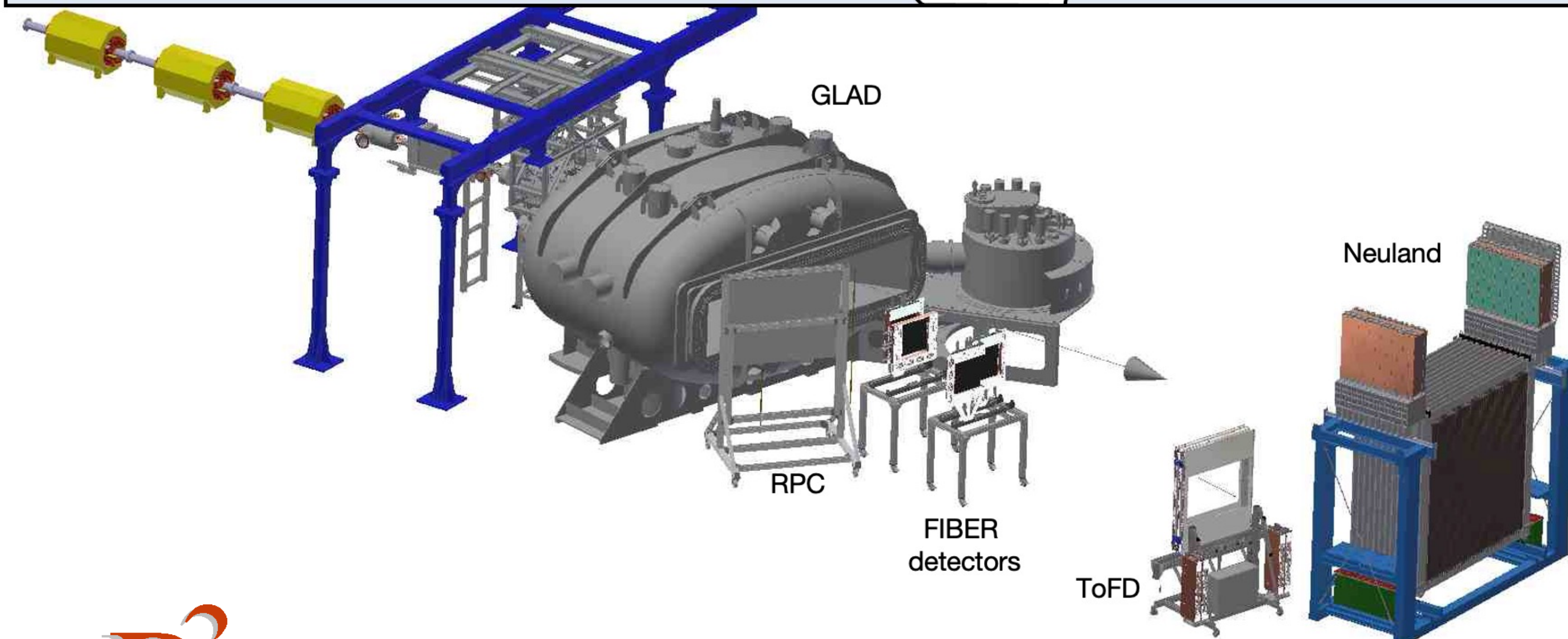


3 shifts for the ^{16}C(p,pd) channel
3 shifts for the ^{14}C(p,pd) channel
3 shifts for the ^{12}C(p,pd) channel
3 shifts for the ^{10}C(p,pd) channel
1 shift for an empty target run
1 shift for setup

Total: **14 shifts approved**
(8h/shift)

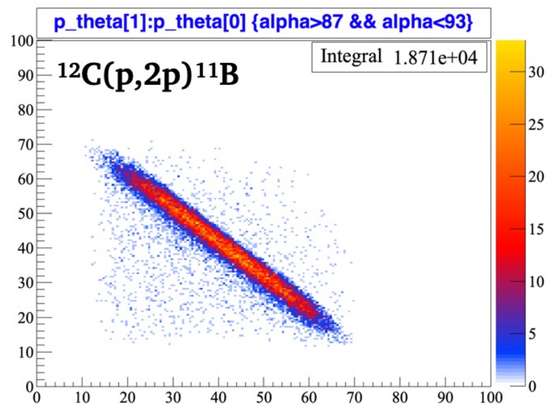


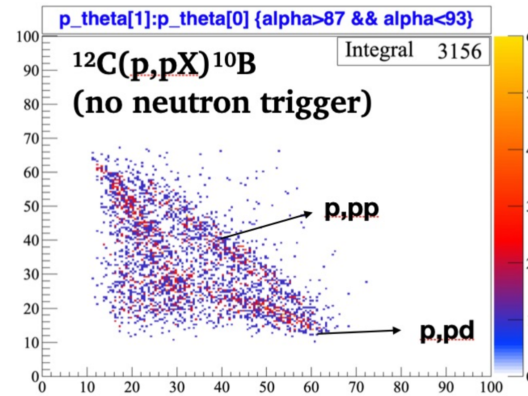
Los
TWIN
Music
ROLU
CALIFA
vacuum
LH2
FOOT
GLAD
Neuland
FIBER detectors
Multi-wire
Sofia
RPC
ToFD
not at scale

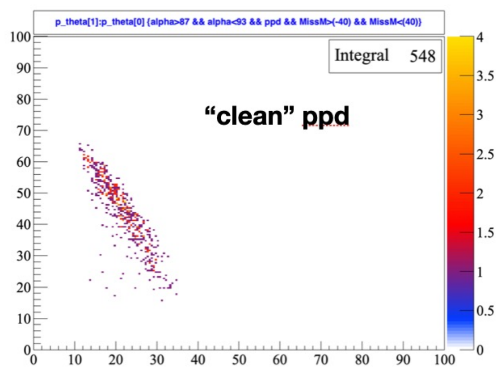


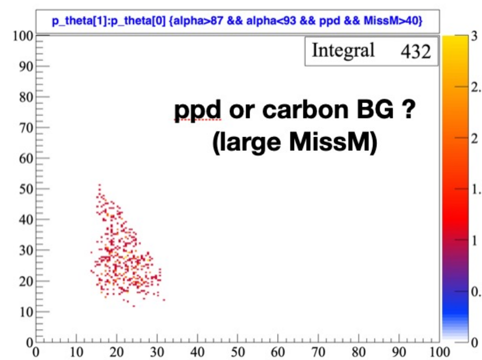
GLAD
Neuland
RPC
FIBER
detectors
ToFD

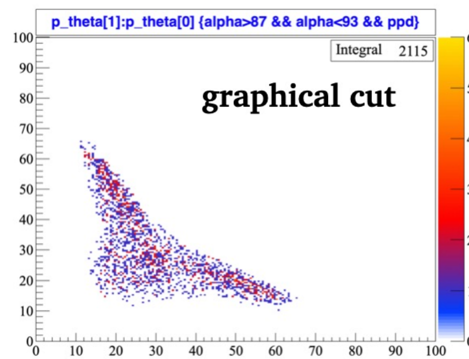
S296 analysis, Valerii Panin











Strong Interest in Theory

PHYSICAL REVIEW C **104**, 034311 (2021)

Short-range correlation physics at low renormalization group resolution

A. J. Tropiano,[1] S. K. Bogner,[2] and R. J. Furnstahl[1]
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(Received 18 June 2021; accepted 30 August 2021; published 13 September 2021)

PHYSICAL REVIEW C **106**, 024324 (2022)

Quasi-deuteron model at low renormalization group resolution

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(Received 25 May 2022; accepted 28 July 2022; published 19 August 2022)

"The nuclear wave function must include two-body short-range correlations (SRCs) with deuteron-like quantum numbers."

Strong Interest in Theory

Eur. Phys. J. A (2022) 58:120
https://doi.org/10.1140/epja/s10050-022-00765-z

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Regular Article - Theoretical Physics

Embedding short-range correlations in relativistic density functionals through quasi-deuterons

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Received: 1 April 2022 / Accepted: 12 June 2022 / Published online: 6 July 2022

Communicated by Vittorio Somà

"The formation of clusters at sub-saturation densities, as a result of many-body correlations, constitutes an essential feature for a reliable modelization of the nuclear matter equation of state (EoS)."

How do the single-particles get dressed in the nuclear medium?

FRIB-TA Colloquium: FRIB TA Dialogues on Nuclear Physics

Tuesday, September 8, 2020
Speaker: Or Hen (MIT)
Title: Nuclear Short-Range Correlations – Part 1
Hosts: Dick Furnstahl and Augusto Macchiavelli
Panelists: Scott Bogner, Alex Gade
Questions for FRIB-TA Dialogues v2.pdf

Tuesday, September 22, 2020
Speaker: Ragnar Stroberg (U. Washington)
Title: Nuclear Short-Range Correlations – Part 2
Hosts: Dick Furnstahl and Augusto Macchiavelli
Panelists: Stefanos Paschalis, Wim Dickhoff
Questions for FRIB-TA Dialogues v2.pdf

Questions for FRIB-TA Dialogues on Nuclear Short-range Correlations

“How do the single-particles get dressed in the nuclear medium?”

- A full understanding of nuclear SRCs and its isospin dependence is pivotal for studies of compact objects like neutron stars and of the nuclear equation of state.

- This experiment puts forward a compelling and complementary approach for studying the isospin dependence of SRCs through (p,pd) quasi-free scattering reactions.

Thank you !